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Global Trends in Small Satellites

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Executive Summary

Small satellites (smallsats) are an emerging class of spacecraft that incorporates recent software and hardware improvements, most notably ones derived from the IT and electronics industries, and benefits from the resulting high capability feasible in small packages. There is no universally accepted definition of a smallsat; various groups and reports have classified smallsats according to their mass, volume, cost, capabilities, or some combination thereof. In this report, smallsats are defined as satellites with masses lower than 200 kg (with some exceptions). Small satellites include CubeSats, special types of cuboid-shaped smallsats that weigh between 1–10 kg, and are created in units of a 10 cm × 10 cm × 10 cm cube. Compared with traditional satellites, smallsats typically have shorter development cycles, smaller development teams, and, consequently, lower cost, both for the development and for the launch of the satellites. CubeSats have the additional benefit of a standardized form-factor and containerization, enabling mass production and easier launch vehicle integration, which can further lower cost. These lower-cost satellites' expendability, faster refresh, and simultaneous deployment in large numbers—to enable lower-cost spatially or temporally distributed data collection—enables greater risk-taking, experimentation, and creation of new applications not feasible with larger satellites. As a result, smallsats are making inroads in almost every area of space—communication, remote sensing, technology demonstration, and science and exploration—and are operated by an ever-growing number of users. The global consultancy Euroconsult predicts that, whereas fewer than 700 smallsats were launched from 2006–2015, up to 3,600 smallsats are likely to be launched in the coming decade for a variety of missions. This number could reach well over 10,000 if even a fraction of the planned broadband constellations are deployed.

Given the growing perception that smallsats may both add to *and* take away from U.S. Government advantages as other entities begin to use them, the Office of the Director of National Intelligence (ODNI) asked the IDA Science and Technology Policy Institute (STPI) to identify global trends that would drive the smallsat sector in the coming decade, with the goal of guiding data collection within ODNI. The report focused on international and private activities in space (as distinct from those within the U.S. Government).

Approach

After an initial survey of current activities and trends in the smallsat sector, a team of STPI researchers selected four scenarios that could come to fruition in the next 10 to 15 years (i.e., 2027–2032). Next, the research team identified drivers that would lead to these scenarios. Our insights were informed by unclassified interviews with 67 experts in government, industry, academia, and the finance community, as well as a review of the publicly available literature.

Scenarios and Drivers

The four scenarios the STPI team selected are as follows:

- **Scenario 1**: **Two or more large smallsat constellations in low Earth orbit (LEO)**. Both broadband and imagery constellations of 100 or more small satellites have been commercially successful in LEO. This scenario considers primarily broadband "megaconstellations," which would provide affordable global broadband internet with low latency.
- **Scenario 2**: **Smallsats near-parity with larger satellites in remote sensing**. In this scenario, as a result of remote sensing capabilities being available commercially and outside the United States, a growing number of countries have access to technology that is at near parity with large satellites in remote sensing.
- **Scenario 3**: **Unsafe for satellite operation in LEO.** In this scenario, as a result of the growing number of smallsats in LEO, it is unsafe to operate satellites in orbits between 500 km and 1,200 km without risking collision. As a consequence, LEO is no longer viable for commercialization and smallsats are larger and more expensive for operation in different orbits.
- **Scenario 4**: **On-orbit servicing, assembly, and manufacturing of spacecraft a reality**. In this scenario, multiple persistent platforms in LEO and geostationary orbit (GEO) are being used by governments and the private sector for on-orbit servicing, assembly, and manufacturing (OSAM). As large satellites become cost competitive and hosted payload platforms become the norm, these platforms offer the satellite industry the flexibility to design, build, and deploy satellites that are best suited for a given application.

An analysis of these four scenarios led to the identification of 62 drivers that were organized into four categories for discussion purposes:

- **Market demand.**
  - *Demand for LEO-based services*, such as space-based communication, imagery-based intelligence, and situational awareness (SA),[*] is the core driver of nearly all the scenarios to varying degrees. This demand, in turn,

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[*] SA refers to a range of space-based sensing activities, such as radio frequency mapping, automatic identification system use, weather monitoring, space-based space situational awareness (SSA), rendezvous and proximity operations, and Automatic Dependent Surveillance—Broadcast (ADS-B).

drives the perception of profitability and consequently injection of funding and talent into other drivers, including the development of new technology, low-cost approaches, and infrastructure.

   - *Technology development* most relevant to the four scenarios examined includes optical imaging, radio frequency interference (RFI), spectrum usage, optical communications on small platforms, and miniaturization of propulsion systems.
   - *Low-cost approaches* to manufacturing, assembly, and robotics are included, as well as alternative business models, such as the use of modularity and standardization.
   - *Infrastructure* drivers include technology and systems to improve space situational awareness (SSA), networks of ground stations and in-space relays, and low-cost ground antennas and user terminals.

- **Access to space.** It is not only the cost of launch but also the availability of reliable launch options that drives whether the four scenarios can come to fruition in the timeframe of interest. Launch price is an especially critical driver of all the scenarios, except potentially for Scenario 1.
- **Competing alternatives.** Alternatives such as terrestrial and airborne platforms, as well as incremental and breakthrough innovations in large satellites drive the relative value proposition offered by smallsats, and can either make or obviate the case for smallsats. Developments in these alternative platforms have implications for Scenarios 1–3 and, to a different extent, Scenario 4.
- **Government policies.** Governments' policies related to spectrum allocation; RFI; protectionism/mercantilism; debris mitigation standards; on-orbit regulation; and space traffic management are driving—both positively and negatively—private sector interest in the smallsat ecosystem. Government policies are especially important drivers of Scenarios 1–3.

Findings

The STPI team took an in-depth look at trends within each of the driver categories alone and in various combinations to assess the likelihood of their contributing to the realization of the selected scenarios. Given trends in drivers, the team believes that the probability of Scenario 1 coming to fruition is high. Demand for broadband and imagery is growing, with funding following; required technology is available or is expected to be in the near future; and infrastructure breakthroughs needed are minimal. There are several rideshare options for launch, and further availability from large launchers and on-demand launch is expected in the next decade. While price of smallsat launch is decreasing, for at least broadband constellations, lack of reduction in price is not a deal-breaker given that these companies are making their business cases using today's launch prices rather than assuming reduced prices in the future.

Scenario 2 is also likely to be feasible. Incremental advances are being made in all three areas considered (ground resolution, synthetic aperture radar, and situational awareness), and costs at every step of the supply chain continue to fall. Companies currently involved in these areas are likely to receive appropriate U.S. Government permissions to operate commercially, and the rest of the world may follow.

Scenario 3 is unlikely to happen, although near misses with strategic assets in space may lead to restrictions on operations in certain valuable orbits. Both technology and policy efforts to develop propulsion capabilities are underway for smallsats, to improve SSA systems and to develop international guidelines for the long-term sustainability of outer space activities.

Scenario 4 is unrealistic for the timeframe of interest, not because of any technological limitations but because of low investment in the area at this time. OSAM capabilities are currently in their infancy, and research and development investment would need to increase significantly to see OSAM platforms emerge in GEO and LEO, something not indicated for the near future. Impetus for future investment is likely to come from private sector satellite manufacturers that wish to reduce cost or increase revenues by assembling or enhancing large satellites in space, though a future large space telescope funded by a government could speed technology development.

Conclusion

Given the trends identified, we recommend that ODNI pay attention to the following:

- *Speed at which enterprise and consumer demand for communication and imagery products/services is materializing.* Proxy measures include tracking the emergence of new funders and funds for smallsat activity; the emergence and success of new start-ups, and their business plans; disruptive developments especially related to high delta-v propulsion, low-cost manufacturing, resolution of imagery, and big data analytics; and foreign investment in upstream technology
- *Rate at which costs of manufacturing and other system costs for constellations are falling*
- *Whether global governmental policies related to spectrum allocation and management and regulations related to SSA and debris are aligned with emerging technologies, and being rolled out at a fast enough rate*

- *Developments in alternatives to LEO-based services, especially terrestrial networks and large high throughput satellites*
- *Alternative means for access to space* as opposed to cost reductions
- *Developments that lower the cost of data transmission from small platforms in space—low-cost mobile antennas, ground stations, and in-space relay stations*

Data-gathering effort along these dimensions would help the U.S. Government understand how the sector is changing, identify which actors have which capabilities, and assess the risks to their own assets, both in space and on the ground. Although it may not be possible for the United States to hold a large technological advantage in space over the rest of the world, it can continue to hold a large information advantage by strategically monitoring how these drivers are changing. Although the U.S. Government may not be able to directly influence or deter some technological advances in unfriendly countries, it can strategically develop its own assets to operate in a new regime of ubiquitous satellite services that are more robust than accidental or intentional data gathering by private companies. Such a strategy requires being informed on the state of the identified drivers. By continually monitoring these drivers, the U.S. intelligence community can be better prepared to navigate the next few decades of space development.

Contents

1. Introduction

A. Background

The space sector is undergoing a major transformation. Major subsectors, from launch to Earth observation, are increasingly being driven by commercial enterprise, which is a dramatic shift from the early days of government management of space activities. The sector is also becoming more segmented and globally integrated and is therefore more open to a variety of participants. These changes are electrifying for some, raising new hope that the vision of incorporating the solar system into the economic sphere may finally be at hand. But the changes are also wrenching for those who created and nurtured the government-led wave of the space enterprise.[1]

In many ways, developments in the sphere of small satellites (commonly referred to as *smallsats*) are the most emblematic of this transformation. Small spacecraft are not new (Figure 1-1); the first satellite in space, the Russian Sputnik 1, was launched in 1957 and weighed 83.6 kg, and a year later, the U.S. satellite Vanguard 1, at 1.5 kg, fit at least a part of the definition of a 1U CubeSat.[2] But low mass is not the only innovation in smallsats. Innovation in the smallsat domain is tied to the fly-learn-refly approach to development and launch of these satellites. This approach leads to shorter development cycles, smaller teams, and lower cost. Indeed, experts have noted that smallsats exhibit many features of a classic disruptive innovation. Like many other technologies that have been disruptive (e.g., personal computers over mainframes), they showed poor performance at start, for example, early CubeSats were essentially “beepsats.” They cost less than large traditional satellites. Hardware for a basic smallsat can be purchased for a few tens of thousands of dollars. They bring in new users and uses. Smallsats and more specifically CubeSats are introducing students and companies to space technology, and introducing the potential for new functionalities such as simultaneous multi-point measurements using multi-hundred/thousand constellations. Their performance has been improving rapidly and at low cost. Smallsats began as platforms for technology testing, and are now considered for advanced deep space missions such as providing real-time relay communication. Their

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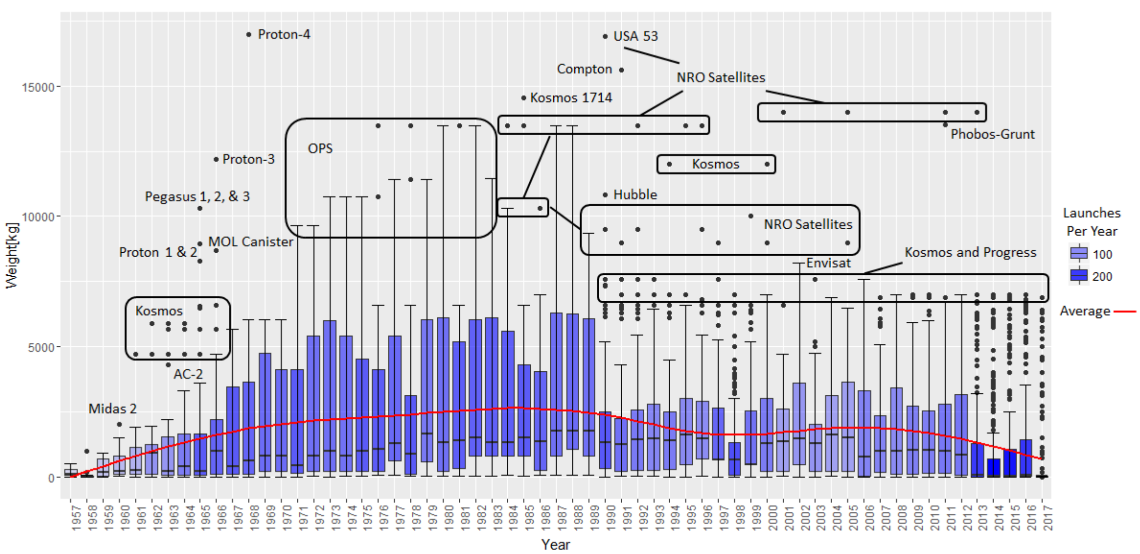
[1] B. Lal, E. Sylak-Glassman, M. Mineiro, N. Gupta, L. Pratt, and A. Azari, *Global Trends in Space*. IDA Paper P-5242, 2 volumes, (Alexandria, Virginia: IDA, June 2015).

[2] CubeSats are cuboid-shaped smallsats that weigh 1–10 kg, and are created in standard dimensions measured in units of 10 cm × 10 cm × 10 cm (1U). National Academies of Sciences, Engineering and Medicine, *Achieving Science with CubeSats: Thinking Inside the Box* (Washington, DC: National Academies Press, 2016), https://www.nap.edu/catalog/23503/achieving-science-with-cubesats-thinking-inside-the-box.

origin was outside the mainstream aerospace sector that emphasizes exquisite capability, long platform lifetimes, and high-reliability components. They are driven by enabling technology such as advances in software, processing power, data storage, camera technology, compression and solar array efficiency, all outside the aerospace sector. They follow different development models.

In this way, the smallsat community's culture seems similar to that of a technology start-up and the maker movement, both of which encourage rapid innovation, even at the expense of mission or platform assurance. This trait contrasts with the traditionally conservative space sector that emphasizes exquisite capability, long platform lifetimes, and high-reliability components.

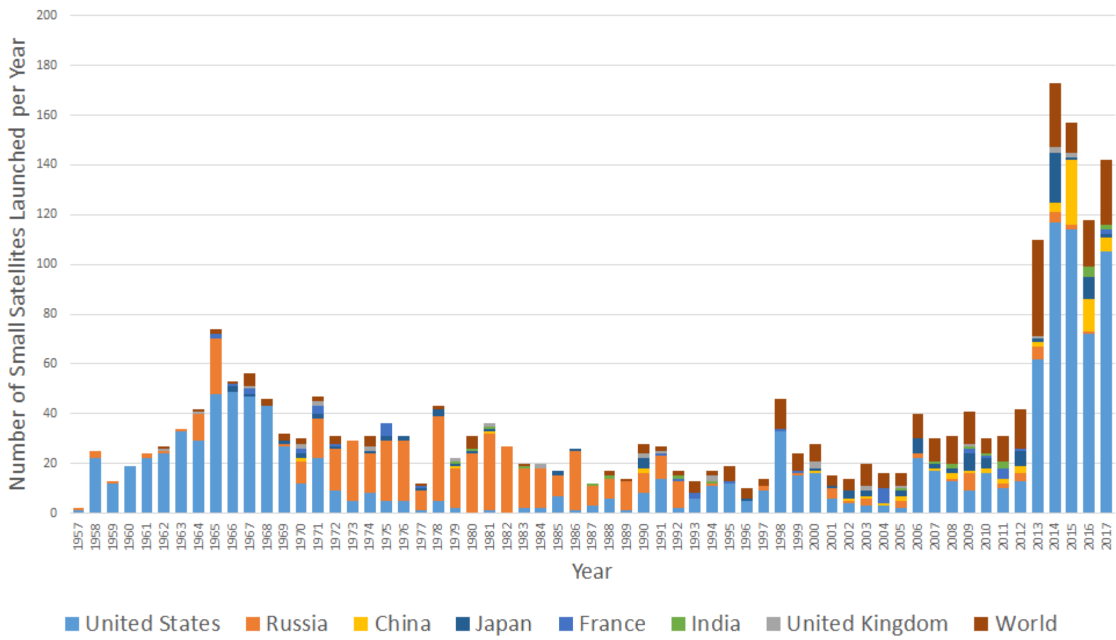
Smallsats are thus making inroads in almost every mission area of space—communication, remote sensing, technology demonstration, science, and exploration—and they are operated by an ever-growing number of users (Figure 1-2).



Source: J. McDowell, June 2017, "Satellite Catalog," http://planet4589.org/space/log/satcat.txt.

Note: Shading represents the number of satellites launched in that year.

Figure 1-1. Satellite Mass by Year



Source: J. McDowell, June 2017. Satellite Catalog, http://planet4589.org/space/log/satcat.txt.
Note: "World" refers to rest of the world.

Figure 1-2. Number of Satellites Under 200 kg Launched by Year and Country

B. Project Description

Given the growing perception that smallsats may both add to *and* take away from the U.S. Government's current advantage in the space sector as other entities begin to use them, the Office of the Director of National Intelligence (ODNI) asked the IDA Science and Technology Policy Institute (STPI) to identify trends that could drive the smallsat sector in the coming 10 to 15 years, with the goal of guiding data collection within ODNI.

C. Defining a Small Satellite

There is no consensus on the precise definition of a smallsat. Most definitions are based on an upper limit on the mass of the satellite, though there is no agreement on where the boundary between and small and larger satellites lies:

- **Under 180 kg.** The NASA Small Spacecraft Technology Program defines a smallsat as a spacecraft that has a mass of less than 180 kg.[3] This definition is likely based on the upper limit for a single slot in an Evolved Expendable launch

[3] NASA, "About SSTP," https://www.nasa.gov/directorates/spacetech/small_spacecraft/smallsat_overview.html.

Vehicle (EELV) Secondary Payload Adaptor (ESPA) system.[4] Other organizations, such as the Air Force Research Laboratory, have a similar definition, but find the “sweet spot” to be 50–100 kg.

- **Under 500 kg.** Euroconsult, a global strategy consulting firm in the space sector sets the upper boundary for a small satellite’s mass at 500 kg.[5, 6]
- **Under 1000 kg.** Other organizations have yet higher thresholds. Surrey Satellite Technology Ltd. (SSTL), one of the first private sector organizations to develop smaller satellites, focuses on the design, manufacture, launch, and operation of smallsats that come in at over 700 kg.[7] This high upper cap is reflected elsewhere as well; the European Space Agency (ESA) considers smallsats to be 350–700 kg.[8] Lockheed Martin has designed and manufactured over 150 spacecraft it classifies as “small satellites,” 1000 kg being the upper limit,[9] and is joined by others from both academia and industry.[10, 11, 12, 13]

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4 The ESPA-ring is a support structure that can hold several smallsats (or one large spacecraft) for launch on a number of different rockets. A variant of the ESPA-ring that can support heavier payloads, the ESPA Grande, is currently in development, which would be able to support 5 payloads of up to 600 kg each. For more details, see: http://kiss.caltech.edu/study/smallsat/KISS-SmallSat-FinalReport.pdf.

5 Irena Nikolova, “Micro-Satellites Advantages, Profitability and Return,” S E S 2 0 0 5 Scientific Conference, 10–13 June 2005, Varna, Bulgaria, p. 2, http://www.space.bas.bg/astro/SES2005/SS3.pdf.

6 Euroconsult, “Prospects for the Small Satellite Market,” 2016.

7 Surrey Satellite Technology Ltd., “About SSTL,” http://www.sstl.co.uk/About-SSTL.

8 “Small Satellite Missions, Background Paper 9,” Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III), 26 May 1998, p. 5, http://www.unoosa.org/res/oosadoc/data/documents/1998/aconf_184/aconf_184bp9_0_html/ACONF_184_BP09E.pdf.

9 Lockheed Martin, “Small Satellites, Big Heritage: Mission Capable, Responsive Development, Assured Performance,” http://www.lockheedmartin.com/content/dam/lockheed/data/space/documents/tradeshows/smallsat2012/2012%20SmallSat%20Fact%20Sheet_Rev3.pdf.

10 James D. Rendleman, “Why SmallSats?” AIAA SPACE 2009 Conference & Exposition, 14-17 September 2009, Padadena, California, Page 1, http://www.enu.kz/repository/2009/AIAA-2009-6416.pdf.

11 Brian Weeden, “Small Satellite Space Traffic Management,” Secure World Foundation, http://swfound.org/media/23310/weeden%20-%20smallsat%20space%20traffic%20management.pdf.

12 Royce Dalby, “Smallsat Market Projections,” Avascent, http://www.avascent.com/wp-content/uploads/2015/10/Smallsat_Market_Projections_White_Paper_10082015.pdf

13 G. M. Webb, Fadeev A. Pestmal N., “The Inexpensive Injection of Mini-Satellites into GEO,” Commercial Space Technologies Ltd, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1747&context=smallsat.

Mass, however, is not the only defining feature of a smallsat. It is, in fact, often a proxy for the common characteristics of a smallsat: affordable development and operations costs, accessibility to a broader set of developers (including universities or small businesses), short timescales to readiness, and shorter lifetimes. Some experts have proposed that spacecraft under a certain cost threshold be referred to as smallsats; others have proposed that the community refrain from using the term at all.[14] Preliminary findings from a study by the International Academy of Astronautics indicate that neither mass nor size is suitable for defining smallsats. Rather, a variety of other factors should be used instead: philosophy of design, mission, program management, risk and reliability, and cost.[15] Borrowing from the automotive sector, the authors imply the term *lean satellites* should be used rather than s*mall satellites*.

> New types of customers are emerging today who want more value from satellites through lower unit prices and faster system delivery. Currently, mega-constellations consisting of hundreds or thousands of satellites are being proposed. Traditional satellite development philosophy cannot be applied to mega-constellations because the total cost would be prohibitively high. Small satellites and mega-constellations can benefit from the application of the lean satellite concept, although it must be modified to accommodate the differences between satellites and automobiles. Space systems engineering has put emphasis on delivering a perfectly working system. On the other hand, lean concept has put emphasis on delivering a high-quality product with the minimum cost and shortest time.

Having examined the range of definitions, the STPI research team chose to focus on satellites with masses at or below 200 kg, regardless of the satellite's capability or cost. While individual smallsat technologies may have a place in systems ranging up to larger masses (e.g., even an 800 kg spacecraft can benefit from a compact guidance, navigation, and control system), satellites offer a unique value proposition at smaller sizes. Under 200 kg, the key smallsat characteristics mentioned previously, such as lower cost, begin to be more dominant. Within this band, we pay particular attention to (and differentiate where appropriate) CubeSats, because here, again, there is a unique value proposition in their standardized form, which can offer advantages in a subset of applications. Figure 1-3 especially highlights the role of CubeSats since 2013.

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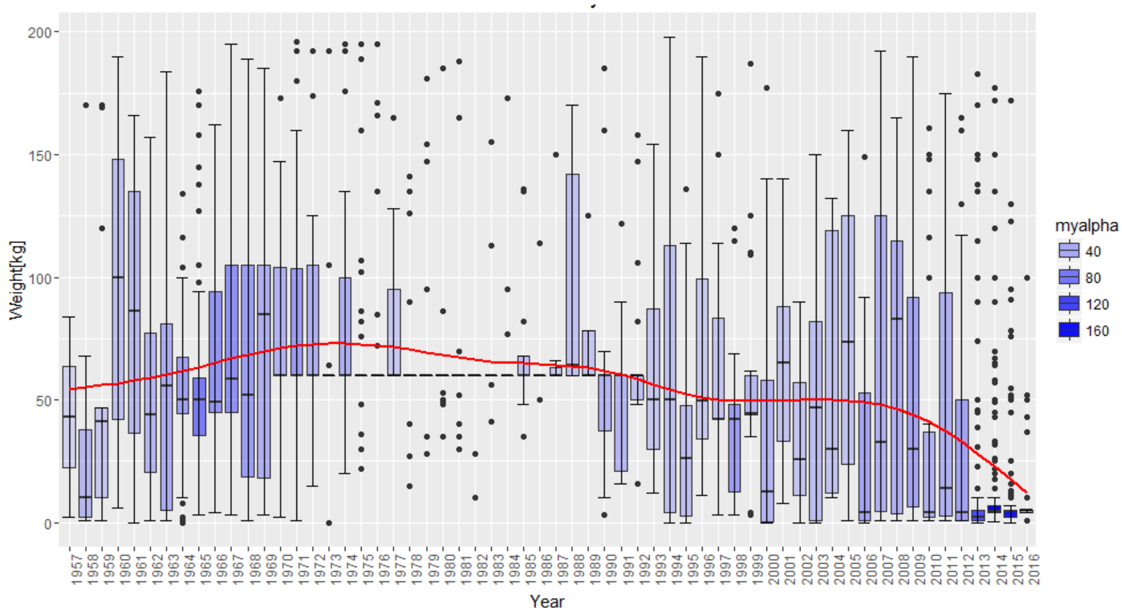
[14] United Nations Office for Outer Space Affairs, International Telecommunication Union, "Guidance on Space Object Registration and Frequency Management for Small and Very Small Satellites."

[15] Mengu Cho and Filippo Graziani. "Lean Satellite Concept," http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3509&context=smallsat.



Source: J. McDowell, Satellite Catalog, http://planet4589.org/space/log/satcat.txt.
Note: Shading represents the number of satellites launched in that year.

Figure 1-3. Satellites under 200 kg by Year

We include larger systems in application areas where 200 kg would be too small and note when we make such application-specific exceptions. For example, when discussing the use of smallsats for broadband internet or space situational awareness (SSA), we include systems up to 500 kg.

D. Approach

The scope of this project is limited to the smallsat ecosystem in 10–15 years from now (i.e., 2027–2032). The STPI team used a scenario-based approach to identify key drivers that may affect developments in the smallsat sector in this timeframe. The team using a three-pronged approach:

1. First, we examined the *small satellite value chain* by developing a database of over 650 actors in the smallsat ecosystem based on expert interviews and literature review.
2. We developed *scenarios* to illustrate the interplay among key external and intrinsic drivers that could lead to specified potential end states (10–15 years into the future) and the implications for each end state on the global smallsat ecosystem.
3. We identified *drivers* that could lead to one or more of these scenarios, and we explored near- and far-term trends in each. We also examined, based on these trends, which scenarios are likely to come to fruition.

These steps are discussed in the following subsections.

1. Examining the Smallsat Value Chain

STPI researchers conducted interviews with almost 70 individuals engaged in the small satellite industry and developed a database of over 650 organizations in the smallsat sector. We found that the smallsat ecosystem could be represented by the model in Figure 1-4. The ecosystem can be divided into three categories: value chain, users and consumers, and foundational actors.

The *value chain* is composed of three segments: upstream actors and institutions engaged in manufacturing and system integration of smallsats; midstream organizations that operate and launch small satellites; and downstream actors and organizations that analyze and package data streams into useful insights and business intelligence. *Users and consumers* of small satellite data and services are not just governments; increasingly, they are businesses and individual consumers (gray boxes in Figure 1-4). Finally, *foundational actors* provide the underpinning necessary for the ecosystem, including research and development (R&D), funding sources, and legal and regulatory support.

This model served as a framework for our understanding of a rapidly growing and evolving industry and guided our assessment of the smallsat activities occurring both in the United States and globally.

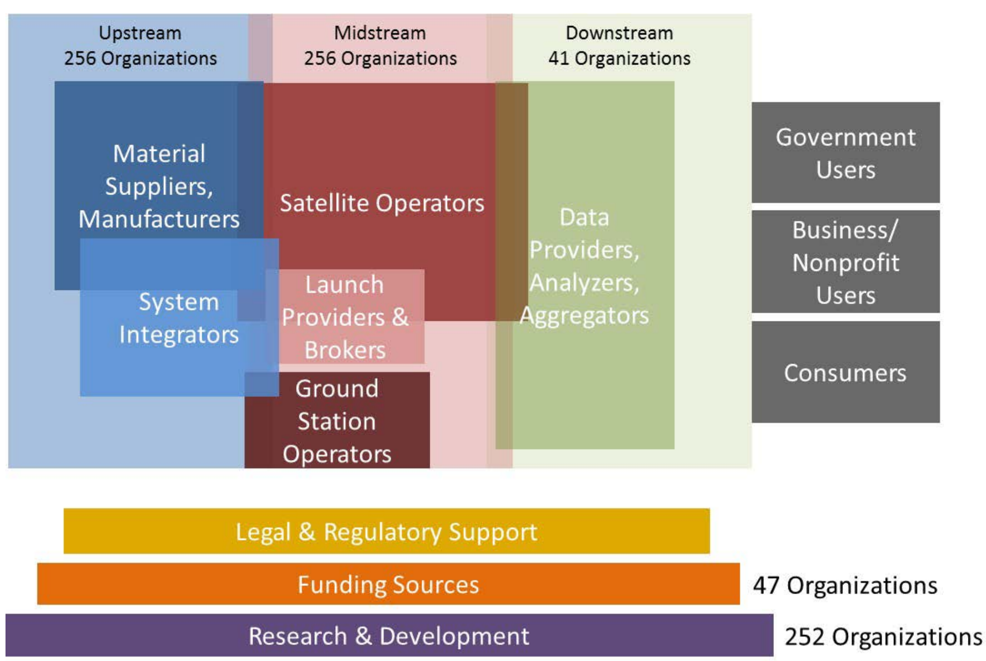


Figure 1-4. Small Satellite Ecosystem by Subsector

2. Developing Scenarios

Scenario-based methodologies are used across disciplines to inform policy, business, and academic endeavors.[16] Across disciplines, the term "scenario" is defined in various ways; we guided our analysis based on the following description:[17]

> A scenario can be defined as a description of a possible future situation, including the path of development leading to that situation. Scenarios are not intended to represent a full description of the future, but rather to highlight central elements of a possible future and to draw attention to the key factors that would drive future developments. Many scenario analysts underline that scenarios are hypothetical constructs and do not claim that the scenarios they create represent reality.

Thus, our purpose was not to create scenarios that depict self-fulfilling scenarios of inevitable futures or to encompass every possible future development. Rather, our intention was to call attention to interactions between key factors and drivers that lead to the described potential end state, to inform decision making and data collection efforts, and to challenge traditional thinking about the applications that could be enabled.

To develop possible scenarios for this analysis, we adapted a generalized five-phase process proposed by a meta-analysis completed by the German Development Institute (Figure 1-5).[18] The scenarios were developed following a hybrid approach in which we used both quantitative and qualitative information, excluding dramatic events, such as malicious acts by hostile actors (e.g., intentional radio frequency interference or antisatellite weapons use). Scenarios chosen illustrate potential end states and the interplay of various drivers that could lead to those states.

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[16] Philip van Notten, "Scenario Development: A Typology of Approaches," https://www.oecd.org/site/schoolingfortomorrowknowledgebase/futuresthinking/scenarios/scenariodevelopmentatypologyofapproaches.htm.

[17] H. Kosow and R. Gassner, "Methods of Future and Scenario Analysis," Deutsches Institut fur Entwicklungspolitik. https://www.die-gdi.de/uploads/media/Studies_39.2008.pdf

[18] IZT/ZVEI (Insitut für Zukunftsstudien und Technologieberwertung/Zentralverband Elektrotechnik- und Elektronikindustrie e. V.), *Integrated Technology Roadmapping: A Practical Guide to the Search for Technological Answers to Social Challenges and Trends*, (Berlin: IZT WerkstattBerichte 87), 2007.

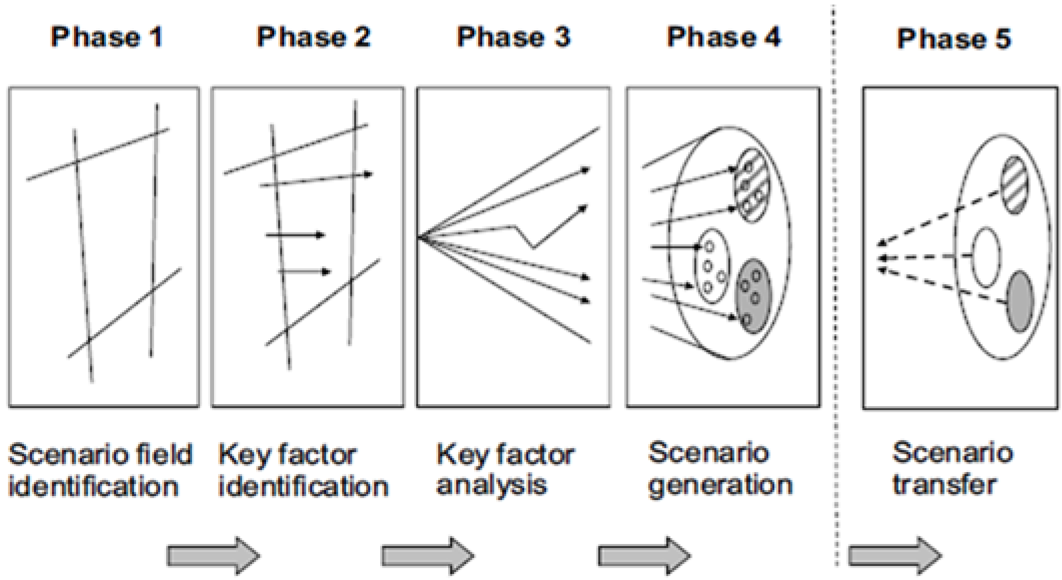

Figure 1-5. Basic Five-Phase Scenario Process[19]

For the team's purposes here, we conducted Phases 1–4 depicted in the figure in a different order, as follows:

- **Phase 1:** We identified the scenario field (scope) as the small satellite ecosystem in place 10–15 years from now (i.e., 2027–2032).
- **Phase 4:** We generated four scenarios. In the first scenario, two or more constellations of hundreds or thousands of smallsats operate together in low Earth orbit. In the second scenario, smallsats are almost as capable as larger satellites in the area of remote sensing. In the third scenario, operating in low Earth orbit is unsafe. In the last scenario, on-orbit servicing, assembly, and manufacturing of spacecraft is a reality.
- **Phases 2 and 3:** Key factors include all external and internal drivers that influence the direction of the small satellite ecosystem to the scenarios chosen. The drivers identified for this project (Phase 2) fall into three categories: market demand, access to space, competing alternatives, and government policy. Analyses of trends, developments, projections, and interactions among these drivers constitute Phase 3.

Transferring insights from our analysis of drivers and scenarios to action (Phase 5) involves additional analyses that is outside the scope of this project.

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[19] Ibid.

3. Identifying Drivers

We used the scenarios as a means to identify drivers propelling the development and direction of the smallsat sector. We identified 62 drivers that could lead to one or more of the scenarios coming to fruition. Of these 62, we selected a subset of drivers most relevant to the scenarios for in-depth analysis. We examined the evolution of the drivers, as well as the current and predicted trends, and assessed the influence of the individual drivers on each scenario. To the extent possible, we also provided our own assessment of how realistic the reported trends in the drivers were.

The drivers fell into four categories: (1) market demand, which includes demand for services based in low Earth orbit (LEO), availability of funding, technology development, low-cost approaches, and infrastructure; (2) access to space; (3) low-cost alternatives; and (4) government policies.

E. Data Sources

The STPI team used multiple data sources to develop our scenarios and drivers (Table 1-1). First, an initial review of available literature was conducted to identify areas relevant to smallsat technology—including technology trends in subsystems and global trends in development, launch, and operation of smallsats that add to their value. We conducted 67 unclassified interviews with experts from government, industry, academia, and the finance community. In addition to relying on expertise of multiple consultants, members of the research team attended conferences and symposia to understand general and technical trends and interview various industry experts and vendors.

Table 1-1. Data Sources

Literature Review				
National Academy of Sciences CubeSat Report (2016)				
NASA Small Spacecraft Technology Program (SSTP)/Ames Research Center State-of-the-Art Report (2015)				
Trade Association and Other Reports: Euroconsult SmallSat Market Analysis, Satellite Industry Association Annual Reports, Space Works, Frost & Sullivan, NSR				
Other Literature—STPI Report on Microsatellites, journal articles				
Interviews with Stakeholders (67 Conducted)				
Industry (37)				
United States (26 total)	Upstream (11)	Midstream (9)	Downstream (3)	Investor (3)
International (11 total)	Upstream (7)	Midstream (4)	Downstream (0)	Investor (0)
Government and Nonprofit Organizations (30)				
United States (27 total)	NASA (12)	University (5)	Nonprofit, Other (5)	DoD & Other Government (5)
International (3 total)	JAXA (1)	University (2)		
Conferences				
Small Sat 2016, Hosted Payload and SmallSats Summit, USGIF Small Satellite Workshop, HTS Roundtable: LEOs—MEOs & GEOs: The New Risk vs Reward Gambit				
STPI Database of Smallsat Organizations				

F. Organization of the Report

The remainder of this report is organized as follows. In Chapter 2, we describe the four scenarios and explain the implications of each in terms of the smallsat ecosystem. Chapters 3–6 are the heart of the report; they discuss the external and internal drivers that influence the future direction of the smallsat ecosystem. The drivers fall into four categories: market demand (Chapter 3), access to space (Chapter 4), competing alternatives (Chapter 5), and government policy (Chapter 6). Chapter 7 examines how combinations of these drivers could pave pathways that lead to realization of our four scenarios. Chapter 8 provides a summary and conclusions. Appendixes A–G provide supporting documentation:

- Appendix A lists names and affiliations of all our interviewees.
- Appendix B identifies global trends in the smallsat market.
- Appendix C presents details of the smallsat ecosystem.
- Appendix D provides projections of the state of the art in smallsat technology.

- Appendix E presents an overview of international activities and trends.
- Appendix F summarizes a range of smallsat applications.
- Appendix G provides case studies of 22 companies involved in smallsat development.

2. Small Satellite Scenarios and Drivers

In this chapter, we introduce four feasible scenarios for the 2027–2032 timeframe. Our goal is to use them as potential end states to identify drivers of developments in the smallsat sector. Scenario 1 relates to the presence of "megaconstellations," constellations of hundreds or even thousands of smallsats that work in concert to achieve goals of interest. In this scenario, at least one broadband and one imagery constellation are commercially successful. For Scenario 2, we assume that smallsats are almost as capable as larger satellites, especially in the area of remote sensing and situational awareness (SA).[20] As a result of these capabilities, a growing number of countries have achieved near-parity in remote sensing and Earth observation (EO) with current spacefaring nations. In Scenario 3, low Earth orbit (LEO) is degraded to the point that it has become unsafe to operate satellites in orbits between 500 and 1,200 km without risking collision. As a consequence, smallsats have become larger, more expensive, operate in different orbits than LEO, and LEO has lost its potential for commercialization. For Scenario 4, we assume that on-orbit servicing, assembly, and manufacturing (OSAM) of spacecraft is a reality, and multiple persistent platforms in LEO and GEO are being used by governments and the private sector for OSAM.

A. Scenario 1: Two or More Large Smallsat Constellations in LEO

1. Description

In this scenario, at least two megaconstellations of 100 or more small satellites each would be operating and be commercially successful. At least one communication constellation would be providing affordable global broadband internet (Table 2-1).[21]

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[20] SA refers to a range of space-based sensing activities, such as radio frequency mapping, automatic identification system use, weather monitoring, space-based space situational awareness (SSA), rendezvous and proximity operations, and Automatic Dependent Surveillance—Broadcast (ADS-B).

[21] While this scenario focuses on broadband, it is important to note that communication constellations can provide other services such as smallsat-based telephony, machine-to-machine (M2M) communication, and Internet of Things (IoT) services. These services can be provided by smaller, less-sophisticated, cheaper-to-launch platforms than broadband, and are therefore of greater interest outside the United States. Kepler Communications (Canada) is planning to use CubeSats to provide M2M communications, and Sky and Space Global (UK) is planning to use CubeSats to provide affordable internet telephony. Compared to OneWeb constellation cost of roughly $3.5B,Sky and Space Global estimates its 200-satellite constellation to cost around $150M inclusive of design, manufacturing,

Table 2-1. Broadband Constellations

	Speed (Mbps)	Cost ($ per month)	Latency[a] (milliseconds)
Fiber (2017)	1,000[b]	$70 with no data cap[c]	10–20[d]
GEO (2017)[e]	25	$130 for 50 GB	500–600
Scenario constellation (2027–2032)	1,000[f]	Proposed to be comparable to fiber	20–50[g]

[a] SpaceX's and Boeing's constellation designs use intersatellite connections, which might enable global low-latency connections. OneWeb's satellites do not communicate with each other and instead communicate with local ground stations, which would allow for local, and not global, low-latency connections within one satellite's operational field of view.

[b] Based on Google Fiber services, https://fiber.google.com/about/.

[c] Based on Google Fiber Plans and pricing for internet services. https://fiber.google.com/cities/kansascity/plans/

[d] Jose del Rosario and Prashant Butani, 2015. "LEO-HTS Constellations Resurrected: Would They or Won't They? Northern Sky Research http://www.nsr.com/upload/presentations/NSR_Webinar-_LEO_HTS_Constellations-_May_2015.pdf.

[e] Information is based on HughesNet Gen5 high-speed internet service, http://ir.echostar.com/news-releases/news-release-details/hughesnet-gen5-surpasses-100000-subscribers-just-two-months.

[f] SpaceX publicly claims up to 1 Gbps per user for its constellation. Jon Brodkin, "SpaceX plans worldwide satellite internet with low latency, gigabit speed," *ArsTechnica*, November 17, 2016, https://arstechnica.com/information-technology/2016/11/spacex-plans-worldwide-satellite-internet-with-low-latency-gigabit-speed/.

[g] SpaceX projection. Jose del Rosario and Prashant Butani, 2015. "LEO-HTS Constellations Resurrected: would They or Won't They? Northern Sky Research http://www.nsr.com/upload/presentations/NSR_Webinar-_LEO_HTS_Constellations-_May_2015.pdf.

At least one other constellation would be providing affordable, near-ubiquitous optical imagery that refreshes at least once per hour with relatively high ground resolution (Table 2-2).[22] This constellation would not provide true ubiquitous video coverage of the entire planet, but with advanced notice, satellites could use tip-and-cue approaches to provide real-time video coverage of small target areas.

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launch and insurance (https://www.spaceintelreport.com/sky-space-global-constellations-need-relief-regulatory-filing-insurance-cost/).

[22] This scenario focuses on ubiquitous, persistent optical imagery. But other remote sensing constellations could provide data in the form of imagery and video (hyperspectral, multispectral, infrared, visual), radar (i.e., synthetic aperture radar), or other signals (radio-occultation, radio frequency, automatic identification system, etc.). Other types of constellations are feasible that are not considered in our scenarios. For example, federated satellite systems could operate as part of a network of independent owners and operators to share resources such as downlink availability, processing power, and potentially electrical power through microwave beaming. Alessandro Golkar, "Federated Satellite Systems (FSS): A Vision Towards an Innovation in Space Systems Design," 2013, http://golkar.scripts.mit.edu/alessandro/wp-content/uploads/2012/12/IAA-SmallSat-2013-FullPaper-Golkar_v4.pdf

Table 2-2. Imagery Constellations

	Ground Resolution (meters)	Frequency/ Revisit Rate	Cost
Space-based (2017)	0.3	4.5 times per day	\$29 per km^2 with a minimum order area of 100 km^2 and minimum order width of 5 km
Scenario constellation (2027–2032)	~ 1	At least 1 time per hour	Almost two orders of magnitude cheaper than 2017

[a] Information is based on the DigitalGlobe constellation.

The satellites in the communication constellation would weigh between 150–500 kg, use either radio or laser communications to communicate with the ground or each other, and have attitude control and propulsion systems onboard. The satellites in the optical imagery constellation would be 3–6U CubeSat or microsatellite platforms (weighing less than 100 kg). Some would have onboard data processing capabilities, and all processing would occur on the ground. Some of these satellites would have propulsion capabilities, and could therefore maneuver and de-orbit; the ones that do not would be in lower orbits that reduce their orbital lifetimes.

These large LEO constellations of smallsats would co-exist with other ground, aerial, and space-based platforms, both with respect to communications (e.g., satellites in other orbits, terrestrial fiber, hot air balloons,[23] solar internet planes,[24] and airplane networks) as well as imagery (e.g., satellites in other orbits, payloads on permanent space stations, traditional aerial methods, and new UAV approaches).

2. Implications

Provision of affordable global low-latency broadband internet and affordable ubiquitous imagery with high refresh rates would have a number of implications for global economic growth, social welfare, and security.

a. Implications of Communication Constellations

Affordable broadband through the large LEO constellation would provide:

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[23] Andrew Dalton, "Alphabet Won't Need All Those Internet Balloons After All," *engadget*, https://www.engadget.com/2017/02/16/alphabet-google-project-loon-internet-balloons/

[24] Ariha Setalvad, "Facebook's Solar-Powered Internet Plane Looks Like a Stealth Bomber," *The Verge*, http://www.theverge.com/2015/7/30/9074925/facebook-aquila-solar-internet-plane

- Better access to healthcare, education, worker training, job seeking, price stabilization, etc. in remote areas, landlocked areas in developing countries, and in polar regions;[25, 26]
- Services to retail/hospitality, social inclusion, energy, military/government, backhaul and trunking, etc.;
- Connectivity to the mobility sectors, especially on shipping vessels and airplanes;
- Low-latency communication, complementing a terrestrial 5G architecture,[27] enabling on-line gaming, decentralized banking,[28] online auctions, and more ubiquitous use of teleconference tools; and
- A simultaneously more resilient and vulnerable communication system—by providing redundancy to terrestrial and GEO-based systems, but also more entry points for cyberattacks.[29]

b. Implications of Imagery Constellations

A LEO constellation providing affordable near-ubiquitous optical imagery that refreshes at least once per hour with high ground resolution would offer affordable data with high-revisit rates in areas of difficult access. The constellation would provide:

- Data to support the geospatial imagery analytics market that has grown over $100 billion,[30] and that commingles space-based and other data sources; a complete optical map of the globe on the order of every few minutes; and maps in other areas of the spectrum on the order of every few hours;

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[25] Compared to terrestrial based broadband, LEO-based connectivity is more affordable, and came sooner than was expected.

[26] Access to education could have long term, generational impacts on birth rates, commerce, and talent pools that would more than likely happen globally simultaneously—as a result of satellite based connectivity—rather than slowly spreading from region to region, which would be the case if connectivity came through terrestrial means.

[27] Figure 3 in Chapter 4 of European Commission. "5G Empowering Vertical Industries" describes the integrated 5G architecture for mobile broadband and vertical services, a satellite network is part of the bottom infrastructure layer: https://5g-ppp.eu/wp-content/uploads/2016/02/BROCHURE_5PPP_BAT2_PL.pdf.

[28] Decreased global latency, may lead to the loci of global banking defocus because actors no longer need to be as physically close to the stock markets. This may affect population centers and real estate prices in major cities if banking centers are not so centralized.

[29] GPS World Staff. "Expert opinions: the effect of LEO constellations on GNSS services."

[30] See Table 3-2 in Chapter 3.

- Applications such as economic forecasting, agriculture monitoring, disaster management, weather prediction, resource management, shipping and aircraft monitoring, criminal monitoring, identification of hazard and bad actors, and security and warfighting that benefit from change-detection capabilities;[31]
- Better science through development of new research platforms that provide a mechanism for scientific collaboration; and
- Impetus for innovation and new technologies for data access, data organization and storage, data processing, data downlink, and data visualization.

c. General Implications of LEO Constellations

The following implications would apply to both types of constellations:

- A world connected through large constellations would pose challenges associated with electromagnetic radio frequency (RF) spectrum allocation and interference. Radio frequency interference (RFI) in particular would need to be mitigated through further collaboration among operators. As LEO constellations proliferate, spectrum would become even more valuable resource, and new domestic regulations through the Federal Communications Commission (FCC) and global regulations through the International Telecommunication Union (ITU) would be needed to manage and allocate RF and to avoid RFI.
- The increased number of users would make it difficult for new providers to get licenses to transmit signal. Already large players would get larger because fewer players would control more of a limited natural resource, resulting in reduced democratization in this area. Simultaneously, the strain on the available spectrum would cause domestic and international spectrum regulatory agencies to create new policies to ensure spectrum remains available to all. Policies could be implemented that set time standards for effective use of spectrum or that reallocate areas currently reserved for government or education purposes.
- Large constellations would lead to concerns that LEO could become unsafe due to overlaunch or unintentional RFI (Scenario 3 presented in Section C). To avoid this scenario, space actors could come together to develop an effective space situational awareness (SSA) system to adapt to constellations needs, debris mitigation guidelines tailored to large constellations, and effective space traffic management (STM) that enforces guidelines and rules of operation to help manage space traffic in the more crowded orbits.

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[31] For further details see “Remote Sensing” in Appendix F.

- As a result of the large number of launches that the constellations would necessitate, the launch vehicle market would be undergoing change as well. The increased launch rates to set up, replenish, and refresh large constellations would lead to a decrease in the price of rideshare launches as well as to developments in on-demand (fast and dedicated) small launchers to space.
- The commercial success of the large constellations, combined with reduced price of launch and higher launch rates, would lead to investment to improve performance and capabilities, to lower technology cost, and to develop low-cost manufacturing techniques. This, in turn, would lead to more actors putting payloads into space and controlling more capable small satellites, and ultimately, resulting in greater democratization of space.[32] Not all actors in space would be responsible, and bad actors would be able to create debris, RFI, and other problems using smaller systems at lower cost.
- A growing numbers of satellites would provide both broadband and imagery. The co-existence of satellite broadband with imagery would help with downlink and storing the volumes of data generated by imagery satellites. Imagery downlink augmented by communications satellites from another satellite operator would lay the groundwork for federated satellite systems, that can share resources such as downlinks, and processing power.

d. Global Security Implications

One important implication of persistent, global internet and imagery coverage is that national governments would have less control. Authoritarian governments would have more difficulty shutting down portions of the internet or connectivity to certain areas within a country during periods of unrest or protest. This security implication carries geopolitical considerations similar to those seen during the Arab Spring that began in 2010 and the attempted coup d'etat in Turkey in 2016.[33, 34] It could also have implications for the nature of internet access in countries like China, where the internet is heavily censored.[35] However, providers would be required to align with local regulations and control,

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32 Lal et al. *Global Trends in Space*.

33 BBC, "Egypt Severs Internet Connection Amid Growing Unrest," http://www.bbc.com/news/technology-12306041

34 B. Norton, "Growing Tyranny in Turkey: Government Shuts Down Social Media, Detains Elected Lawmakers from Leftist, Pro-Kurdish Party," *Salon*, http://www.salon.com/2016/11/03/turkey-shuts-down-social-media-detains-elected-lawmakers-from-leftist-pro-kurdish-party/

35 S. Denyer, "China's Scary Lesson to the World: Censoring the Internet Works," *Washington Post*, https://www.washingtonpost.com/world/asia_pacific/chinas-scary-lesson-to-the-world-censoring-the-internet-works/2016/05/23/413afe78-fff3-11e5-8bb1-f124a43f84dc_story.html?utm_term=.2e9887929abe

especially if ground stations across the globe are necessary; ground stations have to use locally sanctioned internet connections rather than free and open internet.

Because imagery would be collected from low-cost smallsat platforms, governments other than the United States would be able to access satellite imagery data and use it for any desired investigations. For example, police units around the world could invest in the low-cost applications that would be available commercially for tracking individuals. Federal agencies would be able to track malicious or other cargo shipments more easily and prevent smuggling, especially because RF monitoring, infrared imagery, and synthetic aperture radar data would be available in these constellations. Running covert ground operations would still be difficult for, especially because data would be readily available to everyone. Satellite operators would be able to earn additional revenue by agreeing to *not* take satellite imagery over certain areas at certain times. This could enable smuggling operations to continue to exist if the constellation operators are easily bribed. Militaries would be able to purchase observation exceptions to prevent tracking and observation with full, legal cooperation with the operators. For example, the United States could want to reduce the amount of imagery over Groom Lake, and North Korea could want to prevent satellite imagery over its own labor camps.

Finally, hostile nations would be able to use the broadband network to coordinate global attacks or manage forces in a battlefield and get immediate feedback on attack success, positions of counterattacking forces, and options for retreat. In addition, additional cybersecurity would be needed to ensure the network stays online and no malicious actors can bring down the internet for hundreds of millions (if not billions) of users.

B. Scenario 2: Smallsats Near Parity with Larger Satellites in Remote Sensing

1. Description

In this scenario, remote sensing smallsats would have similar capabilities as larger satellites, especially in three specific areas:

- Ground resolution optical imagery would be available at 0.5-meter resolution, the higher resolution a result of both incremental and breakthrough advances, such as growing of aperture in space using three-dimensional (3D) printing techniques or aperture synthesis interferometry (ASI) from linked satellites.
- Smallsat platforms would routinely offer synthetic aperture radar (SAR) affordably, a capability that was limited to larger satellites until the late 2010s.
- Smallsat platforms would routinely offer affordable space-based situational awareness (SA).

As a consequence of this technology near-parity and its global commercial availability, a growing number of countries would have acquired the capacity for space-based remote sensing, achieving near-parity with traditional spacefaring nations such as the United States. This does not mean that all countries would have the same capabilities, but that enough capability would be available at an affordable enough cost to allow more countries to independently meet their societal and national security needs.[36]

Governments would be able to acquire space capabilities related to remote sensing in several different ways: (1) building indigenous capabilities in the country, sometimes by purchasing the first smallsat from an international vendor and building future satellites and associated infrastructure domestically; (2) buying smallsats from commercial firms, but operating the satellites and collecting and analyzing the data themselves; or (3) buying data or data products as turnkey services from global providers such as Surrey Satellites (UK) and others.

2. Implications

First, smallsats would become commoditized in the same way as personal computers and laptops were in the 1980s and 1990s. While there would be high-end smallsats with exquisite capability for niche applications, there would also be smallsats with low-end generic capabilities that can be assembled and deployed inexpensively.

Second, countries would be self-sufficient with regard to improving national security, addressing societal challenges, and creating economic growth. The combination of different types of remote sensing data into integrated data analytic products would lead to the global proliferation of applications previously available only to large commercial operators or to governments of spacefaring nations.

Third, governments, especially in the Western world, would be losing asymmetric advantage because the private sector would be the main purveyor of smallsat technologies, and private products and services would be available to all entities, public or private. Traditional spacefaring nations would be especially at a disadvantage because they would be losing their monopoly over the space governance regime. More countries, incentivized to protect their assets in LEO, would become active participants in developing global governance regimes related to topics such as spectrum allocation, collision avoidance, and debris mitigation. The United States and other traditional spacefaring nations would no

[36] For example, countries such as the Philippines might be more interested in tsunami prediction and subsequent disaster relief, whereas countries such as Norway might focus on illegal oil drilling in the North Sea or iceberg and ice-sheet monitoring to determine shipping routes.

longer be able to retain their customary negotiating advantage or control over global space affairs.[37]

Lastly, as the United States potentially loses its edge in smallsats, the U.S. Government could set out to find a new competitive edge in space. One example is on-orbit servicing, assembly, and manufacturing capabilities, as described in the scenario presented in Section D.

C. Scenario 3: Unsafe for Satellites to Operate in LEO

1. Description

In this scenario, orbits between 500 and 1,200 kilometers have become unsafe for operation of satellites without risk of collision (Figure 2-1). This would be the result of a large number of active and inactive objects in orbital bands around 800 and 1,110 km, or of RFI in LEO. The only available orbits for non-risk-tolerant missions would either be very low Earth orbits between 160 to 500[38] kilometers altitude or orbits higher than 1,200 kilometers.

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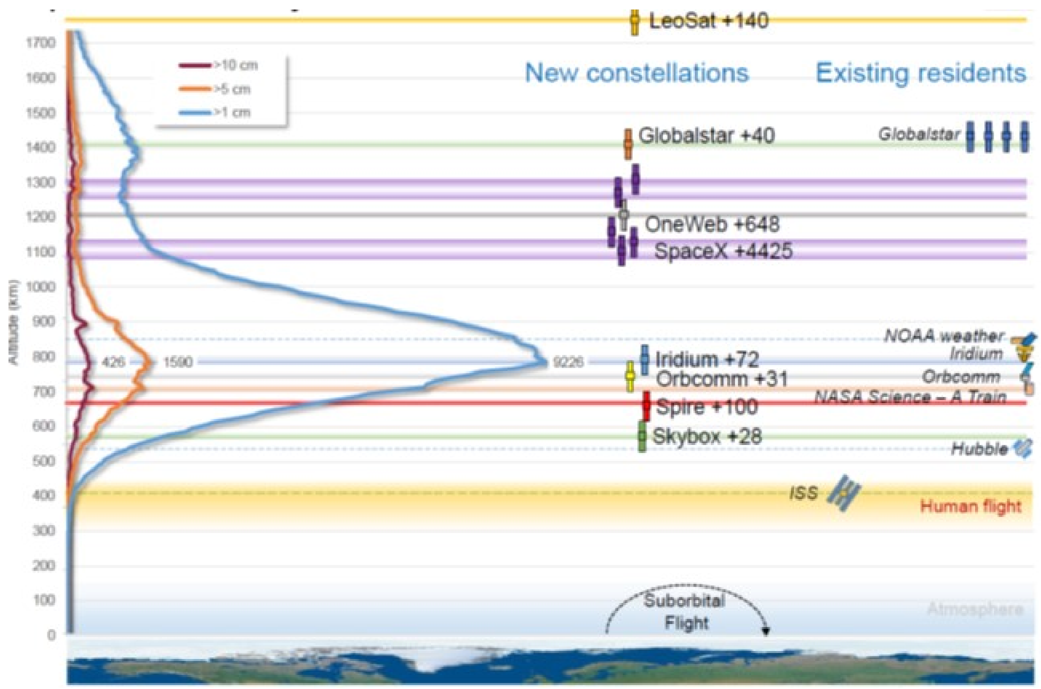
[37] This development is discussed in detail in Lal et al., *Global Trends in Space*.

[38] Orbital lifetimes without propulsion are highly sensitive to altitude and the solar cycle. At 200 km, missions are typically 2 to 3 weeks maximum, whereas at 160 km missions last between 1 and 3 days.



Source: Aerospace Corporation, "Space Traffic Management: Can We Maintain Safe Operation in LEO?"

Figure 2-1. Distribution of Existing and Projected Constellations in LEO in the Next 10 Years and Count of Objects in Common Orbits

2. Implications

First, commercial activity in LEO would be risky. For the private sector, this means that being in LEO would not be profitable, and venture capitalists and other funders would stop funding activities related to LEO commercialization. The predicted democratization of space would stop, because activities. such as Earth observation, remote sensing, and broadband connectivity and telephony, are no longer feasible at low cost.

Second, LEO would be the domain of primarily low-cost educational and short-term data collection smallsats as they might be the only satellites able to tolerate the high risk of collision in these orbits. The U.S Government would not be able to operate its critical and expensive assets (e.g., NOAA-19, Landsat, NASA's A-Train, etc.) related to Earth- and space-based data collection or communication in LEO, all of which would be at risk. Equivalent services would need to be provided at considerable expense in other orbital (or suborbital) regimes. Commercial communications and imaging activities would be performed by a combination of satellites in orbits higher than 1,200 kilometers, by satellites in very low Earth orbit, by airborne platforms in lower altitudes or through terrestrial means.

Third, for imagery, a trade-off between resolution, ubiquity, revisit times, and field of view would determine the most suitable platform for each specific application. For communications, global broadband connectivity and telephony would be provided by a combination of fiber optics, airborne platforms,[39, 40] and satellites at orbits higher than 1,200 km.

Fourth, moving satellites to higher orbits or to very low Earth orbits would make them larger and more expensive to operate. Smallsats in higher orbits would require radiation hardening, more power, and higher launch costs. Smallsats in very low Earth orbit would need continual thrusting[41] or continuous replenishment. Due to the increased cost of manufacturing, launching, and operating satellites in these orbits, the private sector would not be a major player in LEO other than when getting reimbursed for providing government assets.

Fifth, satellites would be required to carry optical payloads to assist in navigation and spacecraft, and rocket shielding would need to be stronger. Launchers would be evolving to accommodate different orbits and larger payloads, and companies that cannot adapt would be disappearing.

Last, many of the currently predicted LEO activities would be disappearing and new activities would be developing. For example:

- SSA and STM activities would gain momentum partly to preserve medium Earth orbit (MEO) and geosynchronous orbit (GEO), which would be more precious as orbits, and partly to safely navigate to orbits higher than 1,200 kilometers because passing through LEO would require avoiding a substantial amount of debris.
- Debris removal, funded either by the government or larger operators with large financial interests in space, would be a major activity in LEO. Technologies and

[39] Alphabet's project Loon experiment is exploring the use of a network of self-navigating, internet-beaming balloons. Current system improvements makes it more realistic the delivery of internet to remote regions of the world. https://www.engadget.com/2017/02/16/alphabet-google-project-loon-internet-balloons/?ncid=txtlnkusaolp00000618

[40] Airborne Wireless Network is in the process of creating a high-speed broadband airborne wireless network by linking commercial aircraft in flight.

[41] The lowest altitude multi-year mission to date, the European Space Agency GOCE mission, used throttleable 100–500W electric ion engines for drag make-up at an altitude of 240km, and maintained this orbit for over 4 years. Propulsion requirements are a strong function of the satellite ballistic coefficient, altitude, and solar cycle, the latter influencing the "ballooning" of the Earth's atmosphere. Development of an "air-breathing" electric propulsion system, which to date has not been successful, could impact these trades.

policies related to debris mitigation are gaining traction. On the technology front, there would be more investment in sensor technologies, collision avoidance hardware and software, and other technologies related to orbit cleanup.

- Interest in on-orbit repair, servicing, and refueling services in orbits higher than 1,200 kilometers would be growing.
- New technologies relevant to operations in dangerous orbits would be brought into use. They include "self-healing" materials, lightweight and efficient aid sensing technologies, miniaturized and efficient propulsion systems and spacecraft shielding.[42]

D. Scenario 4: On-Orbit Servicing, Assembly, and Manufacturing of Spacecraft a Reality

1. Description

In this scenario, multiple spacecraft would be placed into LEO and GEO for the purpose of on-orbit servicing, assembly, and manufacturing (OSAM).[43] These spacecraft would include large, persistent platforms for satellite and spacecraft production as well as mobile smallsats for servicing other satellites. The persistent platforms and mobile smallsats would affordably support or carry out the following types of tasks using raw materials and structural components launched from Earth:

- *Servicing* of existing satellites, including maintenance, refueling, subsystems upgrades, and payload substitution. These services would be primarily carried out by free-flying smallsats that travel to meet spacecraft in orbit and act as robotic "technicians."
- *Assembly* of new satellites from components manufactured terrestrially. Production would be done on large-scale persistent platforms facilitated by modular elements and autonomous systems.
- *Manufacturing* of certain types of components, payloads, and satellite structures, such as panels and antennas, from raw materials. This process would encompasses additive manufacturing (3D printing) along with more

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[42] For more details on the state of the art and future trends in smallsat technology, see Appendix D.

[43] Also see R. Boyd, R. S. Buenconsejo. D. Piskorz, B. Lal, K. W. Crane, and E. De La Rosa Blanco, *On-Orbit Manufacturing and Assembly of Spacecraft* (Alexandria, Virginia: IDA, January 2017), IDA P-8336, https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2017/P-8335.ashx.

conventional welding and chemical techniques. Completed elements would be used in the assembly process.

While OSAM would not be geared specifically toward the smallsat sector, operators could take advantage of these capabilities to deploy smallsats for a wide variety of missions in LEO constellations and deep space. Smallsats could also play an important role in providing on-orbit servicing to other spacecraft. The direct impacts of enabling OSAM, however, would extend well beyond the smallsat community; large spacecraft built and serviced on-orbit would have equal potential to reshape the space industry.

2. Implications

a. Implications for Satellite Production

With OSAM capabilities, satellites would be produced on-orbit. Materials sent into orbit for OSAM could be packaged efficiently without the excess structure needed for ruggedization against the launch process. Satellites could be designed, manufactured, and assembled affordably on-orbit with larger dimensions than terrestrial production or assembly allows, without regard for size or shape limitations imposed by launch vehicle fairings, unlocking new proficiencies in a number of applications such as communications and EO. Routine maintenance, upgrades, and refueling offered via on-orbit servicing could lengthen a satellite's lifespan and adapt payloads for new missions.[44]

For large satellites, the net effect of OSAM would be to reduce production costs, increase revenues, and bolster performance. Operators would stand to benefit from employing large satellites with exquisite capabilities. A communications satellite built on-orbit with greater antenna surface area, for example, could manage more throughput and draw increased revenue of up to $81 million over its lifetime.[45] It could draw an additional $300 million from an on-orbit technology refresh midway through its lifespan.[46] For Earth observation, a satellite built on-orbit with an enormous aperture could gather high-accuracy, high-resolution (e.g., sub-meter) images for intelligence, surveillance, and reconnaissance applications for missions of national defense and homeland security.

The most important implication is that OSAM would offer operators flexibility in choosing the right-sized asset for a given application. In certain applications, for example, large satellites would be competitive with smallsats on the basis of cost. An operator's

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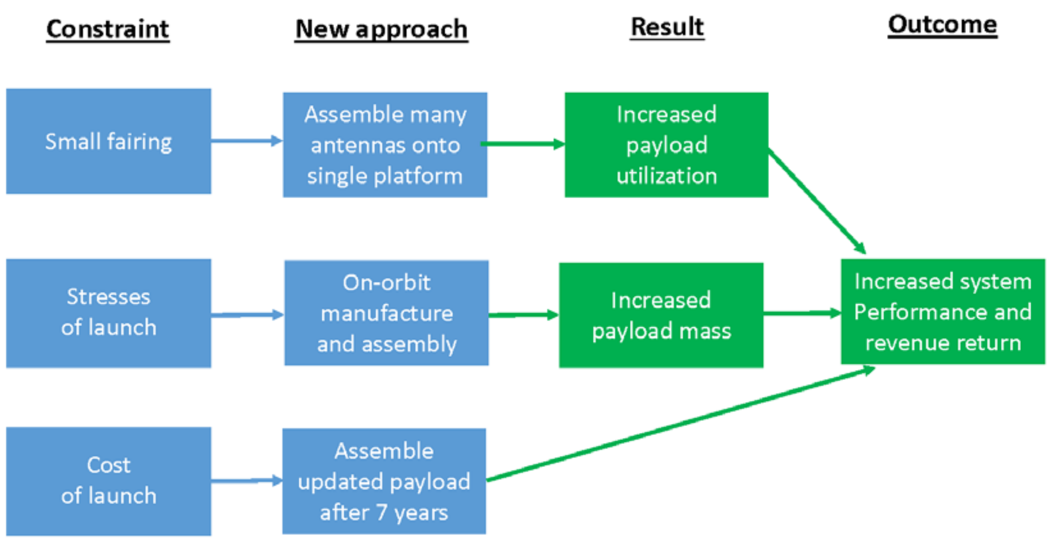
44 Boyd et al., *On-Orbit Manufacturing and Assembly of Spacecraft*.

45 Ibid.

46 Ibid.

choice to utilize a constellation of smallsats, a constellation of large satellites, or a singular, exquisitely capable large satellite would depend on the specific application, and for many applications, smallsats and large satellites would compete directly.[47]



Source: Boyd et al., *On-Orbit Manufacturing and Assembly of Spacecraft*, 26, Figure 13.

Figure 2-2. How On-Orbit Manufacturing and Assembly Approaches Can Alleviate Limitations Associated with Current Approaches to Deploying Communications Satellites to Enhance System Performance and Increase Revenue Return

Although the high capital costs of developing and operating a production platform would far outweigh the marginal revenue to be made in on-orbit assembly and manufacturing of smallsats,[48] building smallsats on-orbit would become affordable through one of two models. The first would be high-volume production of identical

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[47] For EO, constellations provide high revisit rates for tracking hourly changes, but resolution is limited by their small footprint. Large satellites are preferred for applications where resolution is paramount or onboard data processing is required, but cannot be ubiquitous in geographic coverage. For communications, constellations in LEO are essential for low-latency global broadband. However, less interactive services (e.g., TV and radio) can be broadcast from either platform, fostering competition between exquisitely-capable large satellites and smallsat constellations.

[48] K. Crane et al., "Market Analysis for a Private Space Station," STPI (2017).

smallsats for large constellations.[49] The second model would be for persistent platforms to build smallsats as a secondary output to large spacecraft.[50]

b. Implications for Technology Demonstration and Earth Science

On-orbit servicing would enable new avenues for technology demonstration and Earth science research, such as the use of large, multi-use buses in orbit that host several modular payloads at once. Startups and academic institutions could rent payload space from platform operators for technology demonstrations and short-term science missions. The payloads would be readily swapped in and out as needed by autonomous servicing robots, allowing ready access to a variety of users simultaneously. This payload hosting model would alleviate the need to build a new smallsat platform for each mission, reducing costs for space-focused entrepreneurs and researchers. Furthermore, it would decrease the risk of component failure during launch, since all of the systems housed within the platform persist in orbit over the long term. Some technology demonstrations would still require an independent satellite to operate (e.g., debris removal), but many would benefit from the payload hosting model.

c. Implications for Deep Space Exploration

The reality of OSAM would bring about many new ways to explore the solar system and the universe. High-definition space telescopes (HDSTs) built with larger mirrors are much quicker to scan the cosmos for exoplanets that could house extraterrestrial life. An HDST with a 12-m mirror could identify 30 exo-Earth candidates within its operational lifetime (Figure 2-3), to help draw a statistically meaningful conclusion about the prospects of biological life on other planets.[51] The size and cost challenges of building such an astronomical instrument would be easily addressed through on-orbit production. The cost to place a 20-m telescope into orbit would be cut by an estimated $13 billion using modular mirrors and on-orbit assembly rather than traditional deployment methods.[52] Making large-

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[49] Unassembled satellite components and raw materials are able to be packaged into launch vehicles more efficiently than completed spacecraft, reducing the total number of launches required to implement a constellation. Once materials have reached orbit, OSAM platforms act as orbital “factories,” carrying out rapid production and deployment. Dead satellites are quickly replenished by spares made in the factories and stored in an orbital warehouse, without need to wait for a launch window to put a replacement into orbit. The cheaper, streamlined implementation process offered by on-orbit assembly and manufacturing dramatically increases the viability of large constellations.

[50] Capital costs are amortized over the production of the larger, more expensive orders, but smallsat production can be taken on between these orders in order to maintain a constant revenue flow. Once again, on-orbit production facilitates deployment of smallsats, especially in GEO and deep space, which are prohibitively expensive for smallsats to reach.

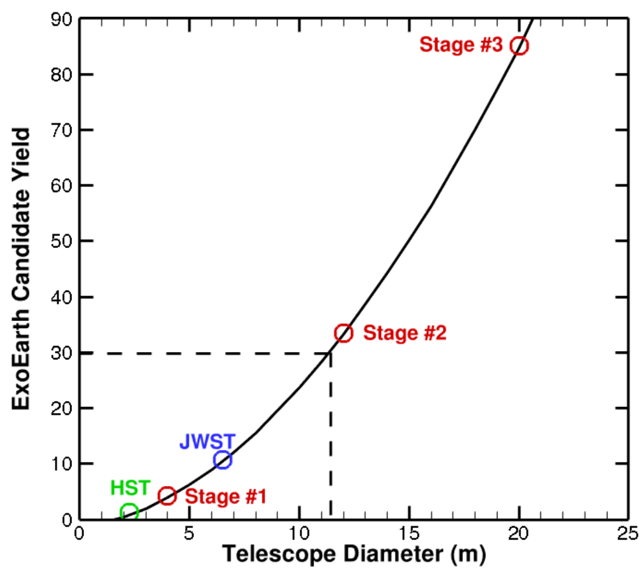
[51] Boyd et al., *On-Orbit Manufacturing and Assembly of Spacecraft*

[52] Ibid.

scale HDSTs feasible and affordable promises exciting breakthroughs in astronomy and cosmology research.

Placing OSAM spacecraft into orbit around neighboring planets would also provide a significant benefit to planetary science missions. Large numbers of remote sensing and imagery smallsats could be deployed in bundles, with satellite components packed efficiently into smaller, more affordable launch vehicles. The length of observation missions would increase with longer satellite lifespans, and on-orbit servicing would allow satellites to be repurposed for multiple missions by having their payloads substituted.

Enormous spacecraft constructed on orbit have the potential for carrying manned missions to Mars and beyond. These spacecraft would be built large enough in size to carry supplies for missions running years in duration. They would also need to carry expansive solar arrays to power subsystems, as access to solar energy is reduced deeper into the solar system. Large, modular vessels assembled on orbit could carry a new generation of astronauts to unexplored frontiers. These space travelers would also benefit from the ability to service their spacecraft in space with tools and replacement parts manufactured on-demand with a 3D printer.



Source: Boyd et al., *On-Orbit Manufacturing and Assembly of Spacecraft*, 9, Figure 4.

Notes: A modular, three-stage evolvable space telescope (EST) concept is compared to the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST). A baseline of 30 exo-Earth candidates must be identified to draw statistically significant conclusions about the likelihood of extraterrestrial life existing on distant planets.

Figure 2-3. Exoplanet Yield as a Function of Telescope Diameter

d. Implications for the Smallsat Market

The most important benefit that OSAM would offer to the satellite industry is the flexibility in designing, building, and deploying satellites best-suited to a given application as large satellites become cost competitive and hosted payload platforms become a norm. Large satellites and hosted payload platforms have displaced smallsats for certain applications, unlocking new markets. For example, with the advent of hosted payload platforms, start-ups and small companies would be able to prioritize developing modular payloads rather than entire satellites during R&D. As a consequence, a market would develop for building, operating, and leasing hosted platforms, allowing new players to get involved in space-related activities ranging from technology start-ups to universities to governments in small nations.

Due to efficient deployment and reduced production costs, smallsats would find their most prominent applications in communications and Earth observation, implemented as large constellations. Despite competition from their larger counterparts, on-orbit assembly would unlock considerable potential for market growth in these areas.

The availability of on-orbit servicing and assembly would have further implications on the private launch market. Smallsat launchers would become less competitive as a significant share of operators shift production to on-orbit factories. Still, there would be demand for affordable transport of payload modules to host platforms, and compact launch vehicles would remain a useful facilitator. There would also be a substantial need to transport structural components and raw materials to production platforms in LEO/GEO efficiently and reliably. Private launch companies would fill this void, and new vehicles for efficient packaging and bulk transport would emerge as the companies shift some of their focus to running materials supply missions. This particular sector of the launch market is open to continued growth as on-orbit assembly expands.

Public and private R&D efforts into some areas of smallsat technology would become obsolete given less pressure to employ smallsats in every application. For example, if imaging apertures could be enlarged through on-orbit assembly, coordinating swarms of microsatellites into complex virtual apertures would no longer be of primary research interest. Other areas of technology would become increasingly vital, such as miniaturizing propulsion systems for use on smallsats to enable deployment from OSAM platforms. These trends would be accompanied by increased attention on developing technologies to facilitate and unlock new capabilities in OSAM.

E. Identifying Drivers

The four scenarios described in this chapter were created not as an end unto themselves, but as a means to identifying important drivers in the smallsat sector. Building on our research and interviews, we identified a total of 62 drivers that could lead to one or more of the scenarios coming to fruition. We do not claim this to be a definitive list of drivers, just those we found to be most important for the scenarios identified.[53] Some experts, for example have identified other drivers such as a low interest rate environment after the 2008 financial crisis, that is pushing investors to seek higher returns, or threats to Net neutrality prompting Internet players like Google and Facebook to eye satellites for transport independence/hedging. These drives were not explored.

From these 62 drivers, we selected those most relevant to the scenarios for more in-depth analysis (Table 2-3).

Table 2-3. Drivers of Scenarios

	Drivers (vectors with magnitude and direction)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Demand	Demand for broadband, backhaul and mobility	Medium	None	Medium	Medium
	Demand for low latency internet	High	None	Medium	Medium (Negative)
	Demand for imagery/analytic products	High	High	Medium	Medium
	Demand for situational awareness	None	High	Medium	Medium
	Demand for On-Orbit Servicing, Assembly and Manufacturing	None	None	None	High
Funding	U.S. Government	Low	Medium (negative)	Medium	High
	Foreign Government	Low	High	Medium	Medium
	U.S. Venture and Equity Capital	Medium	Medium	Medium	Medium
	Foreign Venture and Equity Capital	Medium	High	Medium	Medium
Technology	High Resolution Optical imaging	Low	High	Medium	Medium
	Synthetic Aperture Radar (SAR)	None	High	Medium	Medium
	On-board processing	High	Medium	Medium	Low (Negative)
	Optical Communications	High	Medium	High (Negative)	Medium
	Advances in miniaturization	Low	High	Medium	Low (Negative)
	Spectrum related technologies	High	Medium	High (Negative)	Low
	Propulsion system	Medium	Low	High (Negative)	Low
	De orbital and Orbital Debris Removal technologies	Medium	Medium	High (Negative)	Medium

[53] Some experts identified other drivers, such as the low-interest-rate environment since the 2008 financial crisis, which is pushing investors to seek higher returns, and threats to Net neutrality, which prompted internet players like Google and Facebook to eye satellites for transport independence and hedging.

	Drivers (vectors with magnitude and direction)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Low Cost Approaches	Reliability of COTS components	Medium	High	Medium	Low
	Robotics and automation for satellite integration	High	Medium	Medium	High
	Modularity and Standardization	Medium	Medium	Medium	High
Infrastructure	SSA system	High	High	High	High
	Network of ground stations	High	High	Medium	Medium
	In-space relays	High	Low	Medium	Medium (Negative)
	Low cost ground communication technologies	High	Low	Medium	Low
Launch	Availability of reliable launch alternatives	High	Medium	Medium	Medium (Negative)
	Price of launch	Low	High	Medium	High (Negative)
Competing Alternatives	Terrestrial for broadband	High (Negative)	None	Medium (Negative)	Medium (Negative)
	Airborne for broadband	High (Negative)	None	Medium (Negative)	Medium (Negative)
	Airborne for remote sensing	High (Negative)	Medium (Negative)	Medium (Negative)	Medium (Negative)
	Large satellites for communication	High (Negative)	None	Medium (Negative)	High
	Large satellites for remote sensing	High (Negative)	Medium (Negative)	Medium (Negative)	High
Government policies	Regulating spectrum	High	Medium	High (Negative)	Medium
	On-orbit regulations	None	Low	Low	High
	STM regime	High	Medium	High (Negative)	Medium
	Debris mitigation standards	Medium	Medium	High (Negative)	Medium
	National security (e.g., ITAR)	Low (Negative)	High	None	Medium (Negative)
	Protectionism/mercantilism	Medium	High	Low	Low

As Table 2-3 illustrates, the drivers are not always aligned. For example, any driver that promotes the success of Scenarios 1 and 2 would lead to more active objects in space, which, in turn, would increase the risk of collisions (Scenario 3) and the competition from smallsats to large satellites (negative driver to Scenario 4). The drivers analyzed fell into four categories, each of which is discussed in detail in the chapters that follow:

- Market demand (Chapter 3), which includes demand, funding, technology, low-cost approaches, and infrastructure from Table 2-3;
- Access to space (Chapter 4), which includes the launch category from Table 2-3;
- Competing alternatives (Chapter 5); and
- Government policies (Chapter 6).

3. Market Demand

Demand for LEO-based services is the most powerful driver in the smallsat sector, and, in turn, motivates other drivers such as availability of funding, development of new technology, low-cost approaches, and infrastructure. Each is discussed in turn below.

A. Demand for LEO-Based Services

The demand for LEO-based services, such as broadband or imagery, is one of the most important drivers for Scenarios 1, 2, and 3. This demand is driven by the perception that using smallsats for furnishing affordable high-capacity, low-latency broadband services or remote sensing data (Earth observation and situational awareness) could be highly useful or profitable. If demand for either service increases, or if the companies looking to get involved see the potential for such demand, it is more likely that large constellations would be deployed (Scenario 1) and that more advancements in smallsat technology would be made. This could lead to near parity with large satellites (Scenario 2) and further decrease the cost of smallsats, which in turn would increase the interest of smaller companies or other countries to launch more smallsats. As a consequence, there may be a significant increase in the number of objects in LEO, which could lead to LEO being unsafe (Scenario 3). Demand for LEO-based services is not a major driver for Scenario 4, although an increased demand for Earth observation (EO) imagery may make an OSAM platform slightly more desirable, for the increased ease it would offer in assembling and deploying satellites with larger apertures.

Trends in demand for four service areas—broadband, imagery, situational awareness, and on-orbit services—are discussed in each of the four following subsections.

1. Trends in Demand for LEO Broadband Constellations

In 2015, broadband from satellites was under 6% of satellite services revenues at $7.4 billion in revenues globally.[54] Future demand for broadband depends on whether services are for rural or urban consumers, whether platforms are fixed or mobile, and whether services are for industrialized or less industrialized countries. Latency also plays an

[54] The $7.4 billion corresponds to the sum of consumer broadband revenue ($1.9 billion) and managed services revenue ($5.5 billion). We considers managed services to include enterprise, backhaul, mobility, and government services (http://www.sia.org/wp-content/uploads/2016/06/SSIR16-Pdf-Copy-for-Website-Compressed.pdf).

important role (as discussed in Appendix F, some applications would benefit from the order-of-magnitude lower latency offered by LEO-based internet over GEO-based, and be comparable to terrestrial cell-based internet).

LEO constellations are seen as an option to provide relatively inexpensive coverage to Americans in rural areas, 39% of whom live without access to broadband internet,[55] as well as to provide global coverage to high-latitude regions (e.g., Alaska, Norway, and Russia) that GEO satellites do not cover, and where terrestrial solutions are expensive or do not reach many users.[56] LEO-based internet is also seen as a viable alternative for developing countries, which include 4.2 billion people currently without internet access (although 2 billion of them have mobile phones).[57, 58] See Figure 3-1.

Estimates for broadband demand vary, and some experts predict that satellite broadband capacity demand would grow at a compound annual growth rate of 29% through 2024.[59] Almost 80% of broadband demand is expected to come from consumers, with the remaining 20% from the rest of the markets (enterprise, backhaul, mobility, government, and broadcast). On the revenue side, almost 80% would come from the rest of the verticals (especially broadband and mobility) and 20% from consumer broadband demand.

Experts forecast over three terabits of bandwidth demand for GEO, MEO, and LEO High Throughput Satellite (HTS) data, broadband access, and mobility by 2024.[60] Regardless of the actual demand in the 2030 timeframe, demand for satellite services is expected to increase monotonically as consumers continue to have growing expectations of high-speed internet connectivity in all places and at all times, on airplanes, ships, and remote places in the world. Users with need for low-latency broadband (e.g., streaming

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55 Space and Innovation (OECD 2016).

56 Although not a constellation of smallsats, one of the first customers for LeoSat, a large constellation in LEO, would be the National Science Foundation for broadband data communication at the South Pole and on the Antarctic.

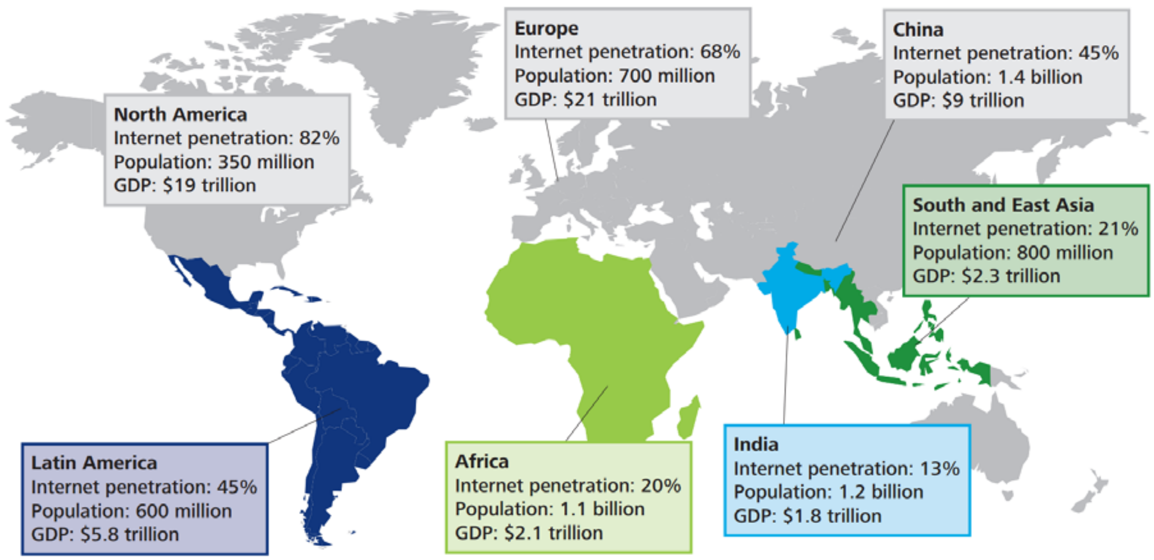
57 World Bank Group, Digital Dividends, World Development Report 2016.

58 Only one third of the population in the developing regions use the internet, compared to 82% in de developed countries. Source: UN Millennium Development Goals Report 2015.

59 Northern Sky Research, “NSR’s Satellite Capacity Study Finds HTS Essential as Traditional FSS Faces Challenges.” http://www.nsr.com/news-resources/nsr-in-the-press/nsr-press-releases/nsrs-satellite-capacity-study-finds-hts-essential-as-traditional-fss-faces-challenges/.

60 Northern Sky Research, “NSR’s Satellite Capacity Study Finds HTS Essential as Traditional FSS Faces Challenges.” http://www.nsr.com/news-resources/nsr-in-the-press/nsr-press-releases/nsrs-satellite-capacity-study-finds-hts-essential-as-traditional-fss-faces-challenges/.

video, augmented reality, online gaming,[61] and banking[62]) may be the early adopters of LEO services.



Source: Deloitte, 2014, "Value of connectivity: Economic and social benefits of expanding internet access"

Figure 3-1. Deloitte's 2014 Internet Penetration Estimates Based on ITU World Telecommunication Database and IMF Data

Once high-speed internet connectivity is available everywhere, new bandwidth-intensive applications are expected to emerge and rapidly grow. They include applications such as the Internet of Things (IoT) or self-driving cars.[63] On the government side, LEO constellations would play an important role at providing low-latency global services for military applications, such as fulfilling the need for persistent intelligence, surveillance, and reconnaissance (ISR) capabilities for both manned and unmanned platforms. On the mobility side, the in-flight connectivity market is expected to grow rapidly as airlines are

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61 Online gaming traffic is projected to grow from 2016 to 2021 with a compound annual growth rate of 62%. "Cisco Visual Networking Index: Forecast and Methodology, 2016-2021." http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/complete-white-paper-c11-481360.html.

62 A banking firm is going to be one of the first customers for one of the proposed LEO constellations according to a discussion with LeoSat. Although this is not a smallsat constellation, it will provide similar services as LEO smallsat constellations.

63 Data aggregation for M2M communications and IoT services would be well suited for LEO constellations or applications that require large data rates and low latency such as critical military or transportation missions, oil and gas industry, mining, or civil government applications in remote areas.

planning to offer high-speed internet connectivity on every airplane (the aviation satellite communications market is expected to generate $3.2 billion by the end of 2024).[64]

While demand for broadband is expected to grow in all markets, it remains unclear how much of the demand needs to be met with LEO constellations. Indeed, if all planned GEO HTS and LEO constellations were to succeed, they could deliver between 20 to 30 terabits of capacity,[65] and the resulting supply could be much higher than the expected demand (3 terabits by 2024). This would lead to some LEO constellations either failing entirely or not fully or partially deploying. There are already signs of this instability. For example, Canadian constellation COMMStellation made a splashy arrival in 2011 via the privately held corporation Microsat Systems Canada Inc. (MSCI),[66] but it appears the project is no longer being pursued. Similarly, Samsung (Korea) had announced a LEO constellation, but no information is available on the project.

In our judgement, it is unlikely that all the organizations that propose to provide LEO-based broadband (Table 3-1) using smallsats would be able to raise the funds needed, or be able to afford the operational costs, especially if their combined supply exceeds demand. As Chapter 5 notes, LEO-based service platforms would be competing with terrestrial, GEO, as well as with other platforms.

64 Northern Sky Research, "Untapped In-Flight Connectivity Market Represents Huge Potential For Satellite Industry." http://www.nsr.com/news-resources/nsr-in-the-press/nsr-press-releases/untapped-in-flight-connectivity-market-represents-huge-potential-for-satellite-industry/.

65 Northern Sky Research, "LEO HTS Constellations: "What Happens If…." http://www.nsr.com/news-resources/the-bottom-line/leo-hts-constellations-what-happens-if/.

66 http://www.commstellation.com/constellation/.

Table 3-1. Sampling of Current Broadband Constellations

Constellation (Ownership)	OneWeb	Boeing	SpaceX
Approximate constellation size	720	2,956	4,425
Country	United Kingdom/ United States	United States	United States
Orbit altitude (kilometers)	1,200	1,000–1,200	1,110–1,325
Mass per Satellite (kg)	150-200	*Unknown*	~450
Throughput	5–10 tbps	*Unknown*	8–10 Tbps
Estimated Cost	$2 billion	*Unknown*	$10 billion
User Speed and Latency	*50 Mbps* @50 ms	*Unknown*	1Gbps @20–30 ms
Operational Status	In-development, plans to start deployment in 2017	Planned	In-development, plans to start deployment in 2019
Spectrum Used	Ka Ku band	V and or C band	Ka Ku band
Key Funders	Virgin Galactic, Softbank Group, Airbus Group, Bharti Enterprises, Intelsat, Qualcomm, Coca-Cola, and others		Elon Musk, Google, and Fidelity
Key Partners	Airbus	None disclosed	None disclosed

Source: 2016 FCC filings and company websites.

Note: Scenario 1 focuses on broadband from smallsats in LEO. Hence, the table does not include LEO constellations that are not under 500 kg (e.g., LEOSAT). We also do not include constellations that provide services other than broadband internet (e.g., Sky and Space (UK) SkyFi (Israel)) or those that are still in their infancy if it is unclear if they can raise the requisite funds (e.g., Astranis).

2. Trends in Earth Observation Imagery and Analytics Demand

As with satellite broadband today, revenue from smallsat imagery is relatively low ($15 million in 2015 but estimated to be increasing by 49% annually[67]) compared with revenue from commercial imagery ($2.5 billion in 2014 and estimated to be increasing by over 11% annually[68]). Table 3-2 uses these growth rates to estimate smallsat imagery revenues in the timeframes of interest—about $2–$15 billion.

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67 Frost and Sullivan using a partial revenue forecast. This revenue represents the partial revenue that small satellite imagery will take away from the existing satellite imaging market.

68 Transparency Market Research, "Emergence of CubeSats Intensifies Competition between Behemoths and Startups in Commercial Satellite Imaging Market." http://www.transparencymarketresearch.com/pressrelease/commercial-satellite-imaging-market.htm.

Table 3-2. Revenue Projections for Imagery

Data Available	2025–2030 Revenues at Same Growth Rate	Source/Note
2015 ($15 million) 2020 ($164 million) *Growth rate = 49%*	$1.2–8.8 billion	Smallsat imagery markets
2014 ($2.5 billion) 2023 ($6.5 billion) *Growth rate = 11.4%*	$8–14 billion	Total commercial satellite imaging market
2016 ($2.8 billion) 2021 ($10.2 billion)[a] *Growth rate = 29.8%*	$28.7–104 billion	Geospatial imagery analytics market

Note: The growth rates used in the tables are the compound annual growth rates listed on the cited references. The revenues for 2025 and 2030 have been calculated assuming the same growth rates.

[a] Markets and Markets, "Geospatial Imagery Analytics Market by Type (Image and Video), Collection Medium (GIS, Satellite, UAV), Vertical (Defense & Security, Insurance, Agriculture, Healthcare & Life Sciences), and Region - Global Forecast to 2021," http://www.marketsandmarkets.com/PressReleases/geospatial-imagery-analytics.asp.

The U.S. Government is the largest purchaser of satellite imagery today.[69] For this reason, most smallsat companies, U.S.-based and others, see the U.S. Government as a stable long-term customer to get started with, although the companies claim that their expectation is to eventually serve a larger base of commercial customers. Although the United States currently has the advantage in the satellite imagery market, the United States does not control this technology. Competition from France, Germany, India, Israel, Japan, and South Korea by the year 2030 could alter the market for imagery needed by governments.

Today, there are more than 15 smallsat firms offering or proposing to offer Earth observation-related products and services.[70] Growth in the small satellite imagery marketplace is expected to be driven by industries such as agriculture, insurance companies, financial trader, hedge funds, energy companies, urban planning, retail, resource management, maritime, media, and others interested in data-driven decision-

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[69] National Geospatial Intelligence Agency (NGA) is paying an average of $730 million per year over the period from 2010 to 2020 for imagery from Digital Globe (Robert A. Weber and Kevin M. O'Connell, "Alternative Futures: United States Commercial Satellite Imagery in 2020," *Innovative Analytics and Training*, http://nsarchive.gwu.edu/NSAEBB/NSAEBB404/docs/37.pdf). NGA also recently signed a contract with Planet for a seven month introductory period worth $20 million (National Geospatial-Intelligence Agency, "NGA introductory contract with Planet to utilize small satellite imagery," https://www.nga.mil/MediaRoom/PressReleases/Pages/NGA-introductory-contract-with-Planet-to-utilize-small-satellite-imagery.aspx).

[70] Based on Table F-5 in Appendix F.

making practices. See Appendix F for a more complete list of applications. Some profit making use is already evident—Cape Analytics (U.S.) is using satellite-based imagery (among other sources) to underwrite property values; and UBS Investment Research and J.P. Morgan (U.S.) provide business intelligence in the retail market using Orbital Insights capabilities. In the future, Descartes Labs (U.S.) plans to provide agriculture crop yield projections and aggregate data from a number of large government satellites, and smallsat operators Planet[71] and BlackSky (U.S.) plan to integrate data from smallsats operated in-house with data from social-media feeds to provide insights on socio-political trends. Outside of the projections above, no firm data supports quantifying the supposedly emerging commercial markets. Japan's one smallsat company, Axelspace, is working to build a commercial market and convince private firms of the value of space-based data and analytics.

The community is already envisioning satellite imagery as a commodity, and companies are either switching from being midstream to downstream service providers, or just adding analytic services (either in-house or partnered) to provide intelligence products to customers. Consumers are not interested in "big data" but in products that provide insights and are easy to understand. This is the reason why some of the companies launching remote sensing constellations define themselves as information providers rather than as satellite companies. Many of these companies have used business models that are unprecedented in the space sector until now. For example, BlackSky (U.S.) plans to act as a one-stop-shop for imagery at different levels of resolution by purchasing from other operators what its own satellites do not collect, and providing customers with analytic insights. Customers are also able to request delivery of imagery on-demand to personal devices that can task smallsats through applications on smartphones by subscription or on a pay-per-image basis.

In our judgement, while non-governmental demand appears poised to grow, and experts estimate large markets in the coming 10–15 years, the EO imagery market is currently too small to point to a trajectory. See Table 3-3 for a sampling of current and emerging EO companies.

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[71] Medium, "This Company Is Using Satellite Imagery & Deep Learning to Predict a $67B Corn Market," December 21, 2015, https://medium.com/planet-stories/this-company-is-using-timely-satellite-imagery-and-deep-learning-to-predict-a-67-billion-u-s-7346bd0f3643#.lpfj3at41.

Table 3-3. Select Smallsat Earth Observation Companies

Company	Constellation Name	Country of HQ	Constellation Size Planned (as of 12/2016)	Payload; Re-visit Rate
Astro Digital	Landmapper HD	United States	20	2.5m (RBG, NIR); every 3–4 days[a]
	Landmapper BC	United States	10	22m (RBG, NIR)
The planned EO constellations will be launched into LEO. The HD constellation will collect images that will be used to provide data products for a range of industries, including agriculture and natural resource monitoring. The BC constellation will support the HD constellation.				
Planet	Rapideye	United States	5 (currently operating)	5m, Ground Sampling distance 6.5 m (RBG, NIR); daily off Nadir, 5.5 days at Nadir
	PlanetScope (ISS orbit)	United States	55, 1-year lifetime	2.7–3.2 m ground sample distance (RBG, NIR); Daily
	PlanetScope (SSO)	United States	150, 2- to 3-year lifetime	3.7–4.9 m ground sampling distance (RBG, NIR); Daily
The first two EO constellations are currently operational in LEO, the third is being deployed. The imagery is processed and delivered through a cloud-based platform for use by end users.				
Satellogic		Argentina	300 (1st constellation of 16)	1 m (multi-spectral); 2 hours with full constellation
The EO constellation is in development, three test satellites were launched over the course of 2013–2014, followed by two more launched in 2016. The complete 16-satellite constellation is expected to be done by 2017. It will provide near-real time imagery of the Earth; pilots are in place in the energy and agriculture sector.				
Spaceflight (Blacksky)	Pathfinder	United States	60	1 m (RBG); 40–70 per day[b]
The EO constellation is in development (6 planned for launch to LEO in 2017). The analysis of the data from the constellation will provide insights to customers, and taskable based on user demands. They are currently integrating satellite images, social media, news and other data feeds for insights.				
Terra Bella (now owned by Planet)	SkySat	United States	21 by end of 2017	<0.9 m (imagery; RBG, NIR), 1.1 m (video, Pan); 3 per day
The EO constellation is partially operational in LEO, with the remaining satellite expected to be launched in 2017. The data from this constellation will be used to provide insights for customers on a range of topics.				
Twenty-First Century Aerospace		China	3	1m (Pan), 4m (Multi)
The EO constellation is currently operational in LEO.				

Note: The total number of satellites intended to be launched may be greater than the numbers provided in the table above; additional satellites may be launched to replenished satellites given short lifetimes. All information is from either public sources (company website and press releases) or conducted interviews. Finally, Terra Bella was recently acquired by Planet, and information in this table is based on plans publicized prior to acquisition.

[a] This is not global revisit, but sufficient coverage to capture all agricultural lands.

[b] Over most inhabited parts of the globe, but not truly global coverage.

3. Demand for Situational Awareness (SA)

Demand for space-based sensing activities for purposes of SA, such as radio frequency (RF) mapping, automatic identification system (AIS) use, weather monitoring, space-based space situational awareness (SSA), GPS-Radio Occultation (GPS-RO), and Automatic Dependent Surveillance—Broadcast (ADS-B) in the space, maritime, and aeronautics domains, is predicted to be large, both from government and business customers.

SA services are expected to grow at a compound annual growth rate of 21% in the next 10 years.[72] While the smallsat market case for these services is somewhat untested, their proposed high revisit rate, low latency, and cost of deployment possibly an order of magnitude lower[73]—make smallsats especially suitable for SA applications. Examples of markets to be served are: aircraft tracking in support of the newly established International Civil Aviation Organization (ICAO) standard for airlines to be able to track their aircraft every 15 minutes; monitoring of suspicious activities in support of the Coast Guard; tracking of ships; and space-based SSA. Although most current SA markets focus on government and military applications, there is expectation of large revenues from new applications, such as those through the aggregation of SA and EO data (e.g., SAR images could be used to verify AIS signals). The 2017 partnership between Kratos Defense & Security Solutions and HawkEye 360 to combine space and terrestrial sensors to offer RF detection and geolocation services is an example of this.

Some companies are already providing AIS and ADS-B services from smallsat platforms, and RF mapping from smallsats are planned to start operations this year. Table 3-4 lists the known universe of SA firms and highlights their global distribution. However, given that SA services are unprecedented not just from smallsat platforms but outside the government, any market estimates need to be treated with caution.

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72 Northern Sky Research, "Situational Awareness a Key Smallsat Target." http://www.nsr.com/news-resources/the-bottom-line/situational-awareness-a-key-smallsat-target/.

73 Jeff Tollefson, "Race to Provide Commercial Weather Data Heats-Up," Nature, February 1, 2017. http://www.nature.com/news/race-to-provide-commercial-weather-data-heats-up-1.21399.

Table 3-4. Organizations Planning/Offering Situational Awareness (SA) Services from Smallsat Platforms

Company	Application	Launch Year	Remarks
Spire (U.S.)	AIS, ADS-B, GPS-RO	Operational	Providing weather tracking, maritime domain awareness. Plans for aircraft tracking in 2017
Karten Space (Spain)	AIS	Operational	KEOSat constellation of nanosatellites to provide AIS that they integrate with optical imagery for final product
Norwegian Space Center (Norway)	AIS	Operational	Constellation of three satellites for government use
Dauria Aerospace (Russia)	AIS	Operational	First Russian satellite funded completely by domestic private capital.[74] Dauria sold their two operational AIS satellites to Aquila Space (U.S.) in 2015
AISTech (Spain)	AIS/ADS-B	2019	
GeoOptics (U.S.)	GPS-RO		
PlanetIQ (U.S.)	GPS-RO		
Chandah Space Technologies (U.S.)	SSA	*Unknown*	Plans to scan the entire GEO arc for all the GEO satellites and provide SSA data to customer and government
MacDonald, Dettwiler and Associates Ltd. (Canada)	SSA	*O*perational	The Canadian Armed Forces operates the satellite and archives and forwards the Sapphire data to the U.S. 18th CSPC as part of the Space Surveillance Network
Hawkeye 360 (U.S.)	RF mapping	2018	Customers: Government and private sector (providing analytics on spectrum use and interference mitigation)
Kleos constellation from Magna Parva (UK)	RF mapping	*Unknown*	Planning a 20 smallsats constellation to provide 40m accuracy with satellites building their own antennas in space[75]

4. Demand for On-Orbit Servicing, Assembly, and Manufacturing

Demand and subsequent investment in on-orbit servicing, assembly, and manufacturing (OSAM) is influenced by developments in upstream and downstream fields (e.g., communications, Earth observation, space exploration, data analytics, private launch

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[74] R. Scharmann, "Dauria Aerospace Launch of Perseus Satellites Successful," *Via Satellite*, June 26, 2014, http://www.satellitetoday.com/launch/2014/06/26/dauria-aerospace-launch-of-perseus-satellites-successful/.

[75] C. Baraniuk, "Signal-Tracking Satellite Would Build its Own Antenna in Space," *New Scientist*, March 7, 2017, https://www.newscientist.com/article/2123740-signal-tracking-satellite-would-build-its-own-antenna-in-space/.

market, etc.). Developments in interconnected markets and actions taken by relevant players would continue to impact the feasibility of OSAM and the nature of its implementation for small satellites. This is a point of critical importance for OSAM, since it is such an emergent area of interest and potential implications for almost every area of space activity.

If, for example, a booming market develops for constellation applications but launch costs do not come down, investment toward the technology drivers enabling on-orbit assembly and manufacturing as an affordable alternative for replacement satellite launches is likely to spike. Alternatively, if drones beat smallsat constellations in providing broadband internet to remote locations, it may not be profitable for production platforms to build smallsats at all, and their use could be limited to building large satellites in GEO. The scope of plausible futures and their impacts on OSAM is too massive to list.

Demand for OSAM to advance science and discovery may be high—but this is not necessarily for smallsats.

If advancement of technology drivers is slow or the government fails to establish a supportive ecosystem for increased private investment, private actors are unlikely to be incentivized to develop on-orbit assembly and manufacturing for commercial application; the capital costs are simply too high and return on investment is too uncertain. In this case, breakthroughs in OSAM would need to be driven by the astronomy and space exploration communities, where there is most necessity to build spacecraft that are larger than what can be manufactured terrestrially. The search for extraterrestrial life or a manned mission to Mars are far-future missions (beyond a decade away) that could spark such breakthroughs. Regardless of how OSAM is brought to fruition, there is ample upside to draw involvement from private-sector operators once the technology is in place.

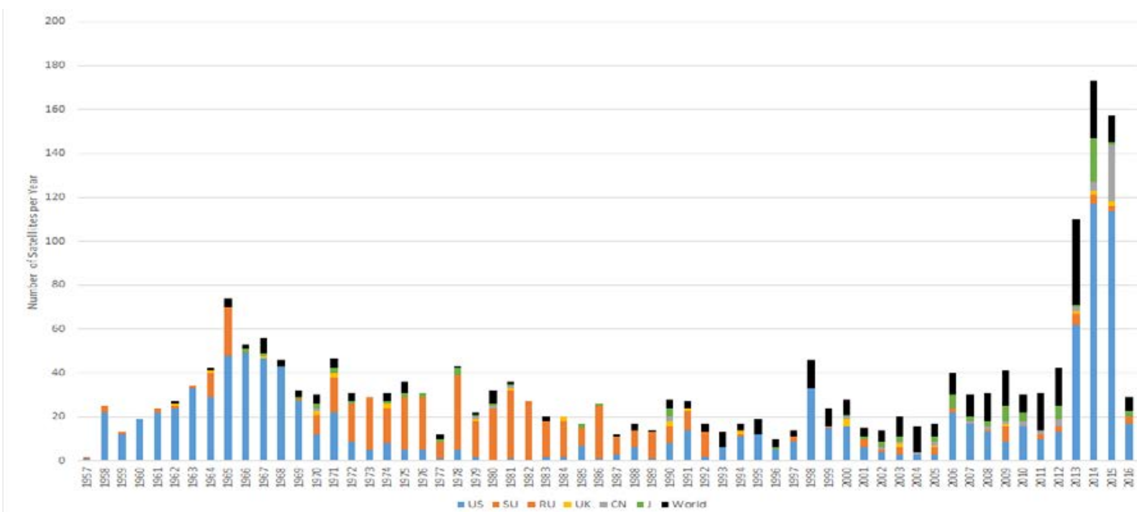
B. Availability of Funding

Funding for small satellites, both from public and private sources, has contributed substantially to the success of and interest in small satellites. Increased funding by the U.S and other governments, as well as private sector investment—both U.S. and non-U.S.—will drive further development and improvements in smallsat technology. This section discusses investment in the sector.

1. Government Investment

In the coming decade, more than 80 countries (up from fewer than 50 a decade ago) could be investing up to $80 billion annually (up from $62 billion in 2016) in space technologies and capabilities.[76] A growing portion of this investment would be for civil space, expected to be around two-thirds in the coming decade (up from about half 10 years ago) [77] Civil space expenditures would most likely be related to Earth observation and remote sensing. Given perceived cost-effectiveness of smallsats, we expect a significant portion of these expenditures to be in the smallsat sector.

The U.S. Government invests in every part of the smallsat ecosystem, and is likely to continue investing, both at the upstream and downstream ends.[78] Figure 3-2 plots historical launch of smallsats by country, and highlights the growing role of the United States, although nearly all of it in recent years in the private sector, principally Planet. The more interesting development is in the increasing investment in smallsats by other governments around the world.[79] While there is no systematic data on this investment, STPI's database serves as a proxy of this interest. Of the 664 organizations engaged in smallsat related activities, 57% are located in other countries (Figure 3-3). For countries with only one type of organization, the most common type is government. Figure 3-4 showcases the growth of foreign attendees, especially from Europe and Asia, at the Utah Smallsat conference.



Source: J. McDowell, June 2017. Satellite Catalog, http://planet4589.org/space/log/satcat.txt.
Note: Satellites under 200 kg only. The legend term World refers to rest of the world

Figure 3-2. Smallsat Launch by Country and Year

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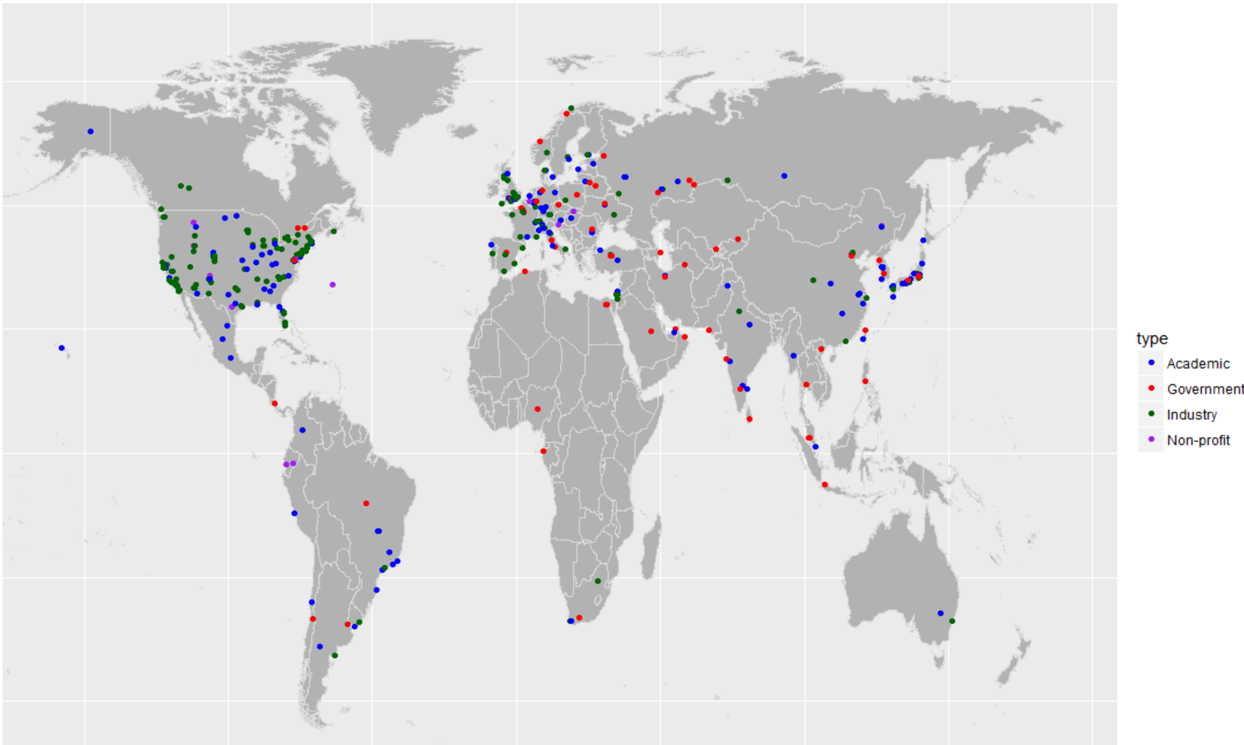
76 Euroconsult, "Profiles of Government Space Programs: Benchmarks, Profiles & Forecasts to 2026." http://www.euroconsult-ec.com/shop/home/94-government-space-programs.html.

77 Ibid.

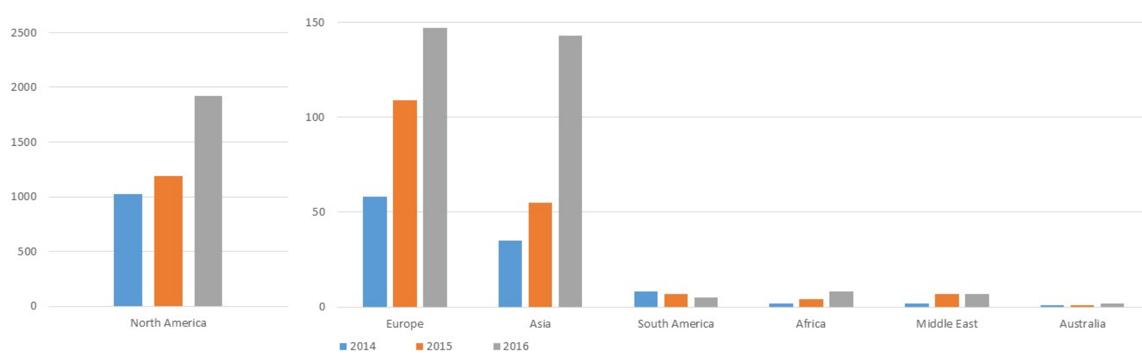
78 See Lal et al. "Trends in Small Satellite Technology and the Role of the NASA Small Spacecraft Technology Program" March 2017.

79 International Space University, Small Sats Big Shift: Recommendations from the Global South, White Paper Southern Hemisphere Space Studies Program, 2017.



Source: STPI database

Figure 3-3. Location of Smallsat Organizations



Source: Utah Smallsat Conference

Figure 3-4. Growth in Foreign Attendance at the Annual Utah Smallsat Conference

Appendix E provides country-level summaries on smallsat investments of about a dozen countries. A common thread from the summaries is that most governments recognize the need for investing in the development of smallsats for the purposes of disaster warning and monitoring. For many countries, government investment generally in R&D and start-ups is seen not only as a way to address societal challenges but also to facilitate independence from imports, and eventually to become a global provider of solutions in a sector such as space. The governments also recognize that they do not have a well-developed venture sector like the one in the United States, and so the governments provide venture capital (VC) funds. The following are a few examples of VC investment vehicles outside the United States.

- Japan has the cabinet-level Impulsing Paradigm Change through Disruptive Technologies Program (ImpACT) program and the Innovation Network Corporation of Japan (INCJ); both have the potential to advance space start-ups.
- The European Commission recently started the Pan-European VC Fund-of-Funds initiative to increase "the scale of VC funds in Europe and the industry's footprint across all Member States, as well as attract private investors" for a variety of sectors.[80] Further, ESA announced a nearly 33 million Euro investment to advance Hall Effect thruster (HET) propulsion technology as well as other business incubators.[81, 82]
- China's government has dedicated $339 billion to start-ups in the nation (not all of which would focus on space), which is a sign that governments compensate for a lack of private funding.[83, 84]
- The Canadian government's Industrial Technologies office plans to provide Canada-based UrtheCast $13 million to support ongoing development of its X-

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80 European Commission, "Commission and EIF seek Pan-European Venture Capital Fund-of-Funds Managers," http://ec.europa.eu/research/index.cfm?pg=newsalert&year=2016&na=na-081116.

81 CORDIS, "Gridded Ion Engine Standardised Electric Propulsion Platforms," http://cordis.europa.eu/project/rcn/206266_en.html.

CORDIS, "High Efficiency Multistage Plasma Thruster—Next Generation," http://cordis.europa.eu/project/rcn/206260_en.html.

CORDIS, "Consortium for Hall Effect Orbital Propulsion System," http://cordis.europa.eu/project/rcn/206269_en.html.

82 G. Degtyareva, "SpaceTech Is Going Global: European Funding Opportunities for Space Startups," February 18, 2017, accessed March 2, 2017, https://medium.com/@GalyaD/spacetech-is-going-global-57ccfe6f654d#.kfluktici.

83 L. Y. Chen, "China Government Is Bankrolling the Boom in Startup Fundraising," *Bloomberg Technology*, April 26, 2016, Accessed March 2, 2017, https://www.bloomberg.com/news/articles/2016-04-26/state-backed-chinese-money-bankrolls-boom-in-startup-fundraising.

84 The United States still has more start-ups (128 start-ups valued above $1 billion relative to China's 52), but China far surpasses any other single nation. The next nation on the list of start-ups valued above $1 billion is the UK, with 11 start-ups. From: Christopher Steiner, "International Venture Capital would soon Pass that of United States," FundersClub, https://fundersclub.com/blog/2016/08/30/international-venture-capital-will-soon-pass-united-states/.

band and L-band synthetic aperture radar (SAR) constellation on a smallsat platform.[85]

It is important to note here that government investments are not necessarily developing indigenous technology. They are purchasing products and services, attracting foreign firms to set up shop in their countries, or funding partnerships that benefit them. Luxembourg, for example, is providing U.S. firm Planetary Resources $25 million for setting up R&D and manufacturing facilities in Luxembourg.[86] In our interviews, we found a growing number of foreign companies selling products and services to a growing number of governments. Denmark-based Gomspace, for example, has active projects in Latin America, Japan, South Korea, China, and Australia, and the company is watching India carefully. Surrey Satellite Technology Ltd. (SSTL), based in the UK, designed, built, and launched a constellation of Earth observation satellites for its China-based client Twenty-First Century Aerospace Technology, and Space Flight Laboratory, based in Canada, is building a smallsat for a research center in the United Arab Emirates. Additionally, analysis from the 2016 Euroconsult report on the smallsat market indicates a growing number of smallsats, to be launched out of non-U.S. or European nations, are relying upon technology transfer partnerships with major European space nations.

2. Private Funding

Recent years have seen growing venture capital (VC) support for smallsat firms, although it is worth noting that a small number of firms dominate this investment (Figure 3-5, Table 3-5). Going forward, given the perceived potential (some real and some hyped) of smallsats, this investment is expected to grow. The hype surrounding the sector is exemplified in the market valuation of the smallsat launcher firm Rocket Lab. Despite having one—partly failed—technology demonstration, it is valued at twice the level ($1 billion vs $500 million) of Arianespace, a company with a demonstrated record of successful rocket launches over many decades.[87]

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[85] K. Russell, "UtherCAst Raises CA$17.6 Million to Support OptiSAR Constellation," Via Satellite, March 15, 2017. http://www.satellitetoday.com/technology/2017/03/15/urthecast-raises-ca17-6-million-support-optisar-constellation/?hq_e=el&hq_m=3373494&hq_l=17&hq_v=2004b29b8b.

[86] In addition, Planetary Resources has raised $35 million from venture capital http://www.planetaryresources.com/2016/11/planetary-resources-and-the-government-of-luxembourg-announce-e25-million-investment-and-cooperation-agreement/.

[87] P. B. de Selding, "Arianespace valuation, $500 million. Rocket Lab, $1 billion: New Space rethinking," Space Intel Report, June 16, 2017. https://www.spaceintelreport.com/arianespace-valuation-500-million-rocket-lab-1-billion-new-space-thinking/.

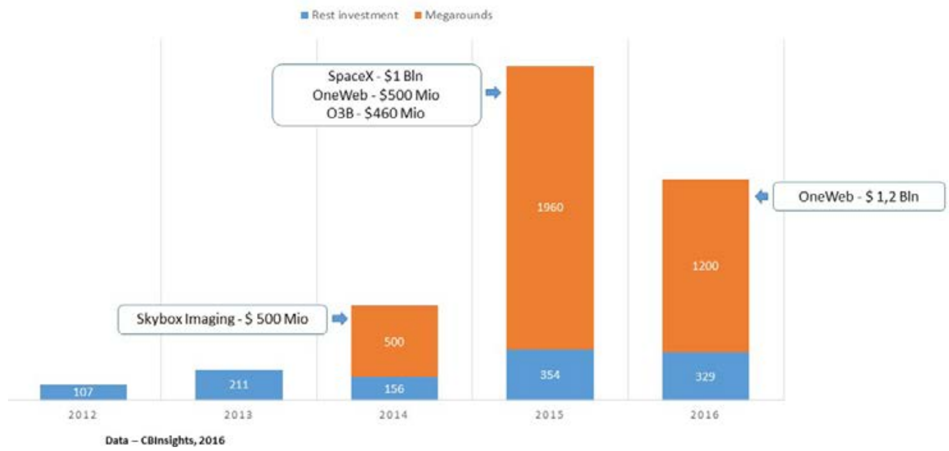


Figure 3-5. Growth in Venture Investment in New Space Startups

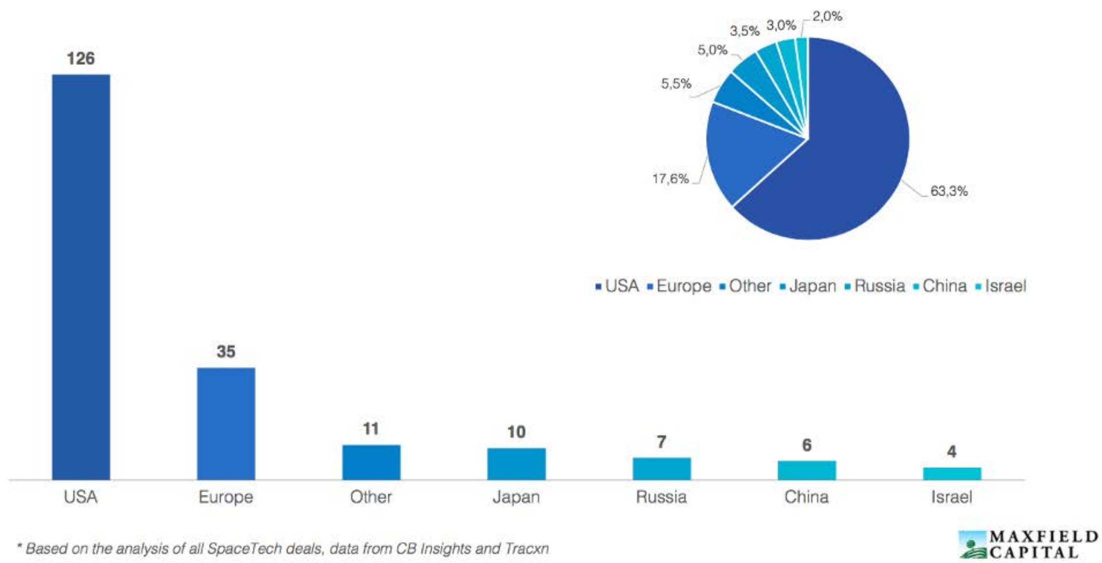
Table 3-5. Venture Capital Financing of Selected Constellation Companies, 2012–2016

Company	Expected Service	VC & Equity Financing through 2016	Major Investors
OneWeb (UK)	Communication	$1,719 million	Japan-based Softbank, Airbus Group, Intelsat, Bharti Enterprises, Totalplay, Hughes Network Systems, Qualcomm, Coca-Cola Co., the Virgin Group
SpaceX (U.S.)	Communication, Imagery, SSA, Other	$1,185 million	Internal funding, Google, Fidelity
Planet (U.S.)	Imagery, Data Products	$171 million	DFJ, Data Collective, Lux Capital, IFC venture Capital Group
Spire (U.S.)	Weather Monitoring, Data Products	$67 million	Bessemer Venture Partners, Promus Ventures, Shasta Ventures, RRE Ventures—William Porteous, Fresco Capital, Jump Capital, Moose Capital, Beamonte Investments, E-Merge, Grishin Robotics, Lemnos Labs, Mitsui and Co. Global Investment, Qihoo 360 Technology, Scottish Enterprise
Blacksky (U.S.)	Imagery, Data Products	$45 million	Mithril Capital Management, RRE Ventures, Vulcan, Razor's Edge Ventures, In-Q-Tel

Source: https://www.cbinsights.com/blog/space-startups-funding-trends/ and http://spacenews.com/oneweb-gets-1-2-billion-in-softbank-led-investment/

Note: Investment figures are based on publically available information for fiscal year 2016. Thus any capital raised and publicized after fiscal year 2016 is not captured in this table.

From a global perspective, United States VC firms dominate the space VC ecosystem (Figure 3-6). VC dominance, however, does not necessarily reflect or predict U.S. dominance in the global smallsat sector, partly because funds are not restricted to just U.S.-based firms, and partly because these firms are expected to eventually sell their products and services globally. We see examples of this already, with interviewees in both start-ups and established companies citing other countries as future customers, and indicating that the U.S. Government was reluctant to invest too heavily in them before they were able to demonstrate a technology—implying that such "watch and wait" policies pushed them to take foreign incentives to grow their businesses.



Source: https://medium.com/@GalyaD/spacetech-is-going-global-57ccfe6f654d#.rwwb9m6w7

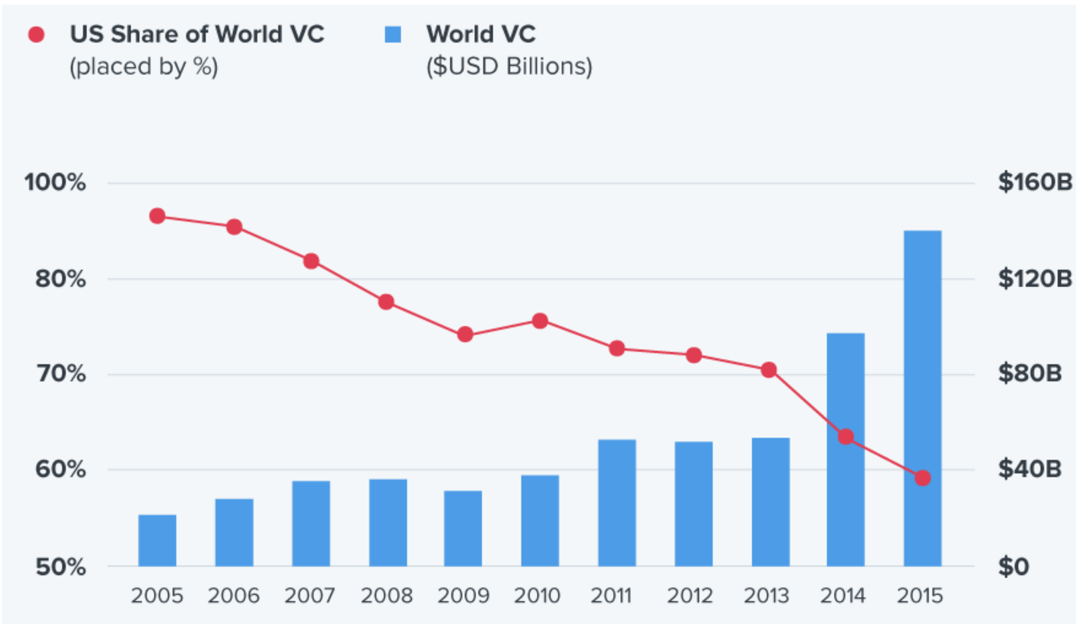
Figure 3-6. Number of Investors in the Space Sector

It is also notable that while the United States currently dominates space VC, and VC generally, its overall share has been dropping (Figure 3-7). The United States is also less dominant when it comes to private equity and later-stage investing, areas where European and Japanese communities tend to focus.[88] However, this trend could change, and foreign companies may play a greater role in earlier, riskier investments in small satellite companies. We already see examples of foreign space VC emerging (Figure 3-8). For example, in Europe, as many as 11 UK investors and 8 Russian and other European investors are investing in space technologies. Canada, Hong Kong, and Jordan also have

88 The Tauri Group, "Start-Up Space" January 2016, https://space.taurigroup.com/reports/Start_Up_Space.pdf.

multiple venture capital firms.[89] If this growth continues, it would further foreign start-up development, further encouraging global parity in smallsats.

We anticipate VC investment to remain stable globally, or to grow, even in light of failures of individual companies (as happened with the dedicated small launch provider Firefly Space Systems[90]) or partnerships (e.g., failure of the OneWeb-Intelsat merger).



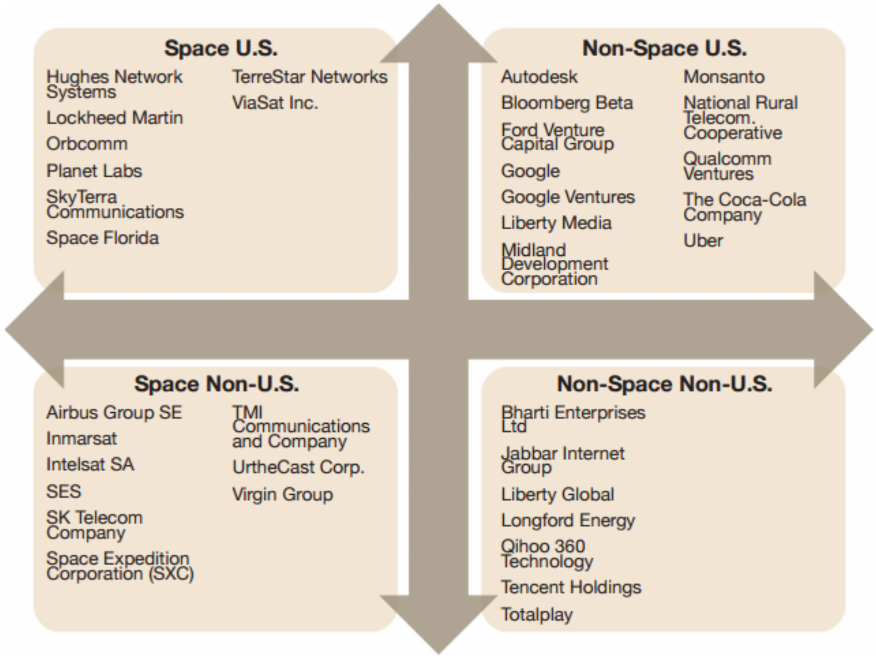
Source: Source: https://fundersclub.com/blog/2016/08/30/international-venture-capital-will-soon-pass-united-states/.

Note: Data not limited to space VC.

Figure 3-7. U.S. Share of World VC Funding

89 Degtyareva, “SpaceTech Is Going Global.”

90 Firefly Space Systems had to furlough their staff after a key investor pulled out, even though the company had no other technical or market failures J. Foust, “Firefly Space Systems Furloughs Staff after Investor Backs Out,” *Space News*, http://spacenews.com/firefly-space-systems-furloughs-staff-after-investor-backs-out/.



Source: Start-Up Space, Tauri Group, 2016.

Note: The non-space companies listed are investing in space ventures, the non-space modifier only indicates that their primary income is not from space ventures.

Figure 3-8. Firms Involved in Space

C. Technology Development

Technology is an important driver (both positive and negative) of the scenarios discussed in the preceding chapter. Sometimes technology exists but needs to be miniaturized. In other cases, technology exists, but needs to be cheaper. In some cases, entirely new technology needs to be developed. In the following subsections, we discuss trends related to the technologies most relevant to the four scenarios.

1. High-Resolution Optical Imaging

The development of high-resolution optical imaging payloads would allow near-parity between smallsats and large satellites in the area of remote sensing and Earth observation and is thus a major driver for Scenario 2; however, it is not an important driver for Scenarios 1, 3, and 4.

Different approaches being examined to make small satellites more competitive in terms of optical imaging include: deploy the space assets at lower altitudes,[91] increase

[91] Lower altitudes allow for better resolution with the same technology simply by being closer to the target. However, lower altitudes create greater drag for small satellites, either reducing satellite

smallsat apertures,[92] use deployable lenses,[93] employ post-processing software,[94] develop aperture synthesis interferometry technologies,[95] and use in-space manufacturing technologies to increase smallsat size in space. Trends in the different approaches (and organizations focusing on each approach) are presented in Table 3-6.

Table 3-6. Organizations Planning/Offering High-Resolution Optical Imagery Services from Smallsat Platforms

Approach	Company	Launch Year	Ground Resolution	Remarks
Low altitude operation	Planet (U.S.)	Operating	Under 5 m	Operate at 420–475 km, operate at ISS and SSO orbits and have a lifetime of 1–3 years
	European consortium[a]	Not known (TRL 2)	Not known	Research project scheduled to run 4 years from January 2017. Satellites would operate at 200-450 km.
Approach used to increase resolution on these smallsats is unknown	Digital Globe (U.S.)[b]/Taqnia Space and KACST (Saudi Arabia)	2018-2019	Sub-meter	Six small optical Earth observation satellites to complement DigitalGlobe fleet of large high resolution satellites
	ImageSat International (Israel)	2019	0.50 m[c]	Developing the Eros C satellite (350 kg). This program suffered delays from the original date of 2008.
	Dauria Aerospace (Russia) with China	Not known	0.7 m[d]	Developing 10 smallsats to track life in major cities worldwide. Dauria Aerospace is launching a prototype in 2017[d]

lifetimes or requiring changes in propulsion to keep small satellites in orbit. Lower altitudes also require more satellites to achieve global coverage, as each satellite would have a narrower field of view using the same technology.

92 Increasing apertures would increase imaging resolution. However, small satellites would still be stymied by physical limitations in trying to create large enough apertures to compete with larger satellites. Small satellite resolution of around a meter requires satellite apertures of >300mm, and have been proposed as >500mm. For CubeSats, which are more limited in size, Planet's Doves (4 kg) operate at 420–475 km and use 90-mm apertures to capture resolution at just under 5 m.

93 Deployables have been suggested as a means of creating larger apertures while retaining low weights and small bus sizes.

94 Post-processing software increases signal to noise ratio and decreases the ground sample distance by combining data from multiple frames taken with medium resolution cameras (http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1916178)

95 Aperture synthesis interferometry involving several small imaging satellites flying in formation could produce high resolution images such that those provided by a large satellite

Approach	Company	Launch Year	Ground Resolution	Remarks
Post-processing software	Terra Bella (U.S.)	Operating	0.90 m	Operate at 600 km. Combines data from multiple frames taken with medium resolution cameras
Deployables	Space Dynamics Laboratory (U.S.)	Not known	Not known	Designed a deployable telescope for use on CubeSats. Deployable telescope technologies still require significant on-orbit testing before they can make it into the mainstream small satellite industry
In-space manufacturing	Tethers Unlimited (U.S.)	Not known Currently at TRL3	Not known	Use of in-space manufacturing technology to enable smallsats to grow larger structures in space
Aperture Synthesis Interferometry	None known[e]			
Formation Flying	NASA	Not known (low TRL)	Not applicable	Early research on the use of magnetic waves to control a fleet of satellites to get the capabilities of a large aperture satellite[e]

[a] Partners in this research are the University of Manchester, Elecnor Deimos Satellite Systems, GomSpace AS, University of Stuttgart, Universidad Politecnica de Cataluna, University College London, TechToyBox, and Euroconsult.

[b] http://spacenews.com/digitalglobe-and-saudi-government-sign-joint-venture-on-satellite-imaging-constellation/.

[c] http://spacenews.com/imagesat-exec-says-eros-c-will-equal-markets-best-resolution/.

[d] https://www.rbth.com/science_and_tech/2015/10/13/70_mln_russian-chinese_satellite_project_will_monitor_life_i_50027.html.

[e] None of the key smallsat players that were interviewed were particularly interested in conducting aperture synthesis interferometry. The complexities of non-Keplerian orbits, inter-satellite communications, and in-space interferometry make this challenge an area that may not be tackled by private companies anytime in the next 10 years.

[f] http://www.technology.org/2017/05/12/electromagnets-offer-tantalizing-options-for-satellites/.

Given our research, we expect high-resolution optical imagery around 0.5 m to be available using smallsats in the next 10–15 years. Using imaging post-processing techniques, Terra Bella has shown resolution of about 0.9 m from a smallsat platform and expects further improvements.

2. Synthetic Aperture Radar (SAR)

The development of SAR payloads for smallsats is also a major driver for Scenario 2, but not an important driver for Scenarios 1, 3, and 4.

The biggest challenge for the success of SAR technologies on smallsats is the need for a large amount of power, typically not feasible on a smallsat platform. However, in recent years, low-power smallsat-suitable SAR based on existing technology used in airborne platforms, such as Frequency Modulated Continuous Wave (FMCW) technology,[96] has been being explored. Table 3-7 shows six organizations engaged in smallsat SAR, with only two being U.S.-based.

Table 3-7. Organizations Planning/Offering SAR Services from Smallsat Platforms

Platform/Mission	Operator	Projected Deployment	Remarks
NovaSAR-S (400 kg platform)	Surrey Satellite Technology Limited (UK)	*Not known*	Working with Astrium UK and partly funded by the UK. Plans to provide SAR imagery at 20% the cost of conventional.
	XpressSAR	2022	
Harbinger Mission (85 kg platform from York Space)	Iceye[a] (Finland)	2017	Planning to provide SAR with 1-hour response. Developed with York Space Communications for U.S. Army Space and Missile Defense Command
PanelSAR[b]	SSBV Space and Ground Systems (The Netherlands)	2017	FMCW-based X-band smallsat SAR for infrastructure monitoring
CubeSat platform	Capella Space[c] (U.S.)	2017[d]	30 CubeSats. Adjustable resolution (1 m to 30 m). Revisit rate of 3–6 hours globally and planning for every hour in 3–5 years. Antennae would be folded and packaged in the satellite body.
	Planet (U.S.)	*Not known*	Development confidential
	JAXA (Japan)	*Not known*	Participated in collaborative project to develop the antennae for a small SAR satellite under the Cabinet-level Impulsing Paradigm Change through the Disruptive Technologies Program (ImpACT) program[e]
Platform 50–80 kg	Tyvak (U.S.)	*Not known*	Program funded by Norway to track ice flow and shipping lanes. Able to provide 5-m resolution.

[a] http://www.itu.int/en/ITU-R/space/workshops/2016-small-sat/Documents/ICEYE-SSS-16.pdf.

[b] https://www.researchgate.net/publication/298792537_PanelSAR_an_FMCW_based_X-band_smallsat_SAR_for_infrastructure_monitoring.

[c] http://www.satellitetoday.com/nextspace/2016/12/06/capella-space-ceo-cost-enabling-inexpensive-sar/.

[d] http://spacenews.com/with-cash-infusion-capella-prepares-its-first-sar-cubesat/.

[e] The ImpACT program is one of two government-funded programs designed to compensate for the relative lack of venture capital in Japan by funding innovative technologies.

Given the variety of cost and application-based approaches being tested, and the current investment by governments and private firms, we expect commercial-quality SAR to be available on smallsat platforms by the 2030 timeframe.

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[96] FMCW technology transmits and receives continuously requiring less power than traditional SAR. Traditional SAR technologies uses pulse-based radar technology, which transmits short and high energy RF pulses and requires large amount of power. In reality, the traditional SAR technique and FMCW use the same amount of energy; however, the way the energy is delivered means that the required amount of power is different.

3. High-Bandwidth Communication and Data Download

a. Onboard Processing Technology

Onboard processing, such as data compression, data synthesis in orbit, and high-level modulation schemes, is important for imagery constellations in Scenario 1 as it minimizes bandwidth needs and reduces spectrum requirements.

Basic forms of onboard processing, particularly for video, simply remove individual frames at a set rate before sending data back, which lowers the amount of data to be transmitted while reducing data quality across the board. Hyperscout by Cosine (Netherlands) is a miniaturized commercial hyperspectral imager for land and vegetable inspection. It has been available for smallsats since December 2016, and it has onboard data processing, which reduces the amount of data that needs to be downloaded and processed. Current limitations for onboard processing for small satellites include cost of high-quality, radiation-hardened chips and the weight and power limitations of small satellites.[97] Improvements in onboard processing is a stated need in industry and government. For example, NASA's technology roadmap has cited 50% data reduction as a needed capability,[98] with additional goals of moving the proportion of satellite downlink decisions made autonomously from 30% to 100%.

b. Optical Communication

Communications equipment, both on the satellite and on the ground, is a major driver for Scenario 1 because of bandwidth limitations. Bandwidth is required for downloading the petabytes of daily imagery data that would likely be generated by observation constellations and for the functioning of communication constellations.[99] This subsection focuses on space-based communication equipment. Ground communication equipment is addressed in the discussion of infrastructure drivers (Section E of this chapter).

Spectral bandwidth congestions could be alleviated by advances in optical communication, especially in inter-satellite links.[100] Table 3-8 shows current trends in the

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97 Trends in power generation and storage are described in Appendix D.

98 In 2015, NASA's data reduction for Earth Observation satellites was 5% (https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_11_modeling_simulation_final.pdf).

99 Assuming 71% of the globe is covered by water, a refresh rate of once per day, and using four spectral bands, we computed that a single image of the world's land area with 5 m resolution using 16 bits per pixel requires nearly 10 petabytes of data. Constellations generating global maps at this resolution and bits per pixel in only four different spectral bands hourly would generate more than an exabyte of data per day.

100 In optical communications, beaming information with lasers significantly increase the amount of information transmitted over the same time period when compared with radio communications avoiding

use of optical communications on smallsats. Although the Laser Communications Relay Demonstration (LCRD) is not focused on smallsats, it is important to note NASA's efforts through the LCRD to use optical communications for near-Earth and deep space missions. Most of this effort is based in the United States or Europe.

There are several constellations with near-term (within 5 years) plans to use laser intersatellite links, and satellite-to-ground laser communication is on track to be demonstrated in 2017.[101] Given these efforts, we expect development and use of optical communications in 10–15 years.

Table 3-8. Organizations Planning/Using Optical Communications on Smallsat Platforms

Company	Projected Deployment	Remarks
Aerospace Corporation (U.S.)	2015	NASA sponsor. Failure with attitude and control prevented optical communication testing
Fibertek (U.S.)	Not known	NASA sponsor. 6U lasercom system
SpaceX (U.S.)	2019	Internal funding. Planning for intersatellite links in their +4,400 satellites communication constellation
Optical terminals from BridgeSat (U.S.) to use on York Space Communications (U.S.) bus	2017	U.S. Army Space and Missile Defense Command sponsor. Satellite to ground optical communication developed for smallsat SAR demonstration with Iceye
Kepler Communications (Canada)	2019	Planning for intersatellite links on CubeSat relay communications constellation
Analytical Space (U.S.)	2017	Hybrid radio-laser system: receive with radio and downlink with laser on CubeSat relay communications constellation.
ELSE SA (Switzerland)	2018	Planning nanosatellite constellation (Astrocast) for M2M

4. Advances in Miniaturization

Miniaturization is an important technology driver for the success of smallsats in general, and it is showing accelerating improvements, particularly of: attitude and orbit determination and control technologies that are continuing to get both smaller and more accurate; electrical power generation and storage technologies, mainly miniaturization of fuel cells, batteries, and non-solar power sources adapted from those used on traditional

radio frequency interferences. There is also less chance of satellites or ground systems accidentally interfering with each other because the beam widths involved in optical communication are much narrower.

[101] Companies investing in optical communications see that intersatellite links could eliminate RFI, reduce the number of ground stations, and simplify the required ground infrastructure. Optical communication is also expected to enable the allocation of broadband resources where it is needed, allowing for flexible routing of traffic in space.

spacecraft; thermal control technologies, focused on miniaturization of active thermal control systems; and avionics more tolerant to radiation. Current state of the art in each of these areas is described in Appendix D. These technologies are on pace to become better and cheaper within the next 5–10 years.

a. Attitude and Orbit Determination and Control

There are several concurrent trends in the direction of attitude and orbit determination and control that should shape technology over the next 10 years. These are highlighted below, and details are provided in Table 3-9.

- *Improvement on the technologies already available*. The trend towards increased precision would be driven by the needs of new applications; optical communications systems, for example, would require precision attitude determination and control
- *Use of propulsion systems for both attitude and orbit control*.
- *Increased production of integrated units*.[102] Demand for these off-the-shelf integrated units would increase as mass-manufacturing of smallsats (perhaps for large constellations) becomes more prevalent

Table 3-9. Organizations Developing Smallsat Attitude and Orbit Determination and Control

Approach	Manufacturer	Technology	Remarks
Improvement on already available technologies	Blue Canyon Technologies (U.S.)	Precision star tracker	Available pointing knowledge of 8 arcse.[a] Expects to achieve star tracker precisions of 2 or 3 arcsec
Propulsion systems for attitude and orbit control	MicroSpace Rapid Pte Ltd. (Singapore)	Micropropulsion	Launched CubeSats using micropropulsion for attitude and control
Integrated units	Maryland Aerospace (U.S.)/Blue Canyon Technologies (U.S.)	Combine multiple attitude and navigation components	Maryland Aerospace technology has been flown by Spire.

[a] This performance beats the previous state of the art, which was flown in the MinXSS mission at the end of 2015.

[102] These units combine multiple attitude and navigation components into a compact unit available off the shelf. For example, a single unit may combine reaction wheels, magnetometers, magnetorquers, GPS receiver, and star trackers into a ½U box.

b. Electrical Power Generation and Storage

In the next 10 years, technology advancements would likely occur in two areas: improvement of solar cell efficiency; and miniaturization of fuel cells, batteries, and other traditional sources of power on larger spacecraft. Trends in each are discussed in turn below.

1) Improvement of Solar Cell Efficiency

- *Solar Cells*. There is substantial work being done on multi-junction solar cells, which improve the efficiency of the already available triple-junction solar cells. Terrestrial applications drive progress in this area, and smallsats may be able to take advantage of the improvements. Fraunhofer Society is currently developing a four-junction solar cell (46% efficiency) and Boeing Spectrolabs is working on 5- and 6-junction solar cells (up to 70% efficiency)—these developments are still in the laboratory, and power-to-weight might not be comparable to current triple-junction cells. In the near term, these technologies are too expensive to justify the improved efficiency over triple-junction cells in smallsat missions, but this may change in the course of the next decade.
- *Flexible and thin-film solar cells*. The use of less photovoltaic material on these solar cells brings manufacturing costs down, but efficiency is lower (by 8–20%) at their current stage of development. As this technology develops further, it may be of interest to the smallsat community as it could open up new possibilities for deployable systems while remaining low cost.
- *Organic or plastic materials*. They offer the potential to be cheaper and more lightweight than traditional photovoltaics. However, they are currently at very low efficiency (4% or less).

If these more efficient solar cells become more affordable, smallsats would be able to perform their missions with less mass and surface area.

2) Miniaturization of Non-solar Power Sources Adapted from Traditional Spacecraft

- *Fuel cells*. Hydrogen fuel cells, including regenerative fuel cells, are garnering some interest for smallsat applications, as they would help enable planetary missions that may have to operate out of sunlight. None have yet been flown.
- *Solid-state battery*. NASA-funded research at the University of Miami is developing a structural battery material that could be especially useful for

CubeSats.[103] This could lead to a battery of 2–3 millimeters in thickness, which could be installed on the payload structure occupying about one-third of the area that is currently used by batteries in smallsats.

- *Radioisotope Heater Units (RHU).* While radioisotope thermoelectric generators (RTGs) will likely be too expensive and massive in the next decade to feasibly be incorporated into smallsat missions, it may be feasible to integrate the heat generating RHUs on small platforms.

All of these "next generation" power systems would likely only see adoption in the smallsat community when the smallsat market grows significantly. The cost of developing miniaturized nuclear energy sources, such as RTGs, for example, is well beyond what the industry can currently support, although it is technically feasible.

c. Thermal Control

Passive thermal control systems are more commonly used on smallsats; however, they tend to require more surface area or the assistance of deployable subsystems to adequately radiate away heat while active thermal control systems can be much more compact. Shown in Table 3-10 are several active thermal control technologies currently under development for smallsats.

Table 3-10. Organizations Developing Smallsat Thermal Control

Technology	Company	TRL	Remarks
Flexible and enhanced active thermal straps (FEATS)	Load Path Aerospace Structures	6	Heat dissipation up to 50 W cm^{-1} and cooling capacity of 35 W
Micro-cryocoolers	Sierra Lobo (U.S.)		Collaborated with NASA on Cryocube-1, the first CubeSat (3U spacecraft) to incorporate cryogenic cooling
	Ricor USA Inc. (U.S.)/Northrop Grumman (U.S.)/ Creare (U.S.)/ Sunpower, Inc. (U.S.)/ Lockheed Martin Space Systems (U.S.)	6–7	*No remarks*
Thermal storage units	Thermal Management Technologies (U.S.)/Active Space Technologies (Portugal)	5	*No remarks*

[103] NASA, "Next Generation Batteries Could Provide Power to Microsatellites, CubeSats," https://www.nasa.gov/feature/next-generation-batteries-could-provide-power-to-microsatellites-cubesats.

Technology	Company	TRL	Remarks
Fluid loops	Lockheed Martin (U.S.)	3	Based on a closed-cycle Joule Thomson cryocooler. Has a mass of 0.2 kg and power requirements of 1.2 W, yet can manage 40 W of spacecraft power as a single-phase loop or up to hundreds of Watts as part of a two-phase loop

d. Avionics More Tolerant to Radiation

Radiation effects on avionics systems remain difficult to predict given the stochastic nature of failures caused by radiation, how radiation doses vary with orbital altitude and solar activity, and the available protection from a small satellite's chassis. However, the industry is steadily improving the tolerable dose for commercial small satellite components. Today, the GOMSpace Nanomind Z7000 computer is qualified for a dose of 20 kRad;[104] if it were encased in a hemispherical aluminum shell that was 2.5 g/cm^2 thick, it could be expected to last 2 years at any altitude below 2,000 km.[105] Other, more expensive flight computers have higher tolerable radiation doses.

5. Spectrum

The development of technologies for more efficient use of the electromagnetic spectrum is a driver for the success of large LEO constellations (Scenario 1), given spectrum congestion and the possible radio frequency interference (RFI), which endangers the functioning and operation of smallsats.[106] It is also one of the major drivers of Scenario 3 as interferences impact the operation of satellites (small and large), which could lead to collisions and LEO being an unsafe environment. RFI is expected to increase once large LEO constellations start being operational due to: further congestion of the spectrum; use by these constellations of higher frequency bands, which are more sensitive to weather and

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[104] http://gomspace.com/UserFiles/Subsystems/flyer/gomspace_nanomind_z7000_flyer.pdf.

[105] Estimated from Figure 7-11 in Space Mission Engineering: The New SMAD.

[106] The more interference exists, the more spectrum is needed to transfer a given amount of information, which means further spectrum congestion and less data rates that could theoretically be realized.

therefore more prone to natural interferences; GEO and LEO satellites emitting signals at different power in same frequency bands;[107] and increased number of ground antennas.[108]

Given growing demand for spectrum, in the next 10–15 years, we expect an increase in R&D in two areas discussed below.

a. Dynamic Spectrum Access (DSA) Technologies[109]

DSA technologies such as software-defined radios (SDR)[110] and cognitive radios[111] are being developed to increase the efficiency of spectrum utilization.[112] SDR technology is now operating in some systems and networks in land and maritime mobile, broadcasting-satellite, and fixed and mobile-satellite services. Companies such as Kepler Communications (Canada) and Hawkeye 360 (U.S.) are planning to use SDR technology on their smallsat constellations. In the case of Hawkeye 360, the technology is being developed by Gomspace (Denmark).

To date, cognitive radio has been used only for terrestrial applications, although companies such as Tethers Unlimited (U.S.), with funding from NASA, are looking at upgrading SDR platforms with advanced cognitive radio.[113] Similarly, in Europe, CoRaSat, a European Commission-sponsored project, is looking to develop and demonstrate cognitive radio techniques to use on satellites.

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[107] A more powerful signal from another satellite could interfere with a weaker one, which could be the case when large GEO satellites using same frequency bands cross over smallsats in LEO constellations passing the equator. For example, SpaceX, Telesat Canada, Spire Global, and Boeing are filling for Ka-band, while SpaceX, OneWeb and Kepler Communications are filling for Ku-band, the same frequency bands as the HTS providers from Viasat and Inmarsat on the Ka-band and SES and Intelsat on the Ku-band. Even when satellites in LEO comply with the equivalent power flux density limits established by the ITU, they can still cause interference to HTS GEO satellites because they operate at lower power levels than non-HTS GEO satellites (http://spacenews.com/low-earth-orbit-constellations-could-pose-interference-risk-to-geo-satellites/) (http://www.intelsatgeneral.com/blog/understanding-the-new-hts-realities/).

[108] The increased number of antennas that would be required to operate the larger number of smallsats could lead to more RFI due to pointing errors from uplink antennas.

[109] Allows secondary users of the spectrum to use spectrum allocated to primary users, either when it is being unused or when the usage would not pose a risk to the primary communication operations.

[110] Software Defined Radio (SDR) can be programmed to transmit and receive on multiple frequencies within their hardware limits.

[111] Cognitive radios can sense unused frequencies and can adapt to automatically make use of those frequencies.

[112] One of the challenges of any of the technologies is to obtain the information required to assess what sections of the spectrum are available at a specific time and in a certain geographic area.

[113] Tethers Unlimited press release, "SWIFT-Thinking Satellite Radios that Adapt and Evolve." http://www.tethers.com/PR/OpenSWIFT_Ph2_PressRelease.pdf.

b. Technologies for the Use of High Frequency Bands (Q/V)

Technologies such as adaptive coding and modulation (ACM) are being developed and some have been successfully tested to reduce signal fading at high-frequency bands (Q/V). Eutelsat Communications together with Space Systems Loral (U.S.) successfully carried out transmissions on the Q/V band at 40–50 GHz using an experimental payload in 2016. ESA, in partnership with Thales Alenia Space (France-Italy), launched Alphasat in 2013, a payload to test the performance of the broadband data traffic in Q/V bands under different atmospheric conditions.

The challenge of ACM technologies is the high cost of the technology itself so further efforts would likely be focused on reducing their cost. Also, the use of frequency bands different than the common ones would require changes in the existing antennas and ground stations, which might require investment, increasing the cost of operating the smallsats.

6. Propulsion Systems

Propulsion systems for smallsats might become critical in the next 10–15 years to enable smallsats to de-orbit, to maneuver to avoid Scenario 3, or to enable high-precision maneuvering for on-orbit servicing. Propulsion for smallsats is a field currently attracting substantial research. Propulsion systems presented in Table 3-11 (and others discussed in Appendix D) would become increasingly available over the next 10–15 years as technology matures. Electric propulsion is less mature than chemical propulsion but might provide the most promising path forward, according to interviewed experts. The major challenge is the development of propulsion systems for CubeSats able to provide delta-v of around 1,000–2,000 m/s, which would be required to increase the lifetimes of CubeSats operating in lower orbits.

Table 3-11. Organizations Developing Propulsion Systems for Smallsats

	Propulsion System type	TRL	Thrust (N)	Impulse (s)	Company
Chemical propulsion system	Hydrazine propellant	6	0.5 to 4	150 to 250	Airbus Defense and Space (Europe), Aerojet Rocketdyne (U.S.), Moog ISP (UK)
	Non-toxic propellant	5-8	0.2 to 26.9	204 to 258	Ecological Advanced Propulsion Systems, Inc.(ECAPS) (U.S.),[a] Deep Space Industries (water-based propulsion system), Aerojet Rocketdyne, the U.S. Air Force, Tethers Unlimited, Inc. (U.S.), Busek (U.S.), NanoAvionics (Lithuania)
	Solid fuel	6–8	0.3 to 258	187 to 900	Industrial Solid Propulsion (U.S.), Orbital ATK (UK), Digital Solid State Propulsion LLC (U.S.)
Electrical propulsion systems	Resistojet (power requirements 30-50W)	9	0.100	up to 99	Surrey Satellite Technologies, Ltd. (UK), CU Aerospace (U.S.), VACCO (U.S.)
	Electrosprays (power requirements less than 5W)	5–6	$6\ 10^{-5}$ to $7\ 10^{-4}$	800 to 2300	Accion Systems (U.S.), the MIT Space Propulsion Laboratory (U.S.), Busek
	Hall-effect thrusters (power requirements 175-200W)	4-–8	$5\ 10^{-3}$ to $15\ 10^{-3}$	1139-1390	Rafael (Israel), Aerojet Rocketdyne, JPL (U.S.), UCLA (U.S.), Busek, Sitael Aerospace (Italy), the University of Toronto's Space Flight Laboratory (Canada)
Other propulsion systems	Radio frequency ion thrusters (power requirements 10-60W)	5-8	$5\ 10^{-5}$ to $1.4\ 10^{-3}$	3000	Busek, Airbus (Europe), University of Tokyo (Japan), ThrustMe (France)
	Pulsed plasma and vacuum arc thrusters (power requirements 1.5-14W)	5–8	10^{-6} to $9\ 10^{-5}$	536 to 3000	Mars Space and Clyde Space (UK), GWU and the U.S. Naval Academy (U.S.), NASA Ames and GWU (U.S.), Busek, Phase Four (U.S.)[b]
	Propellant-free propulsion systems (e.g., solar sail)	6–7	*Not known*	*Not known*	NASA Ames and Marshall Space Flight Center (U.S.), Planetary Society (U.S.)

[a] This non-toxic propellant system has already been successfully flown.

[b] Test results achieved 5.2 mN at 100W.

7. De-Orbit and Orbital Debris Removal Technologies

De-orbit and Orbital Debris Removal technologies are a major driver for Scenario 3 as they either prevent further debris (de-orbit) or reduce the number of pieces of debris (debris removal) in space.

Trends in deorbit technologies are presented in Table 3-12.[114] Deorbit technologies can be categorized as either active[115] or passive. Active deorbit technologies have been identified as a need or area of interest, but have not been given much attention—their needs for excess propellant, maintenance of attitude control over the spacecraft, and continuous operation make them more difficult to develop and more costly than many smallsat missions could afford. However, this situation might change as autonomous operations become more feasible and common.

Smallsats have a greater need for additional de-orbit techniques than do traditional spacecraft, given that they often do not have a propulsion system to use. Technology is in development, some concepts are already matured and more of them would be in the next 10–15 years. However, de-orbit guidelines are not enforced, so operators might choose not to use de-orbit technologies. In any case, operators are aware of the importance of orbital debris mitigation so the team expects operators would either follow the rules with regard to what orbits are best to operate in to avoid debris without the need of de-orbit technologies or would use the available de-orbit technologies.

Active Debris Removal (ADR) has attracted much attention recently as not just mitigation but remediation measures are needed to ensure space sustainability.[116] Some of the technologies under study are presented in Table 3-13. Even when some of the ADR concepts are technically plausible, there have not been successful on-orbit technology demonstrations,[117] and although ADR technologies could be ready to start operating in 10–15 years, the legal and policy challenges associated with active debris removal could hinder their adoption and use.

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[114] The NASA Orbital Debris Program office specifies that spacecraft must deorbit within 25 years after the end of their mission, or be placed into a graveyard orbit following that time.

[115] Propulsion as an active deorbit approach is not discussed in this section. Propulsion systems were discussed in Section C.6 of this chapter.

[116] J.-C. Liou, "Overview of the Orbital Debris Problem," 2015. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150019428.pdf

[117] 2017 JAXA mission to remove a piece of debris using an electrodynamic tether failed. The European Space Agency is sponsoring de e.Deorbit program that plans to capture and remove a heavy ESA-owned piece of debris. RemoveDebris funded by the European Union is planned for demonstration at the end of 2017 to inform the design of the e.Deorbit mission. No U.S. demonstrations or tests have occurred or are planned

Table 3-12. Organizations Developing Deorbit Technologies

	Technology	TRL	Company	Remarks
Active	Steered drag sail	*Not known*	*Not found*	Require a functioning attitude control system
Active	De-orbiting motor	9	D-Orbit (Italy)	Independent motor optimized depending on the satellite orbit, satellite mass and satellite performance for decommissioned maneuvers. Installed on satellites before launch
Passive	Deployable drag sail or boom	9	NASA	NanoSail-D (3U spacecraft) deorbited in 2011
Passive		Installed	UTIAS/SFL (Canada)	CanX-7 would deploy a drag sail to deorbit
Passive		9	MMA Designs of Boulder (U.S.)	DragNET De-Orbit demonstrated in 2013[a]
Passive	Membranes[b]	7-8	Composite Technology Development, Inc. (U.S.)	Roll-Out DeOrbiting device (RODEO)
Passive			Clyde Space and the University of Glasgow (UK)	Aerodynamic End-of-Life Deorbit system (AEOLDOS)
Passive	Re-entry module	Not known	Airbus Defense and Space leading 10 European partners (Europe)	TeSeR—Technology for Self-Removal of Spacecraft

[a] Able to deorbit a 180 kg ESPA-class spacecraft from altitude less than 850 km in less than 10 years.

[b] Lightweight membranes attached to roll-out boom structures to multiply a smallsat's surface area and increase drag in the upper atmosphere.

Table 3-13. Organizations Developing Active Debris Removal Technologies

Technology	TRL	Company	Remarks
Brane Craft	2	Aerospace Corporation (U.S.)	The 30-micron-thick spacecraft would have a very high thrust-to-weight ratio, and would be capable of traveling long distances and warp around debris
Satellite on an Umbilical Line (SOUL)	4–5	Busek (U.S.)	A10-kilogram satellite equipped with a tool that links by a 100-meter cord to a larger spacecraft
ElectroDynamic Debris Eliminator (EDDE) vehicle	5–6	Start Technology and Research (U.S.)	Reusable spacecraft (100 kg that packs into 0.11 m3), uses solar power and electrodynamic thrust, each capable of removing many targets. Captures debris with lightweight nets or grappler
Electrodynamic Tether	8–9	Tethers Unlimited (U.S.)	Deploys a length of conductive wire that generates an electromagnetic force as it moves relative to the Earth's magnetic field with the motion of the satellite's orbit
	Tested but failed to deploy in 2017	JAXA (Japan)	

Technology	TRL	Company	Remarks
Gecko gripper project	6	Jet Propulsion Laboratory (U.S.)	System installed on a robotic arm or leg could grapple objects in space that are spinning or tumbling through non-permanent stickiness of the grippers.
Space Debris Slingshot	Not known	Texas A&M University (U.S.)	No remarks
Space Debris Elimination or SpaDE	Not known	Raytheon (U.S.)	Air burst within the atmosphere to move satellites into a lower orbit
Debris Collection Units	Not known	Launchspace Technologies Corp. (U.S.)	Platform of the size of football field to remove debris from equatorial orbits ranging in size from 1 mm to 5 cm. Planned to be equipped also with SSA sensors
Roaming Dragon	Launched	China	No remarks
End of Life Service (ELSA)	Not known	Astroscale (Singapore)	Smallsat comprised of “Chaser” and “Target.” Chaser is equipped with optical sensing instruments and a redundant capture mechanism, and Target is a docking plate and functions as a “rescue package” bringing debris to low atmosphere.
CleanSpace One	Not known	Swiss Space Center (Switzerland)	Cleanup satellites using an ultra-compact motor and grabs and stabilizes the piece of debris going back to Earth, where both burn on the atmosphere
EUSO and CAN	Not known	Rinken (Japan)	System that combines a super-wide field-of-view telescope (EUSO) to detect pieces of debris with a laser (CAN) to deorbit the selected pieces of debris
e.Deorbit	Not known	European Space Agency (Europe)	Planned to remove a large piece of debris. E.Deorbit would be informed by the outcomes of RemoveDebris[a] planned for launch for end 2017 or 2018 and that would use a harpoon and a net to de orbit a CubeSat previously launched for the demonstration.

[a] The experiment was planned to be launched before mid-2017 for deployment from the ISS. However, the launch has been delayed to allow for additional NASA safety reviews (http://spacenews.com/launch-of-space-debris-removal-experiment-delayed-due-to-safety-reviews/).

D. Low-Cost Approaches

The development of manufacturing and assembling techniques and business models that reduce the cost of developing and operating a constellation is one of the principal drivers that would make LEO constellations commercially successful (Scenario 1) and also would make the development of on-orbit manufacturing possible (Scenario 4). Any reduction in the cost of developing and operating a smallsat is also a positive driver for

Scenario 2, as it would lower the barrier for non-traditional space countries to acquire capabilities to allow global near-parity.

1. Low-Cost Manufacturing and Assembly Techniques/Greater Availability of High-Performance and High-Reliability COTS Components

Typical communications satellites may cost on the order of hundreds of millions of dollars to develop today. In contrast, OneWeb is expecting to bring the price to build one of its satellites below $500,000.[118] Other companies (e.g., Berlin Space Technologies, Germany) are aiming to bring the price of their (smaller) smallsats as low as $250,000. These companies' estimates are credible as they are leveraging advances in low-cost manufacturing technologies, such as additive manufacturing, increasing the use of automation and robotics for satellite integration, and using commercial off-the-shelf (COTS) components. Use of these approaches could lead to three favorable outcomes affecting the success of large constellations and smallsats in general. First, satellite development time can be decreased from years to weeks. Second, development cycle costs can be reduced, not just by reducing the lead times but also the cost of components. Third, more advanced manufacturing would enable operators to hold lots of inexpensive components and satellites in storage ready for a fast launch to re-establish a capability. Even if the components are not on today's cutting edge of technology, having them available for cheap enough can foster a market that gives large constellations a higher probability of success compared to the 1990s or today.

Table 3-14 lists companies using low-cost manufacturing techniques and COTS components to reduce the cost of their smallsats.

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[118] P. B. de Selding, "One year after kickoff, OneWeb says its 700-satellite constellation is on schedule," *Space News*, July 6, 2016. http://spacenews.com/one-year-after-kickoff-oneweb-says-its-700-satellite-constellation-is-on-schedule/.

Table 3-14. Organizations Developing Smallsat Manufacturing Techniques and Using COTS Components

	Company	Plans and Remarks
Mass manufacturing	SpaceX (U.S.)	Building large factories for mass production of satellites
	OneWeb (U.S.)	Because of the large volume of the order, OneWeb Satellites able to build large factories and new designs for mass production of satellites.
		Expecting manufacturing rate of four satellites per day with 50-60 people
	Berlin Space Technologies (Germany)	Working to improve assembly line processes and technologies to reduce the unit cost of satellites
		Able to build a satellite with two people in four weeks
	York Space Systems (U.S.)	Looking to manufacture a standard spacecraft ahead of the need, and not having it be redesigned for every mission.
		Designed the AESV bus that supports payloads of up to 85kg and integrate with existing launch rideshare systems. The system hopes to support faster integration of payloads and the capacity to build constellations
	AAC Microtec (Sweden)[119]	Mass manufacturing underlying components such as avionics
	Spire (U.S.)	Design, build and test 1–2 satellites each week
	NovaWurks (U.S.)	Using standardized modular blocks, building a bus around instruments
	Blink Astro (U.S.)	Additive manufacturing of CubeSats
Use of COTS components	PhoneSat Cubesat	Plans to use a commercial smartphone as an avionics system for a nanosatelite
	Berlin Space Technologies (Germany)	Looking into low-cost, COTS-based systems
	Gomspace (Denmark)	Working to bring developed COTS communications technologies to space
	Surrey Satellite Technology Ltd (UK)	Test COTS parts as redundant systems and hosted payloads
	Iceye (Finland)	Planning to use COTS components for their smallsat SAR systems

2. Integration by Robotics Systems

Today, most satellites are highly specialized, and must be manually assembled. The ongoing trend of standardization in smallsat design has the potential to help boil the process down to simple, routine procedures allowing for satellite integration by using robotics systems. Efforts in this field are underway and accelerating, and come from both

[119] AAC Microtec, "ÅAC Microtec and York Space Systems Announce Agreement to Supply Advanced Avionics for Small Spacecraft Platform," http://investor.aacmicrotec.com/nyheter/aac-microtec-and-york-space-systems-announce-agreement-to-su-50153.

established companies such as Boeing, as well as start-ups such as OneWeb or Berlin Space Technologies.

Current efforts, both in space (e.g., to develop robots for inspecting and servicing existing spacecraft) as well as terrestrial (e.g., leveraging experience gained by terrestrial firms already implementing an assortment of assembly and manufacturing robots that can work reliably alongside human operators and carry out delicate tasks autonomously) are being leveraged. For example, Massachusetts Institute of Technology (MIT) has put forward the Integrated Navigation Sensor Platform for Extra-Vehicular Activity Control and Testing (INSPECT) concept for a free-flying robotic sensor suite intended for inspection of the ISS.[120] Space Systems Loral is working with NASA funding to build a robotic spacecraft for refueling and repairing satellites with hopes for a 2020 launch. Outside the United States, Magna Parva's (UK) Kleos mission is developing large robotic structures in space.[121] Within the next decade, these and other systems are likely to be well-tested and used in a growing number of servicing tasks. If space-focused actors, both in academia and industry, continue to learn and leverage existing models, a proliferation of space-based robotics systems can be expected in 10–15 years.

3. Alternative Business Models—Use of Modularity and Standardization

Organizations are using a variety of business models to increase productivity. There is a push for standardization in many types of smallsat technology to cut down on production costs and accelerate time-to-flight.[122] Trends in modularity, aggregation, standardization, and integration are presented in Table 3-15.

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[120] Boyd et al., *On-Orbit Manufacturing and Assembly of Spacecraft*

[121] https://inspacemanufacturing.com/portfolio/technology-concept/.

[122] See Appendix D.

Table 3-15. Organizations Developing Smallsat Modularity and Standardization

Company	Approach
NovaWurks (U.S.)	Developing HISat—a system of modular, interchangeable satlets, each integrating energy, navigation, processing, and communications[a]—by aggregating decomposed smallsat subsystems based on requirement
Pumpkin Space Systems (U.S.)	Standardizing the bus into a generic hardware platform with capacity to take on pluggable payloads
OneWeb (UK)	Designing satellites in a modular way, not building piece by piece, but building specific panels one by one and then grouping them together for integration and testing; no one has designed like this before
Maryland Aerospace (U.S.); Blue Canyon Technologies (U.S.)	Developing integrated units[b] (TRL 6) that combine multiple attitude and navigation components into a compact unit available off the shelf to fulfill all or most of a smallsat's determination and control needs[c]

[a] These satlets are designed to connect together and serve as an easily-assembled bus system for any payload, without placing requirements on the payload to conform. As capabilities can be switched off based on the needs of the payload, the system spares unnecessary capacity. This also allows customers with irregular payloads to avoid the costs of a wholly custom bus design.

[b] Demand for these off-the-shelf integrated units would increase as mass-manufacturing of smallsats (perhaps for large constellations) becomes more prevalent.

[c] A single unit may combine reaction wheels, magnetometers, magnetorquers, GPS receiver, and star trackers into a ½ U box

E. Infrastructure

The three major drivers under the infrastructure category are: the existence of an effective space situational awareness (SSA) system, the availability of a network of ground stations and in-space relays, and the use of low-cost ground communication technologies such as ground antennas and user terminals.

1. Effective Space Situational Awareness (SSA) System

The existence of an effective SSA system is an important driver for all Scenarios. It is critical for the safe and efficient operation of large LEO constellations of smallsats (Scenarios 1 and 2), making LEO a safer environment to operate in (negative driver for Scenario 3). An effective SSA system is also critical for Scenario 4 as it allows the operation of certain OSAM-related services such as on-orbit satellite servicing.

In general, an effective SSA would help reduce the overall risk of collisions between satellites fostering an environment that would make investors more likely to continue pursuing large satellite constellations. It still may be possible to launch large constellations without an effective SSA system in place, but the overall lifetime of the constellation could be in jeopardy from the risk of collisions and the unnecessary expenditure of propellant to avoid them.

Current state of the art on SSA is presented in Appendix D. Some of the efforts in the United States are highlighted below (efforts in other countries are expected be covered in future STPI work):

- DOD is improving the SSA system by adding new sensors to the SSN, such as the Space Fence.[123]
- The Joint Space Operation Center Mission System (JMS)[124] continues improving the analytical SSA capabilities.[125] An example of this is the recent metric change to predict conjunctions using probability of collision instead of miss distance, a change that decreased the number of close approach notifications sent by the 18 CSPC to operators from around 1,200 to 200 per week.[126]
- There have been discussions related to the provision of civil SSA services by an entity different than DOD.[127] The FAA Office of Commercial Space Transportation is willing to take on the responsibility of providing civil SSA services while DOD keeps supporting military space missions.
- The private sector continues providing SSA support on a fee basis and developing new alternatives for SSA provision. For example, companies today (e.g., ExoAnalytic) and in the future (e.g., LeoLabs) are helping or planning to help increase the fidelity and number of observations of space objects from ground assets. Others still, such as the Space Data Association and Analytic Graphics Inc., have signed agreements to upgrade data services.
- Applied Defense Solutions is supporting the Air Force's development of a space catalog using just commercial capabilities to compare with the space catalog

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[123] The Space Fence is being developed by Lockheed Martin. It is expected to be operational in 2018 and able to track objects to the 2 cm size, increasing the completeness of the space catalog (SSN). The current SSN system cannot track object smaller than 10 cm in size. There are more than 500,000 objects in space that are currently not tracked by the SSN.

[124] JMS is a net-centric, service-oriented architecture of hardware, software, data, and network connectivity that would process, integrate, store, and allow for the compilation, exploitation, sharing, and visualization of SSA sensor data and analysis to support command and control tasking and battle-management decisions for space forces.

[125] FY16 Air Force Programs, "Joint Space Operations Center (JSpOC) Mission System (JMS)," http://www.dote.osd.mil/pub/reports/FY2016/pdf/af/2016jms.pdf.

[126] Rob Wooldridge, "Improvements and Initiatives," SSA Operators' Workshop, 2016.

[127] See E. Nightingale, B. Lal, B. C. Weeden, Al. J Picard, and A. R. Eisenstadt, *Evaluation Options for Civil Space Situational Awareness (SSA)* (Alexandria, VA: IDA, August 2016), IDA Paper NS P-8038, https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2016/P-8038.ashx. Options include provision of SSA by a civil government entity such as FAA's Office of Commercial Space Transportation, by industry itself, and by an international organization.

generated by DOD (specifically the 18th Space Control Squadron) bringing SSA commercial data into the Joint Interagency Combined Space Operations Center.

- The Defense Advanced Research Projects Agency (DARPA) is working with industry to improve current DOD SSA capabilities with two programs, Hallmark[128] and OrbitOutlook.[129]

Abroad, countries in Europe started in September 2016 to operate a space surveillance and tracking system, which is funded by the European Commission. [130] France has been successfully operating the Conjunction Analysis and Evaluation Service Alerts and Recommendations (CAESAR), a “middleman” service that performs risk analysis for a fee for satellite operators. Also, commercial operators from the United States and abroad continue developing internal SSA capabilities and changing their strategy towards SSA,[131] while the numbers of conferences, workshops, and symposia devoted to SSA, both national and internationally, are significantly increasing. These trends show that operators are aware of the importance of SSA and that they are eager to contribute.

We believe that stakeholder awareness, collaboration, and commitment to supporting commercial activities will bring improved SSA capabilities even faster than in the past. Of particular interest are emerging global efforts, such as Europe developing an SST program, probably as a reaction to possible changes in the provision of SSA by DOD. We expect SSA not to be a roadblock for the success of smallsats.

2. Availability of Network of Ground Stations

The availability of a network of ground stations is important, especially for Scenario 1, to accommodate the large amount of data that is expected with large constellations, and for Scenario 2 as it would allow a growing number of countries to operate smallsats.

Emerging breakthroughs both in technology and new business models (Table 3-16) are beginning to address the challenge that smallsat operators face from the high cost of

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[128] Hallmark plan is to develop software to provide real-time space command and control (http://www.outlookseries.com/A0976/Infrastructure/3790_DARPA_Hallmark_Real_Time_Space_Command_Control.htm).

[129] OrbiOutlook plan is to create a diverse network of space sensors for SSA-related activities, including those from academia, privately owned optical telescopes, and commercial and civil radars (http://www.darpa.mil/news-events/2016-06-29).

[130] European Commission, “Horizon 2020. Work Programme 2016-2017.” http://ec.europa.eu/research/participants/data/ref/h2020/wp/2016_2017/main/h2020-wp1617-leit-space_en.pdf.

[131] For example, Intelsat is focusing now on specific close approach events rather than in all the individual close approach alerts that receives daily from the 18th Space Control Squadron (https://advancedssa.com/assets/img/workshop/presentations/SA_Operator_Workshop_Intelsat.pdf).

accessing ground stations to download data from the satellite. Current ground station operators that serve the smallsat community include both large actors (e.g., KSAT (Norway), Swedish Space Corporation (SSC)) that have adapted existing infrastructure, and emerging start-ups (e.g., Leaf Space (Italy), Infostellar (Japan), BridgeSat (U.S.)).

All operators except BridgeSat are focused on radio communications because ground optical stations are more expensive to develop, with more technical challenges to address,[132] and there is not yet a market for it (to the best of our knowledge, almost all future LEO constellations would use radio frequencies to communicate with the ground). However, we expect that in 10–15 years a large portion of the satellite to ground communication would be done by optical means, given the advantages of optical communications and the fact that Bridgesat is partnering with different operators (e.g., Swedish Space Corporation that operates a global network of RF ground stations) and is ready to test their optical system (ground station and low weight space terminal) in 2017.

[132] Apart from the need of more accurate pointing capabilities for optical communications, two other challenges are the effect of weather, mainly clouds and turbulence, and the possibly lack of fiber close to the optical ground stations to pass the downloaded data to the customer.

Table 3-16. Organizations Developing Network of Ground Stations

	Company	Business Model	Remarks
Radio communication	KSAT[a] (Norway)	Adapting their ground station network to support smallsats. Plans to offer two options: 1) traditional fixed 24/7 connection; 2) new shared service where the smallsat is not in constant[b] connection with the ground station	Develop KSAT Lite network 20 station global smallsat ground network (Figure 3-9). Designed specifically for low-cost needs of smallsat operators
	Leaf Space (Italy)	Traditional	Developing a 20 station global smallsat ground network[c]
	Infostellar (Japan)	Brokering system	Developing a system to connect operators with under-used ground stations networks
	Spire (U.S.)/Planet (U.S.)/SpaceX (U.S.)	Self sufficient	Spire and Plant have both built privately owned ground stations
	Spaceflight Industries[d]	Partnerships development for users to pay per minute to communicate with a ground station	Partnered with Tethers Unlimited and Syrlinks to combine its own and partner stations in a single user interface.
	Swedish Space Corporation	Adapting their ground station network to support smallsats	
	Blue Canyon Technologies	Low cost system	Using, as a low-cost alternative, a single antenna installed on the roof of their headquarters
Optical communicatio n	BridgeSat	Optical communication with access on a price per delivered bit basis	The only developed optical ground network in the world based on STPI findings (Figure 3-10). Developed 2 kg optical terminals suitable for CubeSats. The system would go under demonstration in 2017.[e]
Hybrid (Radio-Optical)	NASA	Hybrid system to serve optical and radio communications	Supporting optical communication for deep space communications[f]

[a] Detailed information about KSAT can be found in KSAT study case in Appendix G of the report.

[b] Fluctuating connection speeds based on loading in the region and time of day

[c] C. Henry, "Leaf Space Raises $1.1 Million for Dedicated SmallSat Ground Station Network," *Via Satellite*, July 11, 2016, http://www.satellitetoday.com/publications/st/2016/07/11/leaf-space-raises-1-1-million-dedicated-smallsat-ground-station-network/.

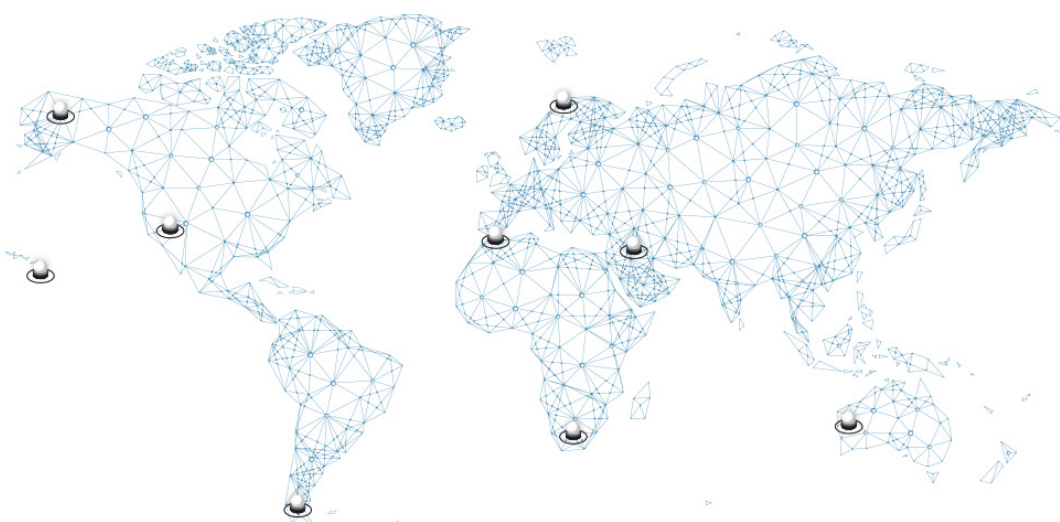
[d] http://www.satellitetoday.com/technology/2015/07/14/spaceflight-teams-with-spire-radio-developers-on-smallsat-ground-communications/

[e] The BridgeSat system is expected to be demonstrated with the inaugural launch of the U.S. Army Space and Missile Defense Command Harbinger Mission in late 2017 (http://www.bridgesatinc.com/york-space-systems-yss-bridgesat-collaborate-bring-optical-communications-capabilities/).

[f] http://kappet.com/uploadinside/TechPort%20pdf%20Download%20-%201453474904212.pdf

Source: J. Van Wagenen, "KSAT Launches 20 Ground Station Network for SmallSats," *Via Satellite*, January 21, 2016, http://www.satellitetoday.com/technology/2016/01/21/ksat-launches-20-ground-station-network-for-smallsats/.

Figure 3-9. Map of KSAT's Small Satellite Radio Communications Ground Stations



Source: BridgeSat website

Figure 3-10. Map of BridgeSat Optical Communication Ground Station

3. Availability of In-Space Relays

The availability of in-space relays is important for Scenario 1 to facilitate the transmission of data to the ground from large constellations. There are two companies developing CubeSats constellations for satellite-to-satellite data relay: Kepler Communications (Canada) planning to be operational in 2018 (although initially the focus would be terrestrial backhaul) and Analytical Space (U.S.). Kepler Communications is planning to use intersatellite links and radio communications with the ground, while Analytical Space is planning to use optical communications with the ground.

4. Low-Cost Ground Antennas and User Terminals

Availability of low-cost ground antennas and user terminals able to integrate multiple signals and to track satellites that move quickly in LEO[133] is a major driver to ensure affordability of services provided by LEO broadband constellations (Scenario 1). However, it is not a driver for any of the other scenarios. Trends related to new approaches such as the development of low-cost phased-array technology[134] into flat panel antennas are highlighted in Table 3-17.

Table 3-17. Organizations Developing Low-Cost Ground Antennas and User Terminals

Company	Partnerships	Applications	Remarks
Phasor Solutions (U.S.)	Intelsat (U.S.)/Thales Alenia Space (Europe)/ OmniAccess (Spain)/ Kepler Communications (Canada)	Mobile (aeronautical, maritime, or rail transportation)	
Kymeta (U.S.)	Intelsat (U.S.)/Toyota (Japan)/Panasonic (Japan)/Inmarsat (UK)/ Intellian (South Korea)/ Airbus Defense and Space (Europe)/Sharp (Japan)/SKY Perfect JSAT Corporation (Japan)	Mobile antenna to install on car roofs (20cm mTenna)[a] Plans to be commercially available in mid-2017 Fully packaged mobile satellite terminals	Using metamaterials. Antennas can be mass produced sharing production lines with TV manufacturers

[a] Successfully connected to an Intelsat satellite constellation in February 2017.

We expect that in the 2030 timeframe, affordable low-cost ground antennas and user terminals would not be a roadblock for the success of LEO communication constellations. This is because of current advances in the field with demonstrations happening in 2017.

[133] Traditional satellite dish antennas cannot be used for LEO applications. Also, the size of the large size of the antenna needed by mobile users would make the service impractical.

[134] Phased-array antennas are electronic steering and scanning antennas. The technology has been mainly used in military applications, as it was too costly for commercial uses.

Judging from the partnerships between satellite operators and manufacturers such as Phasor Solution and Kymeta, interest in this type of antenna would help introduce the companies' products into the market.

Those providing infrastructure services, including a network of ground stations, in-space relays, and ground antennas and user terminals, could be the biggest winners in the early smallsat era[135] in the same way the biggest winners in the days of the gold rush were those selling shovels, and in the early internet days were those selling pipes (e.g., Cisco Systems).

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[135] Experts believe that flat panel antennas could lead to more than $710 million in annual sale by 2025. Caleb Henry, "NSR: Phased Array Antennas Worth $710 Million by 2025, 'Critical' for LEO Success," *Via Satellite*, February 5, 2016, http://www.satellitetoday.com/technology/2016/02/05/nsr-phased-array-antennas-worth-710-million-by-2025-critical-for-leo-success/.

4. Access to Space

Availability of reliable low-cost launch is one of the most important drivers across all scenarios, and will remain a key area to watch in the coming years. That launch is a bottleneck for smallsats was evident in the launch failures and delays during 2016 that prevented smallsats from launching, generating data, and reaching new customers.[136] In this chapter, we discuss launch availability and the cost of launch as drivers of the smallsat sector.

A. Availability of Reliable Launch Alternatives

Availability of reliable and frequent launch alternatives[137] is an important driver for Scenarios 1 and 2. They drive the success of constellations (Scenario 1) because of the need to quickly deploy a constellation of thousands of satellites, especially one that takes many launches to become minimally operable in similar or different orbital planes, or for replenishing of large constellations when individual units fail or when technology refresh is required to continue providing services. Launch is also important for Scenario 2 to enable a growing number of nations to launch remote sensing smallsats and get global near-parity with large spacefaring nations. With regard to Scenario 4, the existence of persistent manufacturing and assembling platforms in space would be a major disruptor to the smallsat launch market.

One of the challenges for small satellites with regard to launch is the lack of on-demand access to space. To address the anticipated high demand for small satellite launches over the next 10 years, we identified 34 companies and government institutionsthat are developing small satellite launchers to LEO (Table 4-1, Figure 4-1).[138] These small satellite launchers span a wide range of Technology Readiness Levels (TRLs), with the Pegasus XL having extensive flight heritage (TRL 9), the Electron with ground

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[136] Debra Werner, "Launch bottleneck keeping smallsat growth in check," *SpaceNews*, March 6, 2017. http://spacenews.com/launch-bottleneck-keeping-smallsat-growth-in-check/.

[137] One of the challenges for small satellites with regard to launch is the restrictions impose by current options (i.e., rideshares and piggybacking missions) in terms of integration and launch schedule, orbit destination and subsystems incorporated in the small satellite.

[138] UK's Satellite Applications Catapult Ltd. has identified 50 launcher options. https://media.sa.catapult.org.uk/wp-content/uploads/2017/07/05135526/Market-Intelligence-Quarterly-Report-Q1_Q2-July-2017_webv2.pdf

flight tests (TRL 9), and the SABRE engine from Reaction Engines in early stage design (TRL 3 and 4).

It is likely that a few of these companies would start commercial operations. ExPace (China) has operated once in 2017[139] and Rocket Lab (New Zealand) started with flight tests in mid-2017. Vector Space Systems (U.S.) successfully tested its Vector-R rocket and is planning to start operations in 2018. It is also likely that not all of the enterprises would succeed, based on the setbacks experienced by some of the small satellite launch companies in the past due to technical or financial difficulties.[140]

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[139] Stephen Clark, “Kuaizhou Rocket lifts off on first commercial mission,” Spaceflight Now, http://spaceflightnow.com/2017/01/09/kuaizhou-rocket-lifts-off-on-first-commercial-mission/.

[140] In late 2015, the DARPA-funded ALASA project with Boeing was canceled as a result of continued test failures. In 2016, Swiss Space System declared bankruptcy after two years of financial difficulties (Doug Messier, “Swiss Space Systems Declares Bankruptcy,” Parabolic Arc, http://www.parabolicarc.com/2016/12/19/swiss-space-systems-declares-bankruptcy/); Firefly Space System Inc., which got a $5.5 million Venture Class Launch Services contract with NASA in 2015, lost a major investor with severe consequences for the company (J. Foust, “Firefly Space Systems Furloughs Staff After Investor Backs Out,” *SpaceNews*, http://spacenews.com/firefly-space-systems-furloughs-staff-after-investor-backs-out/); and Garvey Spacecraft Corporation was acquired by Vector Space Systems (PR Newswire, “Vector Space Systems Completes Acquisition of Garvey Spacecraft Corporation to Enhance Micro Satellite Launch Capabilities,”http://www.prnewswire.com/news-releases/vector-space-systems-completes-acquisition-of-garvey-spacecraft-corporation-to-enhance-micro-satellite-launch-capabilities-300301053.html).

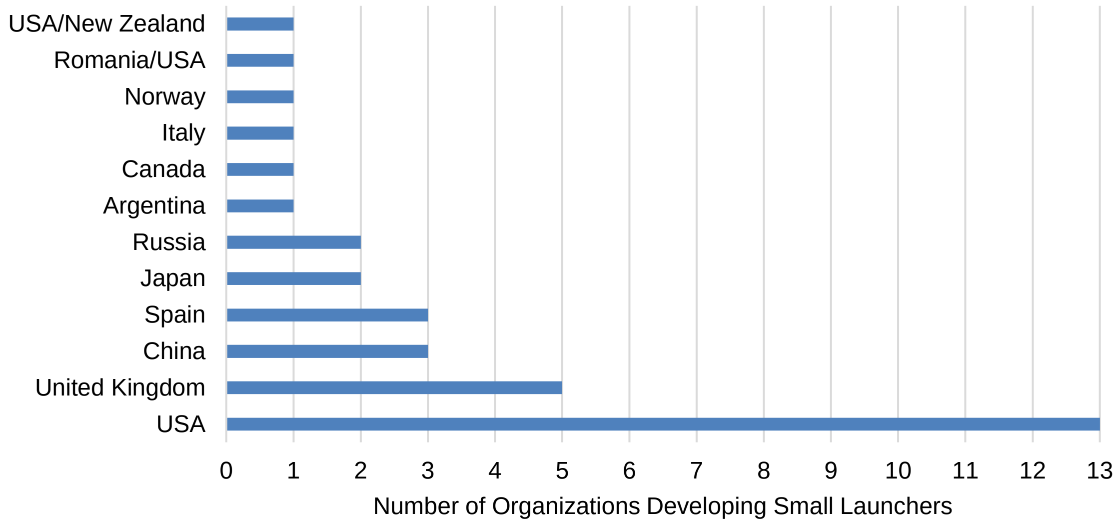
Table 4-1. Small Satellite Launchers in Development with Plans to be Operational Between 2017 and 2021

Manufacturer Name	Country	Vehicle Name	Maximum capacity (kg) to specified orbit	Orbit	Launch Type	Latest Launch Date	Technology details
1. Orbital ATK	United States	Pegasus XL	468	200 km, 0°	Air using L-1011Stargazer	1994	Three stages solid fuel with an optional fourth liquid stage
2. ExPace	China	Kuaizhou	300	LEO		2017	Solid fuel engine
3. Rocket Lab	New Zealand/ United States	Electron	150	500 km SSO	Land	2017	Liquid engine. 3D printed parts for all its primary components with no gas generators using small high-performance electric motors and lithium polymer batteries
4. Interorbital Systems	United States	Neptune N52	40	310 km SSO	Land, Water	2017	Solid rocket engine. Modular rocket to launch to different combinations of orbits and payloads.
5. Vector Space Systems	United States	Vector R (Rapid)	50	LEO	Land, Sea	2017	LOX/Propylene engine. 3D printed rocket engine injector
		Vector H (Heavy)	100	LEO		2019	
6. Virgin Galactic	United States	LauncherOne	200 225	LEO SSO	Air using Boeing 747-400	2017	LOX/RP-1 liquid rocket engine. First version of rocket is expendable but thinking about reusable design.
7. SpaceLS	United Kingdom	Prometheus-1	150–250	LEO	Unknown	2017	Hydrogen Peroxide and Kerosene engine
8. LandSpace Technology	China	LandSpace-1	530 400	300 km 500 km SSO	Land	2017	Solid-fuel rocket
9. zero2infinity	Spain	Bloostar	100 k75	600 km SSO	Balloon	2018	Reusable methane and oxygen engine. No turbo-pump fed engines. Reusable parts
10. bspace	United StatesA	Volant	215	LEO	Land	2018	Using solid rocket motors, proven on dozens of successful flights.
11. CubeCab	United States	Cab-3A	5	400 km	Air	2019	

Manufacturer Name	Country	Vehicle Name	Maximum capacity (kg) to specified orbit	Orbit	Launch Type	Latest Launch Date	Technology details
12. CONAE	Argentina	Tronador II	250	600 km SSO	Land	2019	Liquid expansible rocket system
13. Rocketcrafters	United States	Intrepid-1	376	500 km SSO	Land	2019	Hybrid engine using 3D printed gran fuel
14. Horizon Space Technologies	United Kingdom	Black Arrow 2	500 200	200 km 600 km SSO	`	2019	Liquid Oxygen and Liquefied Natural Gas engine
15. Nammo/Andoya	Norway	North Star Launch Service	35 50	LEO SSO	Land	2020	hybrid engine
16. Open Space Orbital	Canada	Neutrino I	50	LEO	Land	2020	Ethanol/LOX engine
		Neutrino T				2024	Methane/LOX engine. 3D-oriented technologies
17. Celestia Aerospace	Spain	Sagitarius Space Arrow	16	600 km	Air using MiG29UB	2020–2021	
18. Orbital Access	United Kingdom	Orbital 500	500	650 km SSO	Air using a wide body aircraft	2020	Horizontal launch (air launch)
19. Lin Industrial	Russia	Таймыр-1А	12.5			2020	
20. PLD Space	Spain	Arion 2	150	400 km	Land	2021	Liquid Oxygen and Kerosene engine. Reusable launchers
21. Reaction Engine	United Kingdom	SABRE (engine)			Air		Hybrid engine
22. Tranquility Aerospace	United Kingdom	Devon Two	4	LEO	Land		
23. UP Aerospace	United States	Spyder	8	370 km	Land		
24. Bagaveev Corporation	United States	Bagaveev	10	SSO	Land, Water		Pressure fed 3D printed rocket with turbopump

Manufacturer Name	Country	Vehicle Name	Maximum capacity (kg) to specified orbit	Orbit	Launch Type	Latest Launch Date	Technology details
25. Generation Orbit	United States	GO Launcher 2	40	425 km, 30°	Air using Gulfstream		Single-stage liquid oxygen-kerosene propulsion system. COTS for avionics
26. Leap Space	Italy	Primo	50	700 km SSO	Land		
27. Makeyev	Russia	Shtil-1	80 kg, 430 kg or 185 kg	500 km, 79°/200 km or 700 km			
28. Scorpius Space Launch Company	United States	Demi-Sprite	160	LEO	Land		All-composite, unibody structure/propellant tanks with no turbopumps. Only moving parts on the vehicle are valves
29. ARCA Space Corporation	Romania/ United States	Haas 2C	400	LEO	Land		Liquid oxygen and kerosene engine
30. CASIC	China	Fei Tian 1	430	500 km SSO	Land		Solid Fuel
31. MISHAAL Aerospace	United States	M-OV	454	LEO	Land		
32. VALT Enterprises	United States	VALT	25	500 km	Land using portable launch infrastructure, sea or air platform		Hybrid rocket engine
33. IHI Aerospace Company	Japan	Epsilon					
34. Interstellar Technologies Inc.	Japan						

Source: Assembled from various sources including C. Niederstrasser, "Small Launch Vehicles—A 2015 State of the Industry Survey." 29th Annual AIAA/USU Conference on Small Satellites, 2015; D. Lim, "Small launcher market survey—where are we and where are we going?" Room, October 2016; D. Messier, "A Plethora of Small Satellite Launchers" Parabolic Arc, October 2016; and company websites.



Source: Assembled from various sources including C. Niederstrasser, "Small Launch Vehicles—A 2015 State of the Industry Survey." 29th Annual AIAA/USU Conference on Small Satellites, 2015; D. Lim, "Small launcher market survey—where are we and where are we going?" Room, October 2016; D. Messier, "A Plethora of Small Satellite Launchers" Parabolic Arc, October 2016; and company websites.

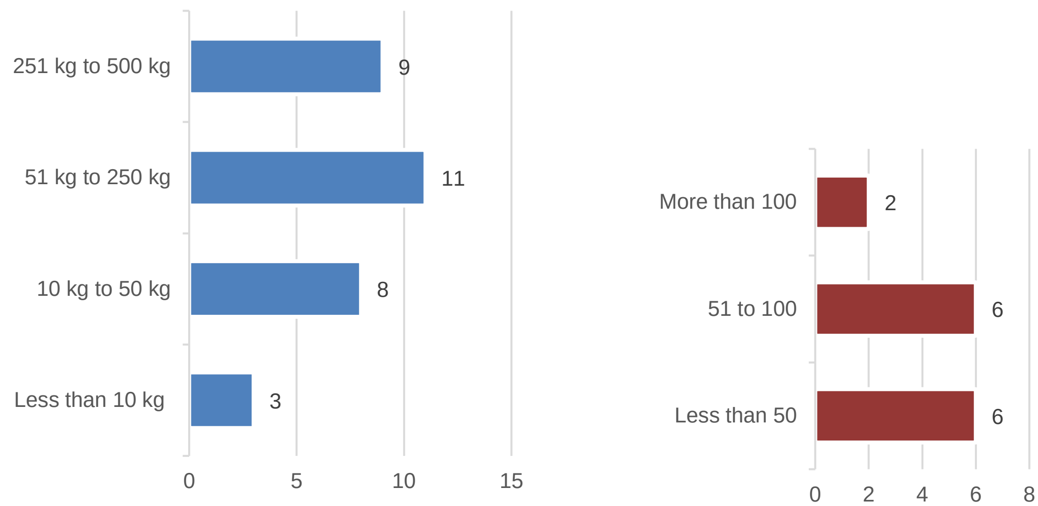
Figure 4-1. Number of Small Satellite Launchers in Development by Country with Plans to be Operational Between 2017 and 2021

Small satellite launch providers are exploring different technologies and launching options. Although most of the companies would use vertical launching from a land site or from a ship on the sea, five of them are looking into air launch using an airplane, and one (Zero2Infinity) is using a balloon from a boat in international waters. The advantages of launching from an airplane or a balloon are the easy access to a launching site, more flexibility on choosing the final orbit, minimal ground support requirements, and fewer launch window restrictions (less air traffic interference or fewer weather delays). For companies using an airplane, a disadvantage is the need to procure, maintain and amortize the cost of the airplane, something that is not required if using a balloon. Most launchers are targeting the non-CubeSat (over 10 kg) market, and the number of projected launches per year varies among the different companies (Figure 4-2).

The high demand for smallsat launch is expected to be filled in the next 10 years by a combination of small launchers and large launchers such as those from SpaceX (U.S.),[141]

[141] SpaceX is planning to launch every 2 to 3 weeks using its reusable Falcon 9 rocket (http://www.popularmechanics.com/space/rockets/a7446/elon-musk-on-spacexs-reusable-rocket-plans-6653023/) and is exploring ways to facilitate the launch of multiple clusters of small satellites into LEO,

ISRO (India), ULA (U.S.),[142] Glavkosmos (Russia), Arianespace (Europe), and MHI (Japan), all of which have announced their desire to support the smallsat market.[143] Some of them are already working with brokers such as Spaceflight Industries (U.S.), Commercial Space Technologies (UK), ECM Space (Germany), TriSept (U.S.), Tyvak (U.S.), and Innovative Solutions in Space (Netherlands). Large brokers serve as mediators between the launch vehicle and the smallsat as operators of large launchers are not generally interested in dealing directly with smallsat operators. Spaceflight Industries uses an interface, called SHERPA, capable of accommodating almost 90 smallsats in a Falcon 9 rocket. Brokers are also acquiring their own rockets; Spaceflight (U.S.) bought a SpaceX Falcon 9 (U.S.) in 2015 and a Rocket Lab Electron (New Zealand) in 2017.



Number of launch companies by mass to orbit **Number of launchers by yearly cadence**

Source: Assembled from various sources including C. Niederstrasser, "Small Launch Vehicles—A 2015 State of the Industry Survey," 29th Annual AIAA/USU Conference on Small Satellites, 2015; D. Lim, "Small launcher market survey—where are we and where are we going?" Room, October 2016; D. Messier, "A Plethora of Small Satellite Launchers" Parabolic Arc, October 2016; and company websites,

Figure 4-2. Small Satellites Launchers: Classification Per Weight and Per Number of Projected Launches Per Year

There have also been announcements on new large rockets such as New Glenn from Blue Origin, the Falcon Heavy from SpaceX projected for launch in 2017, and Vulcan from

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[142] ULA through the CubeSat Rideshare Initiative is working with Tyvak nanosatellite Systems, Inc., to provide low-cost access to space for both commercial and U.S. Government CubeSat customers (http://www.ulalaunch.com/tyvak-nanosatellite-systems-inc-selected.aspx)

[143] Debra Werner, "Launch providers making room for smallsat boom," *SpaceNews*, http://spacenews.com/launch-providers-making-room-for-smallsat-boom/

ULA projected for 2019. For large and medium lift launchers to support the smallsat industry, they need to address the issue of smallsat integration.[144]

Some constellations, especially communication ones with larger smallsats, would rely on large launchers for set up, and smaller launchers for replenishment. For example, OneWeb has contracted with Arianespace to have 21 Soyuz launches at 30 satellites per launch to initially deploy 36 satellites in 18 planes, and has plans to use Virgin Galactic's LauncherOne to deploy 2 satellites per flight for replenishment/fill-ins.[145] Rocket lab is planning to support constellations replenishment by storing small satellites fully integrated into the launcher fairings and ready to be able to launch in a matter of hours if required.[146]

Looking at the planned smallsats to be launched in the next 10 years, around 68% of small satellites less than 50 kilograms and around 20% between 50–500 kg[147] do not have yet plans for a launcher. For constellation set up, there are operators that have not decided yet on a launcher, others that would rely on larger launchers for the initial deployment, and others with contracts with a future small satellite launcher (Table 4-2).

The potential for small satellite launcher market saturation is illustrated in Figure 4-3, which compares the potential supply and remaining demand for 2017–2021. The supply is given by the small launchers planning to be operational within the time period and the remaining demand are the satellites still looking for a launcher in the same time period. If the expected smallsat launches between 2017–2022 succeed, the launch supply would surpass the launch demand. Furthermore, some of the satellites on demand of a launcher might choose a larger launcher making the supply from small launchers even higher.

Based on the findings in this section, we expect that in the 2030 time-frame, launch service availability would not be a bottleneck for the small satellites market. Small satellites operators would likely be able to choose between dedicated rides and rideshares to support their needs.

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[144] In 2013, 47 out of the 82 attempted launches had excess payload mass capacity; however, there were little space for smallsats on the 1-50 kg range due to vehicle integration limitations, 88% of launches to LEO did not have space for CubeSats or microsats.

[145] Interview with OneWeb

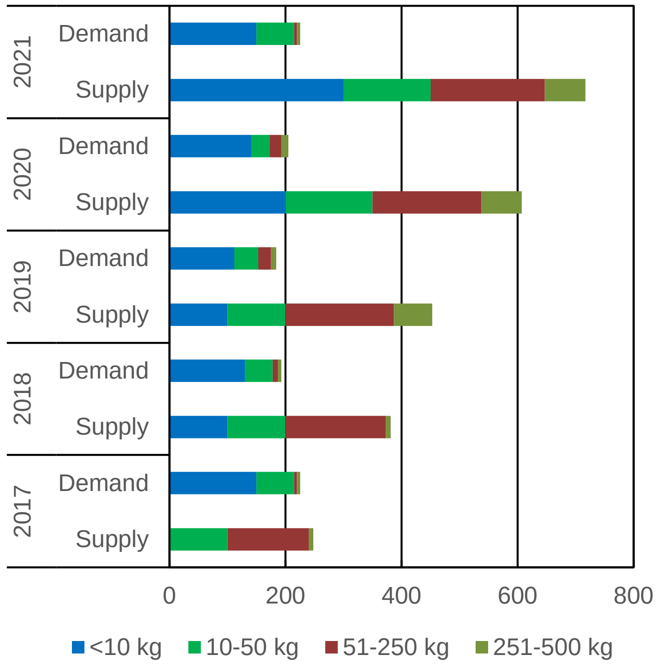
[146] Interview with Rocket lab: Rocket Lab.

[147] Although this report considers smallsats to be below 200 kg, we have extended the definition of smallsat to 500 kg for the analysis of launchers.

Table 4-2. Select Constellations to Be Launched Between 2017 and 2025

	Constellation (Ownership)	Approximate constellation Size	Orbit Altitude (Kilometers)	Projected Launch Provider	Projected Launcher
Communication Constellation	OneWeb	720	1,200	Arianespace, Virigin Galactic	Soyuz, LauncherOne
	XinWei	32	800	CGWIC	Long March
	Boeing	2,956	1,200	TBD	TBD
	SpaceX	4,400+	1,110-1,325	SpaceX	Falcon 9
	LeoSat (not a smallsat)	108	1,400	TBD	TBD
	BitSat	24	*Unknown*	TBD	TBD
	Sky and Space Global	200	*500-800*	ISRO	PSLV
Earth Observation Constellation	Planet	150-1000	420 and 475	ISRO, ISC Kosmotras, Orbital ATK, SpaceX, Rocket Lab	PSLV, Dnepr, Cygnus, Falcon 9, Electron
	Satellogic	300	500	Kosmotras	Dnepr
	BlackSky	60	690	TBD	TBD
	UrtheCast	16	620	TBD	TBD
	OnmiEarth	18	680	TBD	TBD
	Astro Digital	30	600	TBD	TBD
	Hawkeye 360	21	550-650	TBD	TBD
	Planetary Resources	10	*unknown*	SpaceX	Falcon 9
	PlanetiQ	18	800	ISRO	PLSV
	Spire	250	500	Arianespace, ISRO, SpaceX, Rocket Lab	Soyuz, PSLV, Falcon 9, Electron
	Hera Systems	39	*unknown*	TBD	TBD
	TOTAL	9,070+	420 to 1,325		

Source: "Prospect for the Small Satellite Market: A Euroconsult Executive Report," company websites, and http://www.spaceflightinsider.com/missions/earth-science/impact-new-satellite-launch-trends-orbital-debris/



Source: Assembled from various sources, including C. Niederstrasser, "Small Launch Vehicles—A 2015 State of the Industry Survey" 29th Annual AIAA/USU Conference on Small Satellites, 2015; D. Lim, "Small launcher market survey—where are we and where are we going?" Room, October 2016; D. Messier, "A Plethora of Small Satellite Launchers" Parabolic Arc, October 2016; and company websites.

Note: The 18 launchers used to create the figure were selected because they are planned to be operational between 2017 and 2021 and public information is available on their projected number of launches per year.

Figure 4-3. Projected Demand and Supply of Small Satellite (from 1kg to 500 kg) Launches Between 2017 and 2021

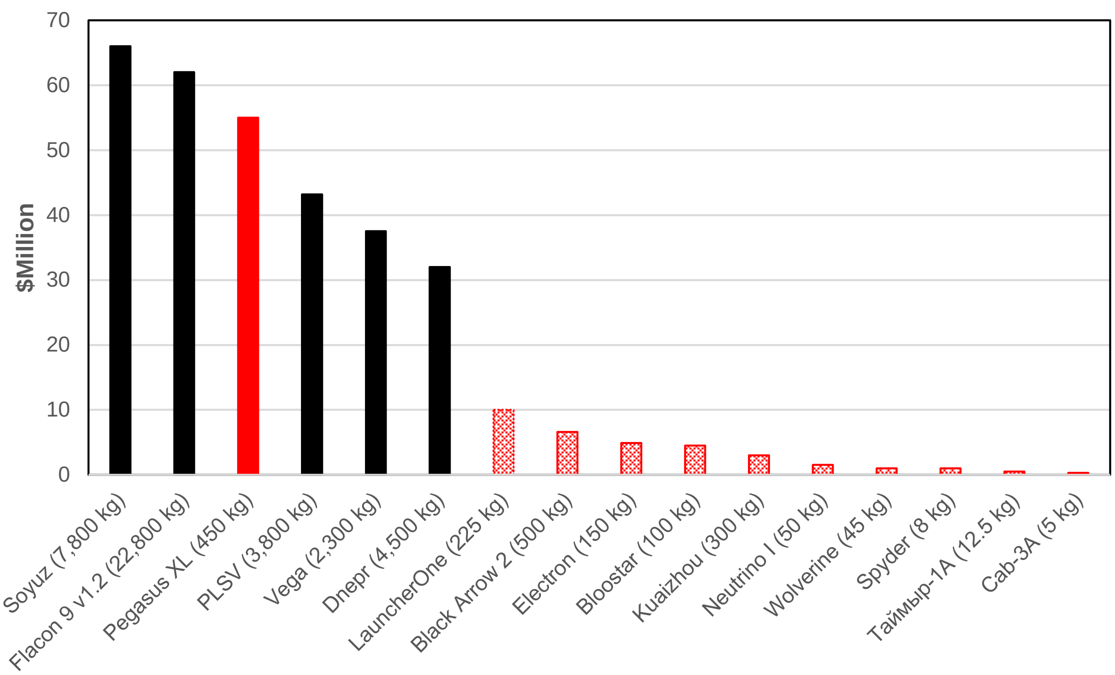
B. Price of Launch

A decrease in the price of launch services is a driver for Scenario 3 as it depends upon a large number of smallsats being launched, and for Scenario 2 to enable global near-parity in remote sensing. A decrease in the price of traditional launch services is a high-priority negative driver for Scenario 4 (meaning it would make the scenario less likely to occur). A large component of the business case for establishing a LEO platform for OSAM is the high cost of getting to LEO from Earth. If traditional launch prices go down, these platforms would become less desirable.

A decrease in both traditional and smallsat-dedicated launch prices is a weaker driver for Scenario 1, as for this scenario to be realized, only a small number of operators need to be able to successfully launch their constellation. As long as these operators can fund these launches (e.g., they are a large company with the capital/capability to do so, or they have received sufficient investment), there is no requirement that launch costs in general decrease. The current slate of large constellations are planned for current launch prices, not optimistic forecasts, so significant drops in launch costs may not be necessary to enable large constellations. However, decreased launch prices, particularly smallsat-specific ones, would make the business case for operating smallsat constellations more compelling.

1. Launch Prices Today

In recent years, the price of rideshares with large launchers has been decreasing for both large and small launchers. SpaceX charges a $62 million base price for 22,800 kg to LEO, and more recently, ExPace in China charged $3 million for 300 kg to LEO (Figure 4-4). Regardless of the price decrease, the price of launch for small satellites still represents a large share of the cost of setting up a constellation. For example, approximately 75% of the total cost of building out the OneWeb space segment is in the launch costs.[148]



Source: Assembled from various sources including C. Niederstrasser, "Small Launch Vehicles—A 2015 State of the Industry Survey" 29th Annual AIAA/USU Conference on Small Satellites, 2015; D. Lim, "Small Launcher Market Survey—Where Are We and Where Are We Going?" *Room*, October 2016; D. Messier, "A Plethora of Small Satellite Launchers," *Parabolic Arc*, October 2016; "Prospect for the Small Satellite Market: A Euroconsult Executive Report," 2016, and company websites.

Note: Black bars represent large launchers and red bars represent small launchers; shaded bars represent launchers in development

Figure 4-4. Price per Launch for Small and Large Launchers

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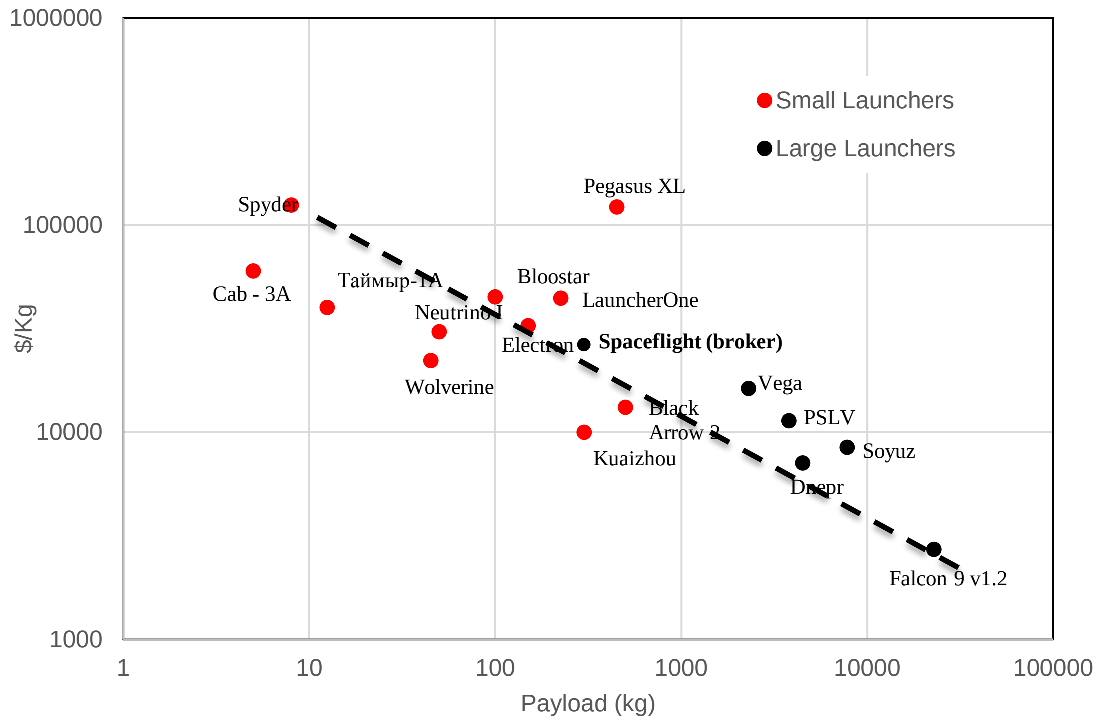
148 Estimation from "Fast Space: Leveraging Ultra-Low Cost Space Access for 21st Century Challenges" Air University, January 2013.

On a per kilogram basis, as might be expected, large launch vehicles are able to offer rideshares for a lower price than the emerging small satellite launchers on maximum capacity flights (Figure 4-5):

- Spaceflight charges a significantly higher price per kilogram than the cost of launching a kilogram directly, without broker assistance, on any of the large launchers at full capacity (e.g., $26,500 per kg for Spaceflight versus $2,700 per kg for Falcon 9). This might reveal that Spaceflight operates under a large profit margin with potential for a decrease on the price of launch given the required competition.
- Orbital ATK with the Pegasus XL at $55 million per launch offers a price per kilogram ($120,000 per kg) that is significantly higher than the projected price for other small launchers (Figure 4-4). The price per mission for Orbital ATK is of the order of the large launchers even when its maximum capacity is one or two orders of magnitude less. The reason for the high price of launch might be the low flight rate. Pegasus XL was launched just once in 2016 to deploy CYGNSS, a NASA-funded constellation. Orbital ATK is probably still amortizing the up-front investment, which reveals the importance of high launch frequencies to benefit from low-cost rides with small launchers.

The major driver that could contribute to low-cost access to space is the development and success of commercial space, as this would lead to a large increase of the launch flight rate. However, commercial developments overlap with other factors—technological, policy related, and other—that would affect how the cost of access to space would change. Each is discussed in turn below.



Source: Assembled from various sources including C. Niederstrasser, "Small Launch Vehicles—A 2015 State of the Industry Survey" 29th Annual AIAA/USU Conference on Small Satellites, 2015; D. Lim, "Small launcher market survey—where are we and where are we going?" Room, October 2016; D. Messier, "A Plethora of Small Satellite Launchers" Parabolic Arc, October 2016; "Prospect for the Small Satellite Market: A Euroconsult Executive Report," 2016, and company websites.

Notes: Performance with regard to payload (kg) to LEO represents maximum capacity. It is difficult to compare price of launch for different launchers as altitude orbits are in some cases not the same even when all of them are in LEO. For the case of Spaceflights, the price per kilogram corresponds to launching a 300 kg satellite class to LEO. The price per kilogram launched decreases with the toal mass launched so higher launched mass means lower price per kilogram. As a reference, the price for launching a 3U Cubesat is $295,000, a 50 kg payload is $1,750,000 ($35,000 per kg) and a 300 kg payload $7,950,000 ($26,500 per kg).

Figure 4-5. Price of Kilogram Launched Versus Maximum Launcher Capacity in kg

2. Technology as a Driver

Four technology drivers could lead to a reduction of launcher cost and eventually a reduction of the price of launch:

- **Disruptive Technology.** Chemical rockets today are almost as efficient as they can be. In order to improve performance, organizations are considering alternative approaches. We identified two disruptive technologies in particular:

– *Air breathing rocket engine on a reusable vehicle.*[149] Two companies are working on this type of engine, VALT[150] (U.S.) and Reaction Engines[151] (UK). Both rely on government support as well as private funding, and expect to use their technology to support the commercial sector. The technology is promising; however, there is little chance that it would be ready in fewer than 10 years (the time frame for this study) from now based on current advances.

– *A ground-based system.*[152] A ground-based system keeps the engine and most of the fuel on the ground, so the spacecraft is almost just the payload. Different concepts under this category include ram accelerators, beamed energy propulsion, and space elevators. The STPI team is not aware of research currently being conducted in these areas and does not expect a breakthrough in the next 10–15 years.[153]

- **Low Production Cost.** Most of the small satellites launch companies are exploring techniques such as 3D printing (e.g., SpaceX, Rocket Lab, Vector Space System, CubeCab and Rocketcrafters), or the use of COTS components (e.g., Cubecab). Both would allow lower cost production of rockets.

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[149] This type of engines eliminates the need for onboard oxidizer until the vehicle leaves the atmosphere. The engine extracts oxygen from the air on its way to space and uses it to burn the fuel combining high-speed air breathing and rocket propulsion. Eliminating the oxidizer would significantly reduce the weight of the rocket, lowering the mission cost. One of the major challenges and key for this engine success is the design of a reliable, lightweight and compact heat exchanger to extract the oxygen from the air.

[150] VALT's initial funding is sourced through U.S. defense and intelligence agencies and its expansion to the commercial sector is dependent on reducing their price of launch. VALT had successful demonstrations of the technology, according to an interview, and they are building a larger version to continue testing the technology. See case studies in Appendix G.

[151] Reaction Engines is not developing a vehicle but an engine (SABRE) as the enabling technology. SABRE is at TRL 3 of development with some component at TLR 4 as subsystems are being designed and tested individually. They expect to test the core engine in 2020 and started building the test facility in 2017In 2015, BAE plc partnered with Reaction Engines to accelerate the development of the SABRE (Synergistic Air-Breathing Rocket Engine). In 2016, Reaction Engines secured funds from the European Space Agency ($11 million) and the UK Space Agency ($53 million). The company is growing in personnel and they have just opened an office in the United States. Although they would need to raise funding for the engine demonstration they are not concerned about this

[152] J. Coopersmith, "The Cost of Reaching Orbit: Ground-Based Launch Systems," *Space Policy* 27(2):77-80, 2011).

[153] Escape Dynamics, Inc. was a U.S. company conducting research on a propulsion system using a high-powered microwave beam transmitted from ground stations. The company closed due to the high cost of completing R&D.

- **Low Operational Cost.** A reduction of operational costs through time efficient operations (i.e., robotic or automated assembly), the reduction of the preflight testing required on the satellites, the reduction of the payload integration process, and low man-hours needed per launch could also lead to a reduction of the cost of launch. The idea would be to have an aviation-like mode of operation.[154] SpaceX's vertical integration is an operating model that is a key factor on SpaceX's low cost of launch. SpaceX also has also optimized its production process for a highly automated bulk manufacturing process.[155]
- **Reusability.** From a technical point of view, reusability is the most promising mean to reduce launch cost as long as the cost and time required for refurbishing the used rocket is reasonable so the vehicle can be used frequently. Reaction Engines (UK), PLD Space (Spain)[156] and Vector Space Systems (U.S.)[157] are the only companies, to our knowledge, that are focusing their research on designing a reusable small launcher. In any case, the technology for first stage recovery (e.g., Blue Origin[158] and SpaceX[159]) as well as for first stage reuse (e.g., SpaceX[160]) has being developed and tested by larger launchers. Future large launchers are also planning for reusability (e.g., Falcon Heavy (SpaceX) and Vulcan (ULA)). It is unknown however, how much price reduction this reusability might bring to a rocket. Originally, SpaceX claimed 30% reduction in cost (which would lower Falcon 9's advertised price to $42 million from $62 million). Estimates of cost reduction by an economist outside the SpaceX team

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[154] Center for Strategic and International Studies, "Implications of Ultra-Low-Cost Access to Space," March 2017.

[155] https://rctom.hbs.org/submission/spacex-low-cost-access-to-space/

[156] On January 2017, GMV, a Spanish company leader in the global space sector, became partner of PLD Space raising also $7.1 million for this company. GMV would develop key technologies for the Arion 1 (sub-orbital rocket precursors of Arion 2) and Arion 2. With this investment, PLD Space would begin the complete development of Arion 1, and all the facilities require for its manufacture, integration, testing and launch.

[157] Vector Space System raised $1.25 million funds from Space Angel Networks at the end of 2016 to support their first flight test with Vector-R in 2017, http://spacenews.com/vector-space-raises-additional-funds-to-support-2017-first-launch/.

[158] Blue Origin has flown and landed the same suborbital reusable rocket five times on suborbital flights (Elizabeth Howell, "Blue Origin: Quiet Plans for Spaceships," Space.com, http://www.space.com/19584-blue-origin-quiet-plans-for-spaceships.html).

[159] SpaceX with Falcon 9 has successfully launched to orbit and landed on land and on a ship six times with different first stages on orbital flights.

[160] For the first time, SpaceX in 2017 reused successfully the Falcon 9 first stage to launch a large satellite from SES. However, they did this after a substantial refurbishment of the rocket (https://spaceflightnow.com/2017/01/17/ses-10-telecom-satellite-in-florida-for-launch-on-reused-spacex-rocket/).

> concludes that in the best of cases and assuming 15 launches per year and SpaceX passing 50% of the cost savings to customer, the price could be reduced by 21%.[161] Regardless, quick turnarounds for reusable rockets are required to get a reduction on the cost of launch. For a quick turnaround, the rocket design must enable rapid assembly, integration, and anomaly recovery. The Space Shuttle did not meet the cost goals because of two reasons. One was its high level of complexity, which required costly and lengthy launch integration and checkout procedures. Another was the unanticipated low flight rate.[162]

It is likely than in the 2030 time-frame, both low production cost and reusability on launchers would be a reality. However, neither low-cost production and operation or reusability on their own can significantly reduce the cost of launch (i.e. by orders of magnitude).

3. Policy as a Driver

Many governments provide lower launch prices, which makes launch on their vehicles more affordable for their foreign customers and creates opportunities to generate revenue.

Governments also encourage the domestic satellite industry to launch with domestic launch providers for both competitiveness and national security reasons. In the United States for example, U.S. companies are prohibited from launching with foreign organizations such as India's ISRO (waivers have been granted frequently since 2015, but on a case-by-case basis) [163] and China.[164] This policy has both supporters and opponents; launch providers and their representatives (e.g., the Commercial Space Transportation Advisory Committee or COMSTAC) support it because in theory, foreign launchers take business away from U.S. launch providers. On the other hand, operators such as Planet or

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[161] P. B. de Selding, "SpaceX's reusable Falcon 9: What Are the Real Cost Savings for Customers?" *SpaceNews*, http://spacenews.com/spacexs-reusable-falcon-9-what-are-the-real-cost-savings-for-customers/.

[162] Dana Andrews, "Space Shuttle 2.0: What Did We Learn?" *Space Review*, http://www.thespacereview.com/article/1881/1.

[163] P. B. de Selding, "U.S. Launch Companies Lobby to Maintain Ban on Use of Indian Rockets," *SpaceNews*, March 29, 2016, Accessed February 20, 2017, http://spacenews.com/u-s-space-transport-companies-lobby-to-maintain-ban-on-use-of-indian-rockets/.

[164] Y. Jinjie, "US Excludes China from Satellite Deal," *Global Times*, http://www.globaltimes.cn/content/754153.shtml.

Spire oppose it because their priority is to procure timely and low-priced launch, and whether it is on a U.S. carrier or a foreign one is less important to them.[165]

4. Other Drivers

a. Increased Flight Rate

The major driver that could contribute to the reduction of the cost of launch is the increase of launch demand, which would lead to a flight rate increase. This could be a result of the success of commercial space driven by demand for communications, imagery and other space activities. An increase in the flight rate would amortize faster the cost of development, hardware and building launch facilities, and improve operations and maintenance through repetition, which could reduce their cost, and finally, reduce the cost of insurance that could go down due to an increase in reliability. Expectations for higher demand for communications, imagery and other space activities exist, as explained in Chapter 4, so it is likely that in 10–15 years from now there would be a significant increase of the launch flight rate.

b. High Revenues for a Selected Number of Actors

High revenues coming from the high demand of communications and imagery could eliminate launch costs as a mission constraint for some smallsat operators. For example, SpaceX expects revenues from its broadband constellation to be over $30 billion annually starting in 2025.[166] Although not likely, if such a scenario were to be realized, it would reduce the impact of launch costs on the companies offering high revenue services without any reduction in the price of launch.

C. Assessment of the Launch Sector

There is no single driver that could lead to an order of magnitude reduction of the cost of launch. Trends may go in three different directions:

- **None of the small satellite launchers succeeds.** If, as announced, large launchers increase their support to the small satellite market and small launchers

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[165] House Committee on Science, Space & Technology: Subcommittee on Space, "Hearing on 'The Commercial Space Launch Industry: Small Satellite Opportunities and Challenges': Testimony of Eric Stallmer, President, Commercial Spaceflight Federation," http://docs.house.gov/meetings/SY/SY16/20160419/104814/HHRG-114-SY16-Wstate-StallmerE-20160419.pdf

[166] Rolfe Winkler and Andy Pasztor, "Exclusive Peek at SpaceX Data Shows Loss in 2015, Heavy Expectations for Nascent Internet Service," The Wall Street Journal, https://www.wsj.com/articles/exclusive-peek-at-spacex-data-shows-loss-in-2015-heavy-expectations-for-nascent-internet-service-1484316455

cannot offer the projected reliability and/or price of launch (between $20,000–$40,000 per kilogram), all small satellite launch companies could eventually fail. Although small satellite operators are looking for on-demand access to space, they also care about the price of launch.

It is unlikely that *none* of the small launchers would succeed considering the large number of companies both domestically and internationally that are developing small satellite launchers (at least 34 companies that we identified; there are likely others). Some, such as Rocket Lab, have already shown early successes.

- **A few small satellite launchers would succeed.** The demand for dedicated rides is expected to continue as it is likely that some of the projected large constellations would become operational in the next 10 years. However, in this case, just a few small launchers would succeed, for two reasons. First, large launchers are planning to increase their support to small satellites, so many would still choose lower cost rideshares as their availability would increase. Second, it is likely that many of the small satellite launchers would fail due to lack of funding, technology failure, or because the demand from the small satellite market would be unable to support most of the companies. In this case, small launchers cadence would adjust to the demand, and depending on the number of successful small launchers, cadence might be lower than the projected number of launches of once per week.

  The price of rideshares would continue to drop, especially those arranged by brokers. However, the price for dedicated launches, although it could eventually decrease from the $20,000–40,000 per kilogram, would probably not experience the same drop as rideshares.

- **Many small satellite launchers succeed.** Enough of the projected small satellite launchers might succeed, leading to the launch supply surpassing the launch demand, and resulting in intense price competition. If sustainable price competition materializes, this could enable further growth of the small satellite market further incentivized by low-cost launches.

  Although less likely than the previous one, this pathway could unfold as a consequence of the democratization of space currently underway and the possibility of small satellites enabling global near-parity in space, as presented in Scenario 2.

Realistically speaking, in the time horizon of interest, it is likely that a few small launchers would succeed, and that there might be a 40% drop in the price of launch for rideshares, based on advances in reusability and an expectation of an increased flight rate.

However, it is unlikely that the price of launch would decrease by an order of magnitude, as per some industry claims.[167]

[167] Jeff Bezos, NGA Symposium 2017.

5. Competing Alternatives

Competing alternatives such as unmanned aerial vehicles (UAVs), aerial balloons, and other terrestrial, airborne or MEO/HEO/GEO based platforms could provide similar broadband and imagery products and services as smallsats, sooner or more affordably. They could therefore be a major driver for Scenarios 1 and 2, as their success would adversely affect the development of smallsat. Presence of these competing alternatives would reduce the risk of LEO being congested (negative for Scenario 3). Any new developments that make large or GEO-based satellites more efficient would also incentivize the establishment of OSAM platforms, increasing the likelihood of Scenario 4 coming to fruition. Trends in competing alternatives are highlighted in Table 5-1 and discussed briefly in the sections below.

Table 5-1. Platforms Competing with Smallsats

	Competing alternative	Application	Example Operator/Provider	Remarks
Terrestrial	Cellular towers	Broadband		Currently dominates markets in cities
	Fiber optics	Broadband	Google fiber	
Airborne	Unmanned Aerial Vehicles	Remote sensing		Sensor technologies deployed on smallsats have been flown on UAVs, including RBG, near-IR, thermal IR, hyperspectral, and LiDAR[a]
		Communication	Facebook	Successfully tested UAVs and high-altitude balloons that could deliver internet to remote regions
	Balloons	Communication		
			Google Alphabet's project Loon	Exploring the use of a network of self-navigating, internet-beaming balloons. The technology seems feasible and the service could be provided earlier than expected but new company's strategy scales back to move from building a global network to supporting just specific region in need of internet access [b]
		Communication/ Imagery	World View Enterprises	Using high-altitude balloons able to fly different trajectories or hove a specific location for days, weeks and eventually months. Balloons can carry different commercial payloads (sensors, telescopes, communication arrays, etc.)
	Airplanes	Communication	Airborne Wireless Network	Planning to create a high-speed broadband airborne wireless

	Competing alternative	Application	Example Operator/Provider	Remarks
				network by linking commercial aircraft in flight.
Space	Large MEO HTS/GEO HTS satellites	Communication	Broadband satellites: Viasat (U.S.); Hughes (U.S.); Clarke Belt 2.0 (Canada)	Planning to offer services at a lower cost.
	HEO constellation		Mobility satellites: Inmarsat GX (UK) Data satellites: Intelsat EpicNG (U.S.); Yahsat (UAE); Avanti Hylas (UK)	Planning to offer services at a lower cost.
	Large satellites	Remote sensing	DigitalGlobe	Provides high-resolution, high-accuracy imagery.

[a] M. Jarman, J. Vesey, and P. Febvre, “White Paper: UAVs for UK Agriculture,” *Catapult*, July 19, 2016, https://sa.catapult.org.uk/wp-content/uploads/2016/07/White-paper-UAVs-and-agriculture_Final2.pdf.

[b] M. Bergen, “Alphabet Scraps Plan to Blanket Globe with Internet Balloons,” *Bloomberg Technology*, February 16, 2017. https://www.bloomberg.com/news/articles/2017-02-16/alphabet-scraps-plan-to-blanket-globe-with-internet-balloons.

A. Terrestrial Alternatives

Proliferation of terrestrial networks remains as a threat to satellite broadband networks. In the 1990s, terrestrial technologies outpaced the eventual capabilities of satellite telephony. This was partially due to how long it took to design, build, and launch those satellites to get a minimally acceptable level of service, partly their cost, and partly quality of service. Today, again, better mobile telephony networks are being built and fiber optic networks being installed that could satisfy much of the broadband demand. For example, Verizon purchased 37.2 million miles of optical fiber in 2017 to increase capacity ald lower latency in its wireless network. Widespread cellular towers offering 5G network service and fiber optic infrastructure are likely to continue to dominate markets in cities. Google Fiber is able to offer gigabit speeds in the few cities it has been installed in, but even Google may be divesting in the solid infrastructure and opting for wireless options in the future because they require less infrastructure.[168, 169]

Regardless, satellite broadband plays a role in the 5G ecosystem as a backhaul for a hybrid solution where terrestrial and space based alternatives would play together to deliver continuous connectivity, and where satellite networks can be used for backup options for wireless and terrestrial providers to avoid overflowing of their networks. Satellite

[168] K. Finley, “Google Fiber Sheds Workers as it Looks to a Wireless Future,” February 15, 2017. https://www.wired.com/2017/02/google-fiber-restructure/

[169] S. Dent, “Google Fiber Launches its First Wireless Gigabit Project,” February 23, 2017. https://www.engadget.com/2017/02/23/google-fiber-launches-its-first-wireless-gigabit-project/

broadband would also fill the gap, for example, for maritime and government applications that need to avoid terrestrial links. Similarly, satellite broadband has a role in rural, landlocked and remote areas where terrestrial alternatives either cannot reach or are too expensive to be developed. Also, satellites could provide broadband choices to users in some large cities where competitive options for high speed services do not exist. In summary, space infrastructure is expected to complement terrestrial infrastructure.

This complementarity isn't limited to just broadband systems. In other applications such as RF monitoring, the recent partnerships between Kratos Defense & Security Solutions and HawkEye 360 (to combine sensors to offer RF detection and geolocation services) is an example of how terrestrial and space platforms can work together to improve the quality of service provided.

B. Airborne Platforms

For Earth observation, UAV proliferation in the coming years is expected to be driven by the law enforcement and agriculture sectors. The UAV market within agriculture is projected to continue to grow, with one study projecting a compound annual growth rate of 42%, from 2015 to 2020, reaching a market value of $5.6 billion.[170] According to these studies, advances in drone technologies could lower the price point of imagery data to the point where satellite-based EO is no longer commercially feasible.

We expect Earth imaging from aerial platforms and from smallsats to complement and not replace each other with multiple sets of data being synthesized for the development of data analytics products. Smallsats would bring more frequency revisits on a global basis, operations under any weather, and diversification of imaging sources (optical, SAR, hyperspectral). UAVs could also tap into a satellite-based broadband network and deliver data in real time in concert with orbiting observation satellites to deliver higher resolution data for specific areas of interest. UAVs could fetch the satellite industry nearly $19.9 billion in revenue over the next decade.[171]

There are efforts to use airborne platforms to deliver broadband (Table 5-1); however, they would be competing on a regional level and not globally as provided by large LEO constellations. More importantly, at least in the next decade, airborne platforms cannot compete with smallsats in non-cooperative territory.

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[170] Jarman, Vesey, and Febvre, "UAVs for UK Agriculture."

[171] J. Van Wagenen, "NSR: Drones Offer $19.9 Billion Opportunity for Satellite," *Via Satellite*, December 14, 2016.

C. Larger Satellites in GEO and MEO and HEO

GEO and MEO satellites can currently provide broadband internet to customers around the world but the price point has not been competitive compared to current terrestrial options. There are proposals for providing broadband from HEO as well.[172] However, advances in high throughput satellite[173] (HTS) technologies are on track to make GEO-based internet more competitive.[174] As an example, Kymeta and Intelsat have partnered to deliver Kalo, a broadband data service planning to be operational in mid-2017 for a fraction of the cost of today's satellite services.[175]

HTS satellites are in operation now (Figure 5-1). ViaSat, Hughes and Intelsat expect mobility especially in-flight services to commercial airlines to be responsible for the largest market growth, while some operators also expect growth on the DOD market and on WI-FI services in developing countries or rural areas.

While technologically it appears that smallsats compete with traditional larger satellites, from a business perspective, mergers between GEO and LEO operators such as Telesat Canada with its own LEO system, ELE SA (Switzerland) with Thuraya (UAE), and SES's "open mind about LEO satellites"[176] either reveal that GEO and LEO services are complementary, or that there is fear of excess supply of capacity once the smallsat LEO constellations become operational. LEO constellations would preferentially serve markets where low latency is paramount, such as banking and on-line gaming. However, where latency is not an issue, the constellations may not be able to compete with MEO and GEO HTS, which would likely mean that not all planned LEO broadband constellations would succeed.

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172 Clarke 2.0, https://gvf.org/about-gvf/membersdirectory/767.html?view=companyprofile.

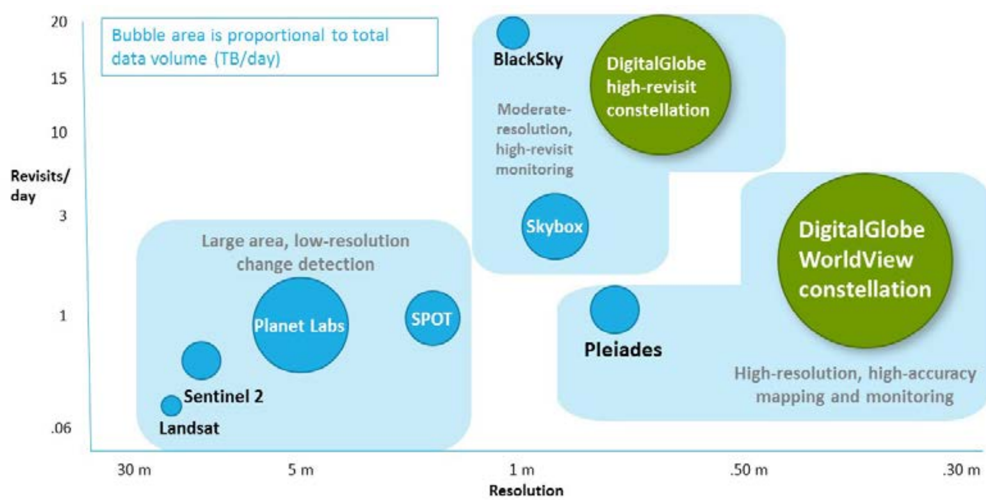
173 An HTS offers a significant increase in throughput for the same amount of allocated orbital spectrum due to high level frequency reuse and spot beam technology enabling multiple narrowly focused beams instead of a broad single beam or a few beams.

174 An HTS would offeri services at a lower cost because it would enable a significant increase of capacity as compared with traditional large satellites. While Ku and FSS bandwidth could cost over $100 million gigabits per second in space, an HTS like ViaSat-1 could supply a gigabit of throughput in space for less than $3 million (http://www.newtec.eu/article/article/the-future-of-high-throughput-satellites-for-service-providers).

175 The service would be accessible from anywhere in the world, the bandwidth can exceed 100 megabits per second, which is comparable to cable modem speeds, the antenna and terminal would be available for $25,000 and charges for the service would range from $29 for a gigabyte of data to $899 for 80 gigabytes (http://www.geekwire.com/2017/kymeta-intelsat-unveil-kalo-satellite-service-antennas/).

176 J. Worthy, "Satellite & Space Project News—April 2017," April 7, 2017. http://www.fieldfisher.com/publications/2017/04/satellite-space-project-news-april-2017#sthash.xn2vV4HS.dpbs.

In remote sensing, large satellites provide not just high resolution but also high accuracy. Even when advances are happening to increase resolution on small satellites, smallsats are not expected to compete with large satellites on accuracy because of the need of higher stability, which currently implies more sophisticated systems and an increase in size and cost of the platform. In any case, except for military applications, most of the customers are expected not to be interested in high accuracy imagery. Smallsats are expected to deliver services at a more competitive price and offer high revisit rates. However, large satellites could be a threat to remote sensing small satellites if they can offer high revisit rates, as Digital Globe is planning with its WorldView-Legion that purports to offer high revisit rates (40x per day for some locations when combined with other DG satellites).[177]



Source: Walter Scott, Digital Globe. Presentation 2016.

Figure 5-1. Evolution of the Imaging Industry through 2020

In our judgement, the likelihood of alternatives replacing smallsat in the next 10–15 years is fairly low, partly because they are not perfect substitutes (e.g., UAVs can only image "cooperative" territories, GEO satellites cannot offer low-latency, and terrestrial means are expensive to reach remote and rural areas). Also, for the case of GEO-based platforms, even with improved capabilities, satellites would not have the emergent benefits that small satellites in LEO have (such as shorter development cycles, lower cost, higher risk tolerance, and quick replenishability).

[177] A. Datta, "DigitalGlobe reveals plans for WorldView-Legion; to be made by MDA's SSL," February 26, 2017. https://www.geospatialworld.net/digitalglobe-reveals-plans-for-worldview-legion/

6. Government Policies

Government policies are critical drivers of developments in the smallsat sector. In each of the sections below, we first discuss how the specific driver affects and scenario, and then trends in each. Our specific focus was on government policies globally, rather than U.S. Government policies, which were deemed out of scope. In the sections below, we note interviewee responses with the caveat that these are impressions of the interviewees themselves rather than our assessment of the impact of U.S. policies.

A. Regulating Spectrum

Policies to promote spectrum availability and the efficient use of the spectrum and radio frequency interference (RFI) regulations are particularly important to Scenarios 1 and 3. Spectrum availability is a key driver for Scenario 1 because smallsats in most large constellations are planning to use radio frequencies (RF) to communicate with ground stations and to communicate with each other. As the spectrum gets congested, the lack of spectrum availability or RFI could hinder the development of LEO constellations, due to delays in or denial of a license. Not addressing the challenge could lead to enough signal interference that LEO could become unsafe to operate in(Scenario 3).

According to some experts, spectrum availability is not currently a challenge for future smallsat missions especially commercial ones. However, there are concerns that insufficient collaboration and communication among current and future operators and regulators from the different countries could be problematic. For example, spectrum allocation for commonly used frequencies is competitive and the current system, both at the national and international levels, is faced with a backlog of “paper” systems that may never actually be launched. On this front and in terms of satellite constellation approval, the Federal Communication Commission (FCC), the International Telecommunication Union (ITU) and organizations of other countries, such as Ofcom in the United Kingdom, greatly differ.[178] As happens with all regulations, making procedures more burdensome in one country would dissuade operators from filling and setting up their headquarters there.

[178] P. B. de Selding, “ITU, FCC: Satellite constellations surge requires new rules,” Space Intel report, March 16, 2017. https://www.spaceintelreport.com/itu-fcc-satellite-constellation-surge-requires-new-rules/

There are other topics that specifically affect smallsat operators. For example, smallsat operators seek allocation of a different radio frequency band for short term duration missions (up to 3 years on-orbit life), which could benefit the setup of smallsat constellations.[179] The FCC and other foreign entities in charge of spectrum management are repurposing parts of the spectrum allocated to space use to other terrestrial uses, as happened with the C-band.[180] This trend will continue and satellite operators including smallsats ones, fear[181] governments repurposing part of the spectrum to support the much more profitable wireless industry. In the United States, the FCC is working on the sharing of federal portions of the radio spectrum with commercial entities, including smallsats, a practice that is not currently common.[182,183]

There are two trends to watch in the smallsat industry with regard to spectrum, one is the sector moving to higher frequency bands (e.g., Q/V-bands to keep up with the demand for more capacity), and another one is the development of optical communications. Both trends might require further development of regulations related to those frequency bands, which are currently either underdeveloped or not developed at all. Also, as RFI becomes more of a problem, an enforcement of current national and international mechanisms to regulate radio frequency to prevent interferences might emerge.

In our judgement, government regulations related to spectrum, nationally and internationally, will continue to evolve with technology developments, and to align with commercial needs.

B. On-Orbit Regulation

Several activities in space may require an on-orbit regulatory regime (see Appendix F for details). However, as of 2017, there is no comprehensive global or domestic on-orbit regulation regime. While there are regulations related to launch and re-entry, spectrum, and remote sensing in the United States, there are no regulations related to on-orbit activities such as rendezvous and proximity operations (RPO), space-based SSA, or radio frequency mapping. Domestically, there are efforts to address the challenge, but no consensus on how

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[179] Resolution 659 (WRC-15), "Studies to accommodate requirements in the space operation service for non-geostationary satellites with short duration missions." http://life.itu.int/radioclub/rr/res-659.pdf

[180] P. B. de Selding, "Satellite based aircraft tracking joins C-band fight on WRC-15 agenda," *SpaceNews*, April 2, 2015, http://spacenews.com/satellite-based-aircraft-tracking-joins-c-band-fight-on-wrc-15-agenda/.

[181] M. Holmes, " LEO Constellation Announcements: The Industry Reacts," *Via Satellite*, March 23, 2015. http://interactive.satellitetoday.com/leo-constellation-announcements-the-industry-reacts/.

[182] "NASA's Management of Electromagnetic Spectrum," March 9, 2017.

[183] In November 2016, an NTIA study determined the government frequency bands, which could be susceptible of sharing with commercial users (https://www.ntia.doc.gov/report/2016/quantitative-assessments-spectrum-usage).

to proceed, and what role the government should have in regulating them. Internationally, with over 80 countries having space-based interests, there is even less consensus, and little expectation that there would be a comprehensive global regime beyond the high-level dictates in the Outer Space Treaty.

In the United States, there has been activity with direct implications for Scenario 4. DARPA has proposed a Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), a collaborative approach between government and industry to define clear technical and safety standards for on-orbit servicing.[184] The consortium is still in its formational stages, but within the next few years aims to establish important benchmarks and serve as a model for similar bodies to form. There is technical activity in Germany with respect to on-orbit assembly, but little on regulation related to it.

The United Kingdom is facing its first major test in regulation with the launch of the first three satellites for narrowband communication. The law is expected to treat Sky and Space's 220 CubeSats no differently than it treats its larger satellites. "Each satellite is subject to a licensing fee of…$8,400 and must carry third-party-liability insurance coverage of…$68 million per satellite for the full life of the spacecraft."[185] If the same law applies to each of Sky and Space's short lived CubeSats, the company may consider switching registration to a different country. This situation is likely to be repeated in any country with any regulation related to satellites, because no country currently has laws and regulations related to smallsats.

C. Space Traffic Management (STM) Regime

The lack of an efficient STM regime to manage space traffic and debris or an overbearing STM regime, especially if relies on poor SSA, could affect the success of large LEO constellations (Scenario 1), where hundreds or thousands of objects apiece in overlapping orbits are being operated and need coordination to avoid interference.

Both the lack of a regime or the presence of an overbearing one could discourage manufacturers and operators, or potentially cause companies to move abroad if the regime can be avoided outside the country of interest. An extreme position could also demotivate public and private investments in large constellations if investors believe that the risk of a collision taking out part of the network is too great to justify. Although the lack of an effective SSA system and STM regime would increase perceived risk for operating

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[184] The ultimate goal of the effort would be to ensure space remains a safe environment for all actors through responsible behavior. DARPA, "DARPA Creating Industry/Government Group for Safe Operation of Space Robotics," November 29, 2016. http://www.darpa.mil/news-events/2016-11-29.

[185] https://www.spaceintelreport.com/sky-space-global-constellations-need-relief-regulatory-filing-insurance-cost/

megaconstellations, other drivers such as lower per-unit small satellite costs or cheaper access to launch, could help justify higher risk taken by operators.

The existence of an effective STM regime including debris mitigation standards is a high-priority driver for Scenario 3, where it is a negative driver in that if it does exist, the scenario is much less likely to come about.

The only body that considers the topic of space objects internationally is the Inter-Agency Space Debris Coordination Committee, under the aegis of the United Nations Office for Outer Space Affairs. An efficient and coordinated STM regime, among other things, could support licensing on-orbit activities, support industry best practices, and create government-set regulations for preventing collisions. If the SSA system improves and operators act responsibly following STM established rules, there might not be a need for restrictions, enforcement or sanctions.

Many U.S. operators are in favor of developing guidelines and standards of operations to help with the safe operation in space and foster an environment that would continue gaining the confident of investors. In general, operators ask for transparency, predictability and certainty in operations without burdensome regulations that could later be adopted by other countries. It is likely that in the 2030 timeframe, there would be some kind of STM regime in place although given that the timeline in which operators and policymakers operate does not always align, and the significant effort involved in creating international community agreement, developing policy and regulations for the quickly evolving commercial space industry would be a challenge.

Another possible scenario could be the United States imposing unilateral restrictions due to, for example, a collision of a small satellite with a key U.S asset. In this case, several options are possible, including banning small satellites below a certain size from launch altogether; imposing stringent requirements on propulsion or transponders; requiring operators to have more expensive insurance; or making regulatory frameworks more onerous. Any of these possible responses—or perhaps preemptive measures—can only be imposed on U.S. operators, and in effect drive up the cost of operating small satellites in the United States, and encourage small satellite companies to move their work elsewhere. The effort may not be entirely unilateral, an approach taken with a few other countries, in the hopes of getting others to join, may lead to such a reaction if there is not wider international buy-in.

D. Debris Mitigation Standards

A 2013 study performed by six space agencies using six different models found that even with 90% adherence to the commonly adopted mitigation measures, there will likely be an increase of approximately 30% in LEO orbital debris population over the next 200 years, and that catastrophic collisions would continue to occur every 5 to 9 years. The study concluded that additional measures such as remediation measures (i.e., active debris removal) should be considered.[186] These catastrophic events may lead to restriction of operations in some LEO orbits. Today, there is no comprehensive debris regulation standard, either in the United States or internationally, that includes debris mitigation,[187] remediation,[188] or spacecraft reentry.[189] Current national and international debris mitigation policies, guidelines and standards, which were developed years ago,[190] are not tailored to smallsats, especially large constellations in LEO. However, efforts to address this gap are underway. In 2016, the Long-Term Sustainability of Space Activities working group within the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) agreed to a first set of guidelines for the long-term sustainability of outer space activities, which includes guidelines for smallsats. Work continues, and the full compendium would be referred to the UN COPUOS General Assembly in 2018. While there have been repeated calls in the United States for the development of a comprehensive national strategy,[191] no publicly available strategy currently exists or appears imminent.

It is our assessment that even if globally accepted guidelines are generated, given the current regulatory environment, a comprehensive U.S. strategy would be developed in the next decade only if there is a mishap that affects a strategic U.S. Government asset. Otherwise, stopgap measures would likely be taken. Smallsats are inexpensive and do not have long lives; without an external event, no national or international action is likely.

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[186] The study was led by NASA and conducted by NASA, ASI, ESA, ISRO, JAXA, and UKSA (http://www.iadc-online.org/Documents/IADC-2012-08,%20Rev%201,%20Stability%20of%20Future%20LEO%20Environment.pdf).

[187] NASA defines mitigation as "the prevention of new debris, where measures can take the form of curtailing or preventing the creation of new debris, designing satellites to withstand impacts by small debris, and implementing operational procedures such as using orbital regimes with less debris, adopting specific spacecraft attitudes, and even maneuvering to avoid collisions with debris."

[188] NASA defines remediation as "the reduction of the existing orbital population debris. Debris removal is a form of remediation. If the goal of remediation is to reduce the risk to the current fleet of operational spacecraft, remediation techniques need to focus on removal of small sized (but still damaging) debris. If the goal is to control the long-term growth of the debris population, active debris removal techniques need to concentrate on the removal of large, massive objects such as intact rocket bodies and non-functional satellites."

[189] NASA defines reentry as "one of the proposed methods for post-mission disposal, which allows the reentry of spacecraft, either from natural orbital decay (uncontrolled) or controlled entry in which the spacecraft is intentionally brought back to earth."

[190] All current U.S. Government requirements and commercial regulations for orbital debris mitigation are derived from the 2001 U.S. Government Orbital Debris Mitigation Standard Practices.

[191] NASA Authorization Acts of 2010 and 2017.

E. National Security

Several interviewees noted national security as a driver of the smallsat sector. In the United States, satellites were added as controlled technology under the International Traffic in Arms Regulations (ITAR) regime in 1999, in response to China receiving technical information from U.S. satellite manufacturers, and limited export of U.S. systems and components to other countries.[192] Based on a recent study from the Aerospace Industries Association, a trade association representing the U.S. aerospace and defense industry, this led to an estimated $21 billion lost in satellite revenues from 1999–2009 and 9,000 lost jobs.[193] Industry lobbying led to removal of parts and satellites in 2014, and then again in 2017.[194, 195]

Despite the changes, ITAR continues to rankle smallsat stakeholders, and was cited by several interviewees in this study as a reason for U.S. companies to either move development and manufacturing offshore, or for foreign companies to not add facilities in the United States. Private sector firms especially complain about the cost of compliance (e.g., hiring compliance officers, legal counsel, and training employees on compliance practices).[196] We did not verify the cost of compliance.

Other countries likely have ITAR-like requirements to protect their national security interests. Assuming the cost of compliance is high, these requirements, if not streamlined, could encourage companies to develop abroad, or at least threaten to move offshore.

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[192] Stephen Clark, "Obama signs Law Easing Satellite Export Controls," *Spaceflight Now*, http://spaceflightnow.com/news/n1301/03exportcontrol/#.WKcfCzsrKUk.

[193] AIA White Paper available at http://www.aia-aerospace.org/report/engine-for-growth-analysis-and-recommendations-for-u-s-space-industry-competitiveness/.

[194] Removal of: most radiation-hardened microelectronic microcircuits; communications satellites without classified components; remote sensing satellites with certain performance parameters; additional unspecified parts. Also, the U.S. Government would allow, under specified conditions, CCL-classified satellites with some USML components to be CCL-controlled (Caleb Henry, "New US Satellite Export Reforms Gets Positive Response from Industry," http://www.satellitetoday.com/regional/2014/05/16/new-us-satellite-export-reforms-gets-positive-response-from-industry/?hq_e=el&hq_m=2883331&hq_l=12&hq_v=fce2e0fa19.

[195] Aperture limits for commercial electro-optical remote sensing satellites raised from 0.35.m to 0.50m; still short of the 1.1m requested by some industry actors; Controls for electric propulsion systems were set for systems that provide greater than 300 milli-Newtons of thrust and a specific impulse greater than 1,500 sec, or operate at an input power of more than 15kW (Marcia S. Smith, "Satellite Export Controls Get Another Update, JWST No Longer Under ITAR," Space Policy Online http://www.spacepolicyonline.com/news/satellite-export-controls-get-another-update-jwst-no-longer-under-itar).

[196] Morgan Dwyer et al., "The Global Impact of ITAR on the For-Profit and Non-Profit Space Communities," MIT, http://cahoylab.scripts.mit.edu/cahoylab/wp-content/uploads/2013/02/student_paper-The-Global-Impact-of-ITAR-on-the-For-Profit-and-Non-Profit-Space-Communities.pdf.

F. Protectionism/Mercantilism

All countries find space to be a strategically important sector, and attempt to protect their interests both from security and economic competitiveness perspectives.

As discussed in the launch chapter above, the United States currently restricts U.S. companies from launching on non-U.S. launchers from India and China, though companies have obtained waivers to this policy since 2015 to launch with ISRO. European countries often do the same, requiring that European payload be launched on Arianne rockets.

Any new restrictions have the potential to deter companies from investing. There is nothing to suggest a tightening on restrictions at present. It is within the realm of possibility that launch using foreign launchers could be made more restrictive if, for instance, lawmakers were to believe that their nations' interests were threatened. In recent years, policies globally have been trending toward easing restrictions on private sector involvement and international business development. Continuation of these trends would foreseeably draw more interest from private multinational companies.

Governments around the world are creating incentives for small satellite companies to move to their countries. Several examples of this have been highlighted in this report, one being Planetary Resources, which has negotiated a deal with the Luxembourg government in that they would receive funding in exchange for setting up R&D facilities in Luxembourg. Similarly, a European system integrator (name withheld at request) is moving a part of its manufacturing operations to India in exchange for low-cost PSLV launch. Several interviewees mentioned Singapore as a location for new offices, as the country offers tax breaks, R&D funding, and opportunities to partner with Singapore's universities.[197]

Such incentives and company movement can increase the possibility that small satellite technology, either developed in the United States or outside, is successfully commercialized outside the country where the technology was originally developed. There are parallels for this in other sectors. R&D for Flat Panel Displays, for example, was conducted in the United States in the early 1980s, but commercialization occurred first in Japan and then moved to Korea and Taiwan in the 1990s. Today, the United States imports almost all its flat panel displays including those for sensitive applications.

Interviewees also mentioned immigration policies that encourage foreign students in fields relevant to small satellites returning to their home countries, especially as their home countries offer incentives, including funds to set up start-up firms.

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[197] EDB, "Incentives for Business & Investments," https://www.edb.gov.sg/content/edb/en/why-singapore/ready-to-invest/incentives-for-businesses.html.

7. Pathways to Scenarios

The four scenarios presented in Chapter 2 are not necessarily mutually exclusive, and there is no single driver that is likely to make any of the scenarios a reality. However, a combination of any number of drivers could pave a pathway to the scenarios. As discussed in the preceding chapters, drivers fall into four broad thrusts: market demand, which drives the emergence and affordability of new technologies, new approaches, and new investment; on-demand, reliable and low-cost access to space; developments in competing alternatives; and government policies, which either nurture or deter the development of the sector. In this chapter, we examine the combinations of drivers that could lead to each of the scenarios and consider how realistic each scenario is.

A. Scenario 1: Two or More Large Smallsat Constellations in LEO

Two pathways have been identified that could lead to a large smallsat broadband constellation in LEO becoming a reality (Figure 7-1 provides a visual representation). Common drivers for both pathways are demand for broadband, low-cost ground communication technologies (e.g., ground antennas, user terminals, etc.), availability of network of ground stations, availability, reliability and frequency of launch alternatives and orbital debris mitigation standards. Adding to these drivers and depending on how the smallsats communicate with each other and with the ground, Pathway 1 would require advances in technologies for the efficient use of the spectrum and policies to ensure availability of spectrum if smallsats communicate using the radio frequency bands and Pathway 2 would require the development of optical communications if smallsats use intersatellite links and communicate with the ground using optical frequency bands.

In our assessment, the presence of smallsat constellations in LEO has a high likelihood of being a reality in in 2030 timeframe. While the implications may eventually be off from our predictions, the drivers described in the pathway diagram (Figure 7-1) and discussed in the report show technical progress, industry investment, and low barriers without the need to rely on technological miracles (or high consequence, low probability events) to set the scenario in motion. Four factors lead us to believe the scenario is likely to come to fruition as opposed to the 1990s failure: (1) growing demand for broadband, communications and imagery data; (2) technology availability and the small satellite design philosophy that emphasizes lower costs, rapid turnarounds and quicker replenishments; (3) relatively low cost of constellations including manufacturing and launching; (4) policy environment required, which is already somewhat favorable. The risks of the entire broadband enterprise not succeeding are certainly lower than they were in the 1990s. While competition from other sources of broadband including terrestrial, aerial, and GEO satellites could still affect the success of these constellations, LEO constellations would provide additional benefits such as global low latency services. It is likely that not all of the planned broadband constellations would succeed. Similar risks from aerial platforms and large satellites could also affect the imagery market, but we believe this is less likely because of the additional benefits from satellite platforms such as ubiquity, variety of sensors, high revisit rates and predictable scheduling. In any case, the expectation is that large smallsat constellations would provide services more affordably.

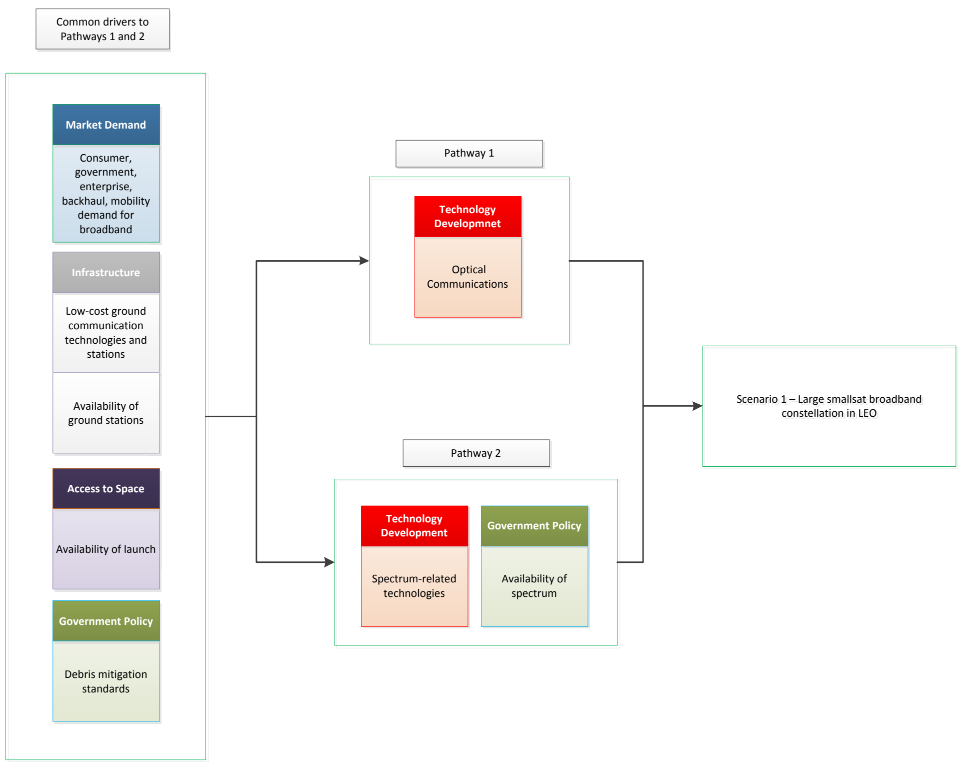

Figure 7-1. Pathway to Scenario 1 (Broadband Only)

B. Scenario 2: Smallsats Near Parity with Larger Satellites in Remote Sensing Enabling Global Near-Parity

Two pathways have been identified that could lead to Scenario 2 becoming a reality (Figure 7-2). Common drivers for both pathways are demand for Situational Awareness, funding from foreign sources (e.g., government, venture capital and/or equity capital), and high resolution optical sensors and SAR for smallsats. Adding to these drivers, Pathway 1 would require advances to reduce the cost of manufacturing and operating smallsats such as development of components miniaturization, availability of reliable COTS components, modularity and standardization of buses and payloads, and decreased price of launch. For Pathway 2, United States policies such as protectionism/mercantilism or national security restriction (e.g., ITAR) could lead together with the common drivers to the realization of Scenario 2.

In our assessment, Scenario 2 (near parity with larger satellites in remote sensing) is likely to be feasible in 10–15 years from now. There are substantial advances in all three technology areas considered (optical ground resolution, SAR, and SA), costs continue to fall and price of launch is expected to continue decreasing. Also, smallsat systems for applications from disaster monitoring to sea ice monitoring off coastlines are increasingly available commercially, and this trend is expected to accelerate. As a result, countries no longer need homegrown development capabilities to operate in space, and would be able to achieve near-parity with spacefaring nations with relative ease.[198]

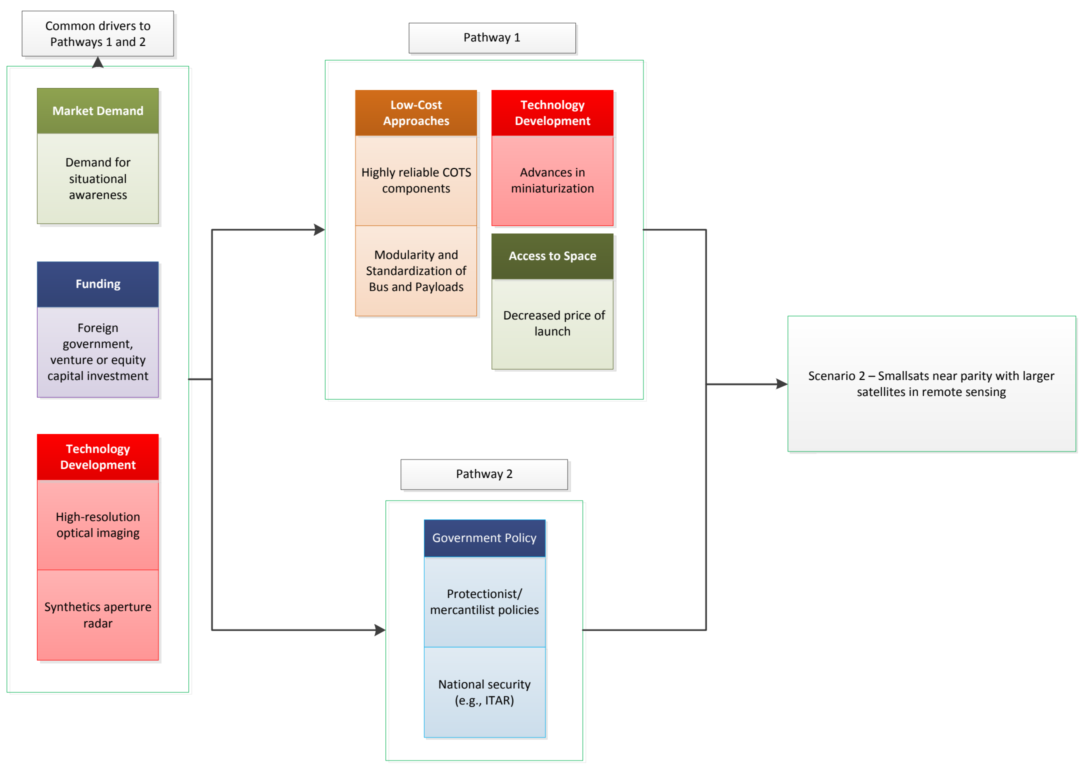

Figure 7-2. Pathway to Scenario 2

C. Scenario 3: Unsafe for Satellites to Operate in LEO

Two pathways have been identified that could lead to Scenario 3 (Figure 7-3). Common drivers for both pathways are the absence of an efficient SSA system, the absence of a global STM regime and the lack of appropriate orbital debris mitigation standards. Adding to these drivers, the realization of Scenario 1 or Scenario 2 could lead to Scenario

[198] Lal et al., *Global Trends in Space*, 4-2.

3 becoming a reality because of the physical congestion of the orbital bands around 800 and 1,110 km or because of radio frequency interferences.

Our assessment is that LEO being unsafe to operate in, as described in Section 2.C is not a realistic scenario in the next 10–15 years even when Scenario 1 and Scenario 2 are likely to become a reality. However, near-misses with strategic assets in space may lead to restrictions on operations in certain orbits. All stakeholders are aware of the need for an efficient SSA system, and efforts by the government and the private sector are underway to improve SSA, which indicate that the SSA challenge would ameliorate in the coming decade and may make for the need of an STM regime less urgent. Furthermore, new debris mitigation guidelines adapted to the new needs are being considered in international fora. It is likely that operators would follow those rules considering the increased stakeholder commitment to safe operations in space. Predictions about intentional jamming or attacks from hostile actors that could make scenario 3 unfold are out of scope of this report.

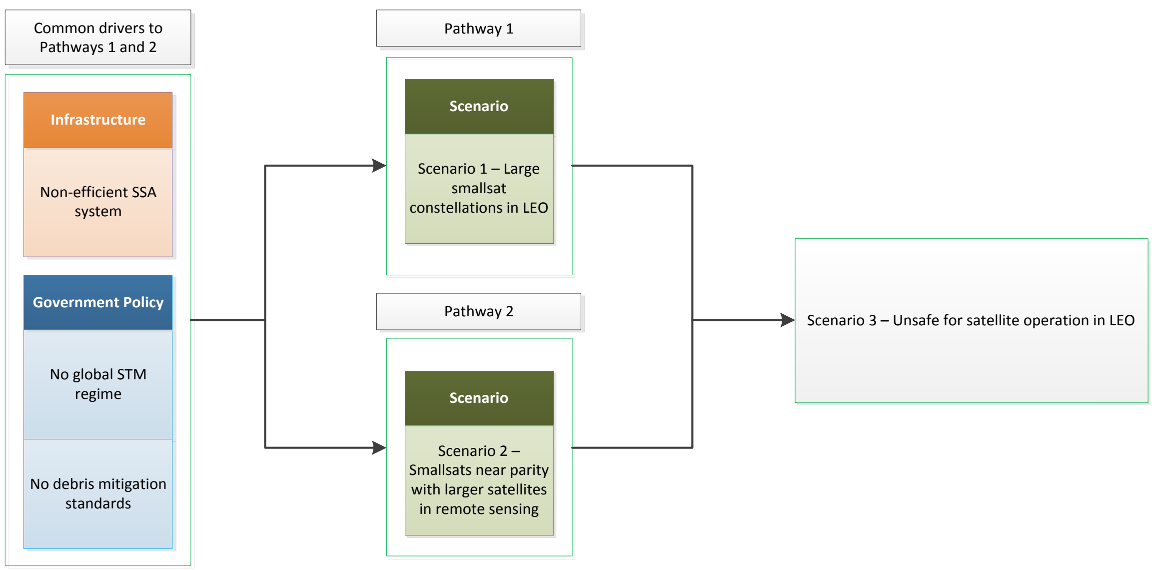

Figure 7.3. Pathway to Scenario 3

D. Scenario 4: On-Orbit Servicing, Assembly, and Manufacturing of Spacecraft a Reality

Two pathways have been identified that could lead to Scenario 4 (Figure 7-4). Common drivers for both pathways are demand for on-orbit servicing, assembly and manufacturing (OSAM), funding either from the United States government and/or foreign governments, technology required to perform activities on OSAM platforms such as robotics and automation for satellite integration, modularity and standardization, an SSA system tailored to the needs of OSAM activities and finally, on-orbit regulations. Adding to these drivers, the lack of reliable and frequent options to access space or a high price for launch could lead to the realization of Scenario 4.

Our assessment is that OSAM becoming a reality in the next 10–15 years is not a realistic scenario. The field of on-orbit servicing, assembly and manufacturing of spacecraft is still in its infancy, with government investments under $50 million a year, and private significantly less than that. The main driver for Scenario 4 to become a reality is for investment on all sides to grow by an order of magnitude or more to make enough progress that we would see sophisticated OSAM platforms, human-tended or robotic, in LEO or GEO. We found no indicators that these investment levels are likely to change. However, the national security space enterprise could see OSAM as cost effective if space-based capabilities of other countries meet or surpass our own.

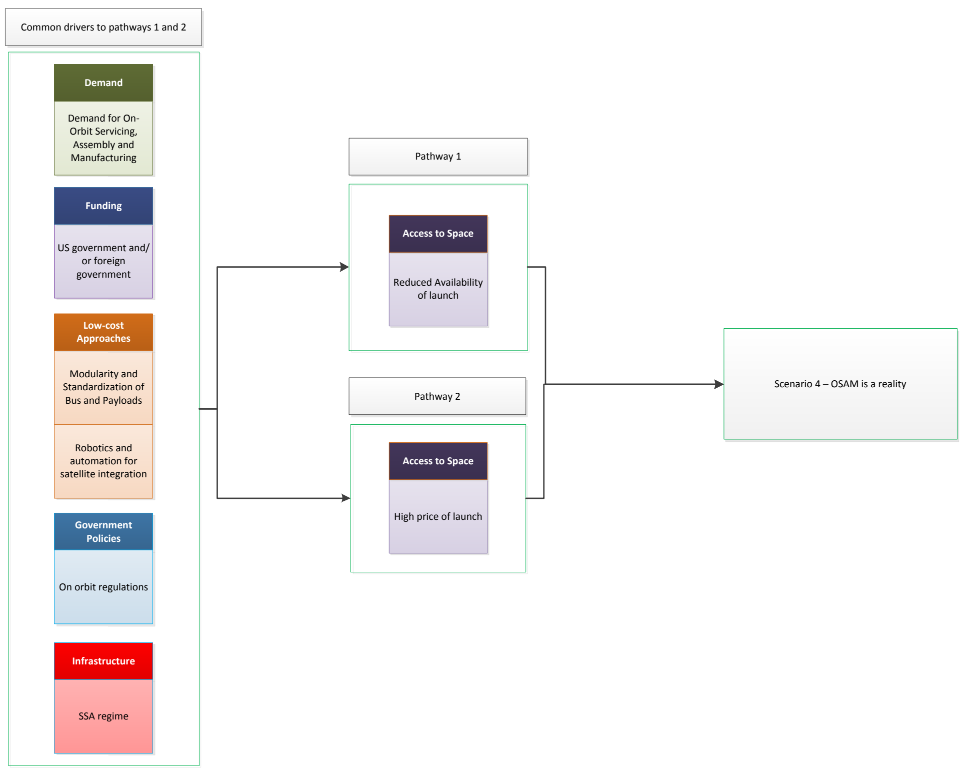

Figure 7-4. Pathway to Scenario 4

8. Summary and Conclusion

As we have seen, smallsats are spacecraft that incorporate software and hardware improvements, especially from the IT and electronics industries and benefit from the resulting high capability feasible in small packages. Compared with traditional satellites, smallsats typically have shorter development cycles and smaller teams, and consequently lower cost, both for the development and launch of the satellites. As a result, smallsats are making inroads in almost every area of space—communication, remote sensing (Earth observation and situational awareness), technology demonstration, and science and exploration—and are operated by an ever-growing number of users. Euroconsult predicts that compared to the fewer than 700 smallsats launched from 2006–2015, in the coming decade, upto 3,600 smallsats would likely be launched for a variety of missions, nearly two-thirds would be part of a large constellation; this number could reach as high as 11,000 smallsats if Boeing and SpaceX broadband constellations are deployed. Almost all are planned for launch into LEO orbit; and over 60% will be CubeSats.

We used a scenario-based approach to identify key drivers propelling the development and direction of the smallsat sector. After an initial survey of current activities in the sector, we selected four scenarios that could become reality 10–15 years from now. We identified drivers that would lead to these end states, and examined their current status and trends. We also assessed the likelihood of the scenarios coming to fruition between 2027 and 2032. All insights were based on analysis of data from unclassified interviews with 67 experts in government, industry, academia, and the venture community, as well as a review of publicly available literature. Intermediate products included creation of a smallsat ecosystem model, a database of organizations involved in the smallsat sector, and case studies of emerging firms around the world. These efforts led to the following observations relevant to the goal of the study:

- The smallsat sector has many different segments, and is becoming functionally disaggregated, while attracting new non-space downstream actors as a result of inexpensive satellite imagery, broadband, and derived insights; the industry looks more like IT than aerospace. We identified over 650 organizations worldwide that are performing functions upstream (e.g., including manufacturing emerging products, such as the virtualized or software-defined satellites[199]), midstream (e.g., operating satellites and ground stations), and downstream (e.g., conducting data analytics a business intelligence). The ecosystem is dynamic and continually evolving with organizations emerging, consolidating, and disappearing globally.

- In the database we assembled, about half the organizations were U.S.-based (defined as having the company's headquarters in the United States) and most of the remaining organizations are based in Europe. While many foreign organizations have a presence in the United States to facilitate partnerhips with U.S.-based commercial and government actors and funders, companies' operations are global, which makes proliferation of smallsats difficult to track. Gomspace, for example, based in Denmark, has offices in the United States and Singapore, and projects in the United States, Latin America, Japan, South Korea, China, Singapore, and Australia. Surrey Satellite Technology Ltd. (SSTL) based in the UK, designed, built, and launched a constellation of Earth observation satellites for their China-based client Twenty-First Century Aerospace Technology, and Space Flight Laboratory, based in Canada, is building a smallsat for a research center in the United Arab Emirates.
- Expectations of future profitability from commercial actors (as distinct from government only, as was the case in the past) is driving current investment in the sector. While this investment is not being systematically captured, private investment may exceed at least the unclassified publicly-available government investment by an order of magnitude or more. There is a sense in the community that smallsats may soon become low-priced commodities. As a result, upstream segments such as manufacturing and system integration appear to receive less attention from large private funders. Downstream segments such as data analytics are viewed as the value-added services, and receive funding from actors not particularly interested in space or satellites, but rather in processing streams of data coming from all sources—terrestrial, social-media, and other. Potential and realized markets for these data processing streams broadly range to include agriculture, resource management and forestry; finance and business intelligence; energy and infrastructure monitoring; tracking and telemetry; disaster preparedness and response, and urban planning; and others.
- U.S. Government agencies are playing an important role in funding low-TRL technologies in upstream activities, and also committing to purchasing products

[199] Virtualized platform, such a that developed by Galactic Sky, that could be used for operators to test different satellite designs and potential issues that may arise during the life of the satellites before the satellite is built, reducing the time traditionally required to take a satellite from a design concept to flight

generated by smallsats. In other countries, governments generally play an even more important role than in the United States, with R&D and operations often occurring in organizations closely affiliated with governments.

- While Earth observation and communications are viewed as the initial lucrative "killer-apps" of smallsats, and comprise most smallsat activity occurring today, other commercial applications such as low-cost rendezvous and proximity operations (RPO) services, space-based SA, and space science are emerging and being tested, primarily through government funding.
- The smallsat supply base is bifurcated. Some providers plan to serve a large number of customers, often enterprises or individuals, who would be satisfied with low-end capabilities as long as they are available at low cost; others focus on a small number of customers, typically governments, who would pay more for high-end capabilities. Given the IT-like behavior of the smallsat sector, exquisite capabilities would quickly be (or are expected to quickly be) commoditized.
- The smallsat ecosystem of today displays many parallels with the IT ecosystem. Two aspects in particular distinguish smallsat firms from traditional aerospace firms. First, many emphasize low cost through the use of relatively cheap COTS parts and software innovation, accepting limited capability initially and incremental development, and minimizing operational costs and bureaucracy. Second, while they aim to have government customers, they believe that non-governmental consumers and commercial markets will grow. This perception allows for investment from non-governmental private actors. Similar to the early days of the World Wide Web, there is both hype and legitimate investment in the smallsat sector. Predicting from investment levels or business models as to whether a company would succeed or not is not feasible. As had occurred with the internet/IT sector, experimentation would occur, and some organizations and ideas would succeed and others would fail. Failure at a company level may still be success for the sector, especially if infrastructure is created and workforce trained. However, it would be instructive to extrapolate from the present time forward to examine the possibilities.

A. Scenarios for the 2027–2032 Timeframe

We selected the following four scenarios to identify drivers of interest:

- Scenario 1: Two or more large smallsat constellations in LEO. There are one or more broadband, and one or more imagery constellations of 100 or more small satellites that are commercially successful. The broadband "megaconstellation" provides affordable global broadband internet with low latency (terabits of throughput at $20/Mbps/month and 25–35 millisecond latency, compared to gigabits of throughput at $25/Mbps/month, and 500 millisecond latency from GEO-High Throughput Satellite). The imagery constellation provides affordable (1–2 orders of magnitude lower cost than today) near-ubiquitous optical imagery that refreshes at least once per hour with low resolution (1–5 m) and on-demand video of target areas.

- Scenario 2: Smallsats near-parity with larger satellites in remote sensing. In remote sensing, including Earth observation (EO) and situational awareness (SA), smallsats have achieved technology near-parity with large satellites, especially in three areas of high interest: high ground resolution (0.5 meter) on optical imagery; synthetic aperture radar (SAR); and SA services such as radio frequency (RF) mapping, automatic identification system (AIS) use, weather monitoring, space-based space situational awareness (SSA), GPS-Radio Occultation, and Automatic Dependent Surveillance–Broadcast (ADS-B). Services such as tipping-and-cueing provided by optical and SAR satellite pairs previously available only on larger platforms are now feasible from smallsat platforms. As a result of these capabilities being available commercially and outside the United States, a growing number of countries have achieved near-parity in remote sensing with spacefaring nations.
- Scenario 3: Unsafe for satellite operation in LEO . As a result of the growing number of smallsats in these orbits, LEO has become unsafe to operate in orbits between 500 km and 1,200 km without risking collision. As a consequence, smallsats have become larger, more expensive, and operate in different orbits than LEO, and LEO has lost its potential for commercialization.
- Scenario 4: On-orbit servicing, assembly, and manufacturing of spacecraft a reality. Servicing, assembly, and manufacturing of spacecraft on-orbit is a reality, and there are multiple persistent platforms in LEO and GEO being used by governments and the private sector for on-orbit servicing, assembly, and manufacturing (OSAM). These platforms offer to the satellite industry the flexibility in designing, building, and deploying satellites best-suited to a given application, as large satellites become cost competitive and hosted payload platforms become a norm. On-orbit space capabilities weaken the case for building and launching smallsats from Earth, though may not completely eliminate the need for them.

B. Trends in Drivers

An analysis of these four scenarios led to the identification of 62 drivers that we organized into four categories: demand for LEO-based services, that drives availability of funding, technology development, development of low-cost approaches, and infrastructure; access to space; competing alternatives; and government policies.

1. Demand for LEO-Based Services

Broadband. Demand for low-cost, high-speed broadband with increased capacity for enterprise data (retail, banking), energy sector (oil, gas, mining), and government in industrialized countries is growing, as is demand for low-cost broadband among individual consumers in less developed countries and rural areas who may not have access to the internet. These market expectations are driving investment in smallsat-based LEO constellations. Estimates for broadband demand vary, and some experts predict that satellite broadband capacity demand would grow at a compound annual growth rate of 29% through 2024.

OneWeb (UK), Boeing (U.S.) and SpaceX(U.S.) have announced their intentions to fly broadband constellations. In our judgement, not all of them are likely to be successful. Although there is high demand for low-cost, high-speed broadband in industrialized countries, if all planned GEO HTS satellites and LEO constellations succeed, the supply could be much higher than the expected demand, which would drive the price per megabit down (experts forecast demand for broadband access from GEO, MEO and LEO satellites could reach over 3 terabits of bandwidth by 2024; proposed LEO constellations collectively could deliver almost ten times as much, if operational). This would lead to some LEO constellations either not deploying partially or fully, or failing entirely. Were this to occur, it would not be too dissimilar to the dot-com bubble of the 1990s where a large number of companies failed, leaving behind a small number of robust ones, infrastructure, and a trained workforce.[200]

Imagery and analytics. Because smallsats offer imagery at lower cost than traditional large satellites, disproportionate growth in the demand for satellite imagery is expected to come from non-governmental actors that would use images and image-based analytics for agriculture, economic forecasting, resource management, urban planning, disaster monitoring, retail, maritime, and other applications. Analysts expect the smallsat imagery market to rise at a compound annual growth rate of 49%, which could take the market from $15 million in 2015 to $8.8 billion by 2030 if growth remains that high. Smallsat imagery is expected to capture a growing fraction of the global geospatial imagery analytics market that is expected to grow to nearly $100 billion by 2030. In our judgement, while non-governmental demand appears poised to grow, it is currently too small to point to a trajectory. As important as collecting imagery and data is to be able to both, find potential consumers and applications and translate the data into useful information for

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[200] In the case of LEO-based broadband, the oversupply of capacity at low prices could lead to a large number of applications that would build on potentially low-cost bandwidth.

them. While some profit-making use is already evident, comprehensive data is not currently available to quantify commercial markets. For example, Cape Analytics (U.S.) is using satellite-based imagery (along with imagery from other sources) to underwrite property values, UBS Investment Research and J.P. Morgan provide business intelligence in the retail market using Orbital Insights capabilities, Descartes Labs (U.S.) aims to provide agriculture crop yield projections and aggregates data from a number of large government satellites and smallsat operators such as Planet and BlackSky (U.S.) is currently integrating data from smallsats operated in-house with data from social-media feeds to provide insights on socio-political trends.

Situational awareness (SA). Traditionally, SA services have been provided from large platforms to large customers—governments and large enterprises—that are able to afford them. The SA revenues are predicted to grow with a compound annual growth rate of 21% in the next 10 years. In our judgement, SA market growth is difficult to estimate given none of them are commercially viable yet. There are at least five commercial smallsat constellations proposing to provide AIS payloads for maritime users, two of which would also support ADS-B; two firms expecting to provide RF mapping services; and two focusing on space-based SSA. Several of these firms are not based in the United States. Examples include Karten Space (Spain) that plans to provide AIS services, and Kleos/Magna Parva (UK) focusing on radio frequency geolocation.

2. Availability of Funding

Because smallsats require lower levels of capital investment as compared with larger satellites, they are of interest to both commercial investors and foreign governments that have smaller space budgets than the U.S. Government. Already, there has been successful development and commercialization of new technologies abroad (Hall thrusters and SAR for smallsats being examples), especially in Europe. Foreign governments are also encouraging (through subsidies and direct funding) innovative companies from other countries to set up manufacturing and R&D facilities in their countries (e.g., Planetary Resources in Luxembourg, unnamed European interviewee in India). Where private funding is lacking, such as in Japan, governments are providing venture funds. A sign of a growing customer and investor base abroad is that U.S. firms are setting up shop in other countries (e.g., Tyvak in Italy).

In our judgement, the U.S. Government is likely to become a smaller player in the smallsat ecosystem especially in the midstream parts (operations) that are expected to get commoditized. Downstream investment (in data analytics and business intelligence) is where the United States dominates and may continue to remain pre-eminent.

3. Technology Development

Many technologies in the smallsat sector are borrowed from adjacent sectors such as IT (e.g., Phase Four (U.S.) borrowing aspects of its propulsion technology from cell phones) and adapted to space (e.g., instruments being made radiation tolerant through software changes rather than radiation hardening). Many of the companies the research team spoke to believe that no fundamental R&D breakthroughs are required for commercial success in the smallsat sector. There is nonetheless investment in the following areas.

High resolution optical imaging. Different approaches are being examined to increase optical imaging resolution in smallsats, for example, deploy the space assets at lower altitudes, increase smallsat apertures, use deployable lenses, employ post-processing software, develop aperture synthesis interferometry technologies, and use of in-space manufacturing technologies to increase smallsat size in space. DigitalGlobe (U.S.) recently announced a partnership with Saudi Arabia to provide sub-meter imaging capabilities on a smallsat platform by 2019; Tethers Unlimited (U.S.) is planning to use in-space manufacturing to enable smallsats to grow larger structures in space.

Synthetic Aperture Radar (SAR). Low power smallsat suitable SAR based on Frequency Modulated Continuous Wave technology is been developed and there are at least six companies engaged in smallsat SAR. Iceye (Finland) plans to test SAR on smallsats under a U.S. military funded mission in 2017 and to become commercially available soon after that; and Capella Space (U.S.) is planning a SAR on a CubeSat test this year. Considering the players and partnerships already underway, we expects high resolution optical sensors and SAR to be available on smallsats in the next decade.

High Bandwidth Communication and Data Download. On board processing technology and optical communications are technologies being developed to help alleviate spectral bandwidth congestion from high bandwidth communication and data download for imagery constellations. In particular, optical communication on smaller platforms is seeing both government and private investment in the United States and in Europe. Examples include York Space Systems (U.S.) partnering with BridgeSat (U.S.) and SpaceX (U.S.), Analytical Space (U.S.), and Else (Switzerland) testing their optical intersatellite links. We expects further development and use of optical communications in 10–15 years given the current advances and efforts to develop optical communications (there are already constellations planning to use laser intersatellite links in the next 5 years (four of them) and satellite to ground laser communication is on track to be demonstrated in 2017 in support of the U.S. Government) and also given the advantages that optical communications would bring to both, broadband and imagery constellations.

Advances in miniaturization. Miniaturization of smallsats subsystems is showing accelerating improvements, particularly of attitude and orbit determination and control technologies that are continuing to get both smaller and more accurate; electrical power generation and storage technologies, mainly miniaturization of fuel cells, RTGs, batteries and non-solar power sources adapted from those used on traditional spacecraft; thermal control technologies, focused on miniaturization of active thermal control systems and avionics more tolerant to radiation. We expect this trend to continue.

Technologies to improve the use of the electromagnetic spectrum and to reduce Radiofrequency Interference (RFI). RFI is the biggest cause of communication disruption in space, and is expected to increase with the advent of LEO constellations. Dynamic Spectrum Access technologies such as software defined radio (SDR) (e.g., Kepler Communications (Canada) and Gomspace (Denmark) and Cognitive Radio (CR), which has only been used in terrestrial applications, (e.g., Tether Unlimited (U.S.) and the CoRaSat program (Europe)) are being developed. Satellite operators, and smallsat ones in particular, are moving to different bands and non-congested parts of the spectrum like the higher frequency Q/V bands. As a consequence, adaptive coding and modulation (ACM) technologies are being developed and successfully tested to help with signal fading (e.g., Eutelsat Communications together with Space Systems Loral (U.S.) and ESA in partnership with Thales Alenia Space (France-Italy)). The challenge of ACM technologies is the high cost of the technology itself so further efforts would likely be focused on reducing their cost.

High delta-v propulsion for smallsats. Most investment in this area comes from the government. NASA and other U.S. Government agencies are funding Busek (U.S.) to develop RF ion thrusters that can deliver delta-v above 1,000 m/s. There is some private investment as well, an example being Deep Space Industries (U.S.) developing a water-based propulsion system. Many of the systems currently under development are relatively immature, and more flight tests are needed. Propulsion systems have not been needed for the bulk of the applications smallsats have been used for to this point—but in the future, the availability of dedicated propulsion systems would allow smallsats to be used in novel applications, as well as engage in more sophisticated collision avoidance maneuvers.

De-orbit and active debris removal technologies. Active de-orbit and debris removal technologies remain relatively immature. Passive de-orbit technologies such as deployable drag sails or membranes are being developed both in the United States and abroad (Clyde Space (UK)). There are many concepts for active debris removal: some retrieve debris (Astroscale (Singapore and Japan)); others wrap around pieces of debris (Aerospace Corporation (U.S.)); some can be deployed as electrodynamic tethers (JAXA (Japan)); and yet others are collection devices to sweep small debris (LaunchSpace (U.S.)). No U.S. ADR demonstrations or tests have occurred or are planned, and Congress has asked NASA to conduct an analysis of all known debris mitigation technologies. Debris removal technologies would likely attract little private investment unless there are government (or large operators with financial interest in risky orbits) customers. In any case, even when some of the ADR concepts are technically plausible and could be ready to start operating in 10–15 years, the legal and policy challenges associated with active debris removal could hinder their adoption and use.

These technologies are at a variety of TRLs. It has been difficult even for government agencies assigned the responsibility to track progress to stay abreast of technology developments. This challenge is likely to exacerbate as more organizations around the world quietly invest in technologies that they perceive would give them a competitive advantage.

4. Low-Cost Approaches

Instead of investing in fundamental research, which they do not believe is required for most of their applications of interest, private sector organizations are investing in reducing cost or increasing reliability—at low cost—of components and systems by investing in the increase of performance and reliability of COTS components, the integration of satellites by robotic systems, the development of mass manufacturing, and the increased use of modularity and standardization. Examples include firms such as York Systems (U.S.) redesigning satellite busses to be low-cost and mass manufacturable; those such as NovaWurks (U.S.) are developing modular reconfigurable satellites; and others such as OneWeb Satellites (UK) are developing standardized satellites that can be produced in robotic factories by the thousands, the first to be built in the United States. Firms are using business models not typically considered by the government, and following a diversity of approaches. Some of the imagery firms, for example, plan to make it easier for individual consumers or enterprises to task satellites and purchase imagery through applications on smartphones on a pay-per-image model or through subscription services (e.g., BlackSky (U.S.)). Government investment on low-cost approaches may be double-edged in that while it may promote technological innovation and potentially speed it up, it may take away private incentives to lower costs.

5. Infrastructure

SSA. Today, the government, in particular national security agencies, provide space situational awareness (SSA) services. While private firms have been involved in SSA as government contractors for years, lately, they are providing not only algorithms for processing SSA data but also radar and optical sensors, and in some cases turnkey operations to non-DOD customers, both in the United States and abroad. Some experts believe the private sector to be on a trajectory to match, and perhaps even surpass, government capabilities for providing near-approach and collision assessments in the near future. This is causing anxiety, especially among U.S. allied nations who do not have extant relationships with entities other than DOD, and there are efforts—especially in Europe—to ensure self-sufficiency. SSA capabilities would continue to improve and be cheaper as a result of the use of smallsat platforms to supplement traditional SSA service provision. In the coming 10–15 years, we do not expect SSA to be a roadblock for the success of smallsats.

Network or ground stations and in-space relays. Access to data from satellites is typically expensive because data download requires multiple and expensive ground stations around the world, limiting smallsat operators' opportunities for low-cost operations. Breakthroughs both in technology and new business models are beginning to address this challenge. Japan's Infostellar is developing an AirBnB-style timeshare model in which down-time from existing ground stations is purchased by the broker and resold to smaller operators who can then have access to ground stations at much lower costs than would be feasible otherwise. Norwegian giant KSAT is adapting its business model to provide smallsat operators a streamlined and standardized process to gain access to its ground infrastructure, built previously for large satellites, at a fraction of the cost.

As with SSA, smallsats enable infrastructure for their own benefit. As an example, Kepler Communications (Canada) and Analytical Space (U.S.) propose the use of smallsat constellations for information relay using optical communications. On the ground, BridgeSat (U.S.) is planning to provide ground stations with optical capabilities.

Ground antennas and user terminals. Availability of low-cost ground antennas and user terminals able to integrate multiple signals and to track satellites that move quickly in LEO is one of the major challenges for the provision of affordable broadband services by megaconstellations. Companies such as Kymeta (U.S.) and Phasor Solutions (U.S.) are developing low-cost phased array technology into flat panel antennas. In particular, Kymeta's metamaterial antennas (which can be low cost because they are expected to be produced on commercial television manufacturing lines) are expected to supplant large and expensive ground stations, making it feasible to imbed antennas in mobile platforms (cars, cell phones), changing the paradigm of communicating with space-based assets.

6. Access to Space

Options for Launch. Current options for smallsat launch are limited to rideshares as secondary payloads on rockets launching large satellites or carrying cargo to the International Space Station. These options impose restrictions in terms of integration and launch schedules, orbit destinations, and loss of flexibility with respect to subsystems in the small satellite. The process of procuring launch is complex enough for smallsat operators that companies such as Spaceflight Industries (U.S.), ECM Space (Germany), TriSept (U.S.), Tyvak (U.S.), and Innovative Solutions in Space (Netherlands) have developed technology to safely include large numbers of smallsats as secondary payloads on large launchers. Some of these companies act as launch brokers, purchasing entire launches from organizations like SpaceX and ISRO, to sell slots to individual smallsat operators, sometimes as part of manufacturing and turnkey operations contracts.

Going forward, expecting large volumes of satellite launches, existing large launcher organizations (e.g., ISRO (India), ULA (U.S.), Glavkosmos (Russia), Arianespace (Europe), and MHI Japan)) are announcing plans to increase number of launches in coming years. Other organizations are developing new large launchers (e.g., Blue Origin, SpaceX, and ULA), which are expected to come online in the next 2–5 years and be available for smallsat rideshares.

The new development in the ecosystem is the emergence of launchers for only small payloads that would in principle provide relatively reliable, fast, and dedicated access to a variety of orbits and planes. We found 34 organizations (13 domestic and 21 international) that are developing small satellite launchers to LEO with reference payload ranging between 40 and 500 kg. ExPace (China) launched three small satellites (300 kg) to LEO, in 2017, and Rocket Lab (U.S./New Zealand), having raised over $150 million, is doing flight tests, and has full manifest for 2017 and 2018. These companies promise the elimination of constraints resulting from catering to the needs of a large primary payload. However, only a few of the small launchers are likely to succeed because: they would not be able to compete pricewise (per kg cost) with large launchers, their technology would fail, they would not be able to raise the funding needed for development and operations, or the market would be saturated and they would not all be able to compete with each other.

Based on the projected increased support to the smallsat market from large launchers and the expectation of successful dedicated launches using small launchers, it is very likely that launch service availability would not be a bottleneck for the small satellites market 10–15 years from now, and small satellites operators would likely be able to choose between dedicated rides and rideshares to support their needs.

Price of Launch. While the price of rideshare launches has been falling in recent years, the price of launch still represents a large share of the cost of launching satellites: approximately 75% of the total cost of building out the OneWeb space segment is related to launch. The cost of rideshares in large launchers is lower than the projected cost of dedicated launches using small launchers: $26,000 per kg for a rideshare using a launch broker versus $32,000 per kg using a dedicated launch as projected by Rocket Lab (NZ), a front runner. ExPace (China) is an exception providing a dedicated launch for $10,000 per kg. Many approaches are in play to reduce the cost of launch. For example:

- Non-traditional rocket technologies, such as air-breathing engines by Reaction Engines (UK), balloon launches by Zero2Infinity (Spain), and air launch by Virgin Galactic (U.S.)
- Production processes and operational processes, such as 3D printing, used by SpaceX (U.S.), Rocket Lab (NZ), Vector Space System (U.S.), and Rocketcrafters (U.S.), or extensive use of COTS components, such as Cubecab (U.S.)

- Reusability, as was successfully tested by Blue Origin (U.S.) with New Shepard on suborbital flights, and SpaceX (U.S.) with Falcon 9 on orbital flights, and is being considered for future rockets, including heavier rockets

In the coming decade, the price of both rideshares and dedicated launchers would continue to drop incrementally due to high demand and supply, especially rideshares arranged by brokers. It is likely that both low production cost and low-cost reusability would be a reality 10 to 15 years from now; however, neither low-cost production and operation or reusability on their own can significantly reduce by an order of magnitude or more the cost of launch.

Over the next 10–15 years, it is likely that a few small launchers would succeed, and that there might be a drop of up to 40% in the price of launch for rideshares (based on advances in reusability and an expectation of an increased flight rate). However, it is unlikely that the price of launch would decrease as much as industry claims.

7. Competing alternatives

Terrestrial, airborne (e.g., UAV), or large GEO satellites that are making both incremental and breakthrough improvements could outpace the eventual capabilities of smallsats, providing services sooner or more affordably, as happened in the 1990s with satellite telephony.

- Airborne platforms such as airplanes (e.g., Airborne Wireless Network), UAVs (e.g., Facebook) or balloons (e.g., Google Alphabet's project Loon experiment) are exploring hosting payloads capable of competing with smallsat broadband. The use of the UAV platform for imagery has proliferated, and sensor technologies similar to those deployed on smallsats have been flown on UAVs. UAVs can compete with LEO constellations only on a regional basis. It is possible that UAVs could tap into a satellite-based broadband network and deliver data in real time in concert with orbiting observation satellites to deliver higher resolution data for specific areas of interest. UAV networks may complement LEO ones rather than replacing them.
- On the broadband front, advances in high throughput satellite (HTS) technologies would significantly increase the capacity delivered at a lower cost by large satellites, and several companies including Viasat (UK) and Hughes (U.S.) offering broadband, Inmarsat GX (U.S.) with mobility oriented satellites, and Intelsat EpicNG (U.S.), Yahsat (UAE) and Avantis Hylas (UK) with data-oriented satellites are poised to do so. LEO communication constellations hold advantages with respect to shorter development cycles, higher risk tolerance, quicker replenishment, and lower latency. On the imaging front, large satellites could be a threat to remote sensing small satellites if they can offer high revisit

rates, as Digital Globe is planning with its WorldView-Legion that purports to offer high revisit rates (40x per day for some locations when combined with other DG satellites).

- Widespread cellular towers offering 5G network service and fiber optic infrastructure are likely to continue to dominate markets in cities. However, satellite broadband have also a role on the 5G ecosystem as a backhaul for a hybrid solution where terrestrial and space based alternatives would play together to deliver continuous connectivity and where satellite networks can be used for backup options for wireless and terrestrial providers to avoid overflowing of their networks. Satellite broadband would fill the gap for example, for the maritime industry, on government applications that for security reasons want to avoid terrestrial links or on rural and remote areas on developed countries as well as remote and landlocked areas in countries under development where terrestrial alternatives either cannot reach or are too expensive to be developed. Also, satellites could provide broadband choices to users in large cities where consumers have no choice but just one single fixed broadband provider with no possibility of competitive options for high speed services. In summary, space infrastructure is expected to complement terrestrial infrastructure.

There are other platforms under consideration by companies such as Clarke Belt 2.0 (Canada) that intends to provide broadband from a highly elliptical orbit. Our assessment is that LEO-based systems would complement others rather than replace them. GEO actors are already partnering and merging with LEO ones (e.g., MDA's with Digital Globe). While some of these alternatives would compete with smallsats in certain markets, the likelihood that they can completely replace smallsat is fairly low, partly because they are not perfect substitutes.

8. Government Policies

Availability of spectrum. Spectrum availability is not currently a challenge for future smallsat missions although this could change. The biggest concern and current bottleneck is the insufficient collaboration and communication among current and future operators of smallsat constellations from the different countries, something that is required to avoid radio frequency inferences. For example, the FCC in the United States and Ofcom in the United Kingdom (UK) are permissive in the sense that they allow operators to function without full coordination. However, broader coordination than what exists today is going to be required. Some of the challenges is that spectrum allocation for commonly used frequencies is competitive and that the current system, both, national and international, is faced with a backlog of "paper" systems that may never actually be launched. On this front and in terms of satellite constellation approval, the FCC, the ITU, and organizations, such as Ofcom, greatly differ, and the FCC is looking into relaxing current regulations as they are currently more strict than in other countries. A topic of discussion during the World Radiocommunication Conference-19 will be the allocation of a different radio frequency band for short term duration missions (up to 3 years on-orbit life), which could benefit the setup of smallsat constellations. In the United States, the FCC is working on the sharing of federal portions of the radio spectrum with commercial entities, including smallsats, a practice that is not currently common.

In the next 10–15 years, new technologies and policies are expected to be developed to ensure spectrum availability and interference avoidance. However, cooperation between satellite operators would need to increase, and RFI avoidance rules might need to be enforced. If rule enforcement exists, increased resources might be needed to watch for unintentional RFI, which might need to be tracked as part of the current SSA system.

On-orbit regulation. There is no comprehensive global or domestic on-orbit regulation regime. While there are regulations related to launch and re-entry, spectrum, and remote sensing in the United States, there are no regulations related to on-orbit activities such as RPO, space-based SSA, or radio frequency mapping. Domestically, there are efforts to address the challenge, but there is no consensus on how to proceed nor on what role the government should have in regulating them. Internationally, with over 80 countries having space-based interests, there is even less consensus, and little expectation that there would be a comprehensive global regime beyond the high-level dictates in the Outer Space Treaty.

Although operators have expressed interest in developing "rules of the road" that would provide certainty to investors, there are concerns about burdensome regulations that could drive companies to move abroad. Given that the timeline in which operators and policymakers function does not always align, and the significant effort involved in creating international community agreement, developing policy and regulations for the quickly evolving commercial space industry would be a challenge for the next 10 years.

Debris regulations standards. Current guidelines on debris mitigation are not enforced (or waivers are frequently granted by governments), and are not tailored to smallsats, especially large constellations in LEO. There have been calls in the United States for the development of a comprehensive national strategy; however, no publicly available strategy currently exists or appears imminent. There are collaborations, both multilateral (e.g., Inter-Agency Space Debris Coordination Committee under the UN Office for Outer Space Affairs, European Space Agency, Permanent Committee on Space Debris within the International Academy of Astronautics) and bilateral (e.g., United States with Japan/India/Australia, U.S. Department of State and China) that work towards space debris mitigation, and some efforts are focused on smallsats. In 2016, the Long-Term Sustainability of Space Activities working group within the UN COPUOS agreed to a first set of guidelines for the long-term sustainability of outer space activities, which included smallsats. Work continues and the full compendium would be referred to the UN COPUOS General Assembly in 2018. It is our assessment that in the current regulatory environment, a comprehensive national strategy would be developed in the next decade most likely if there is a mishap that affects a strategic U.S. Government asset. Otherwise, stopgap measures would likely be taken. Smallsats are inexpensive and do not have long lives; without an external event, no national or international action is likely.

National security and protectionism/mercantilism. In all countries, mercantilist policies (e.g., tariffs, lending for foreign customers, restrictive immigration), if enacted could protect the nascent smallsat ecosystem as it matures, but simultaneously spark trade wars across countries. In most countries, export control policies, designed to protect national security interests, would not significantly affect the smallsat sector because the supply base is broader, and it is easier to develop smallsats that use international components or systems. However, the *perception* of such policies being restrictive has an effect. For example, some companies, such as Singapore's Astroscale have chosen not to open offices or operate in others to remain free of regulations that do not best serve their interests. Others, such as Spire, have global offices to ensure access to international markets without overreach by specific governments.

Going forward, most governments may be motivated to promote their nations' smallsat sector not only for economic development reasons but to also maintain global pre-eminence in space. For the United States in particular, these goals would be more feasible to achieve if technology development occurs in the United States, and firms are U.S.-based rather than foreign. Further, the smallsat sector may continue to gain support from pockets of Congress that prefer to see a more laissez faire development of the space sector. It is therefore likely that government policies would favor smallsat interests.

C. Overall Assessment

Given trends in drivers, we believe that the probability of Scenario 1 (at least two large constellations of 100 or more satellites) coming to fruition is high. Demand for broadband and imagery exists and is growing, with funding following; required technology is available or is expected to be in the near future; and infrastructure breakthroughs need to be minimal. There are several rideshare options for launch, and further availability from large launchers and on-demand launch is expected in the next decade. While price of smallsat launch is decreasing, for at least broadband constellations, lack of reduction in price is not a deal-breaker given that these companies are making their business cases using today's launch prices rather than assuming reduce prices in the future.

Scenario 2 (near parity with larger satellites in remote sensing) is also likely to be feasible. There are incremental advances in all three areas considered (ground resolution, SAR, and SA), and costs at every step of the supply chain continue to fall. It is likely that companies currently involved in these areas would receive appropriate permissions from U.S. Government, and the rest of the world may follow.

It is unlikely that scenario 3 (unsafe to operate in LEO) would come to fruition, although near-misses with strategic assets in space may lead to restrictions on operations in certain valuable orbits. There is effort underway both from a technology and policy perspective to develop propulsion capabilities for smallsats to improve SSA systems and to develop international guidelines for the long-term sustainability of outer space activities.

Scenario 4 (OSAM of spacecraft is a reality) is unrealistic in the timeframe of interest, not because of any technological limitations but because of low investment in the area. OSAM capabilities are currently in their infancy, and there is need for significant increase in R&D investment to see OSAM platforms emerge in GEO and LEO in the near future. There is no indication that investment levels would change soon; impetus for future investment is likely to come from private sector satellite manufacturers that wish to reduce cost or increase revenues by assembling or enhancing large satellites in space, though a future large space telescope funded by a government may speed technology development.

Given these trends, we recommend that ODNI pay attention to the following drivers:

- Speed at which enterprise and consumer demand for communication and imagery products/services is materializing as expected, and if actors are successfully bridging the gap between the data satellites are providing and the needs of non-space end users. Proxy measures include tracking the emergence of new funders and funds for smallsat activity; the emergence and success of new start-ups, and their business plans; disruptive developments especially those related to high delta-v propulsion, low-cost manufacturing, resolution of imagery, and big data analytics; and foreign investment in upstream technology.
- Rate at which costs of manufacturing and other system costs for constellations are falling.
- Whether policies, in countries of interest, related to spectrum allocation, spectrum management, and SSA and debris regulation are aligned with emerging technologies and being rolled out at a fast enough rate.
- Developments in alternatives to LEO-based services, especially terrestrial networks and large HTS satellites.
- Alternative means for access to space (rather than cost reductions).
- Developments that lower the cost of data transmission from small platforms in space - low-cost mobile antennas, low cost ground stations, and in-space relay stations.

Data-gathering effort along these dimensions would help the U.S. Government understand how the sector is changing, identify which actors have which capabilities, and assess the risks to their own assets, both in space and on the ground. Although it may not be possible for the United States to hold a large technological advantage in space over the rest of the world, it can continue to hold a large information advantage by strategically monitoring how these drivers are changing. And although the U.S. Government may not be able to directly influence or deter some technological advances in unfriendly countries, it can strategically develop its own assets to operate in a new regime of ubiquitous satellite services that are more robust to accidental or intentional data gathering by private companies. Such a strategy requires being informed on the state of the identified drivers. By continually monitoring these drivers, the U.S. intelligence community can be better prepared to navigate the next few decades of space development.

Appendix A.
List of Interviewees

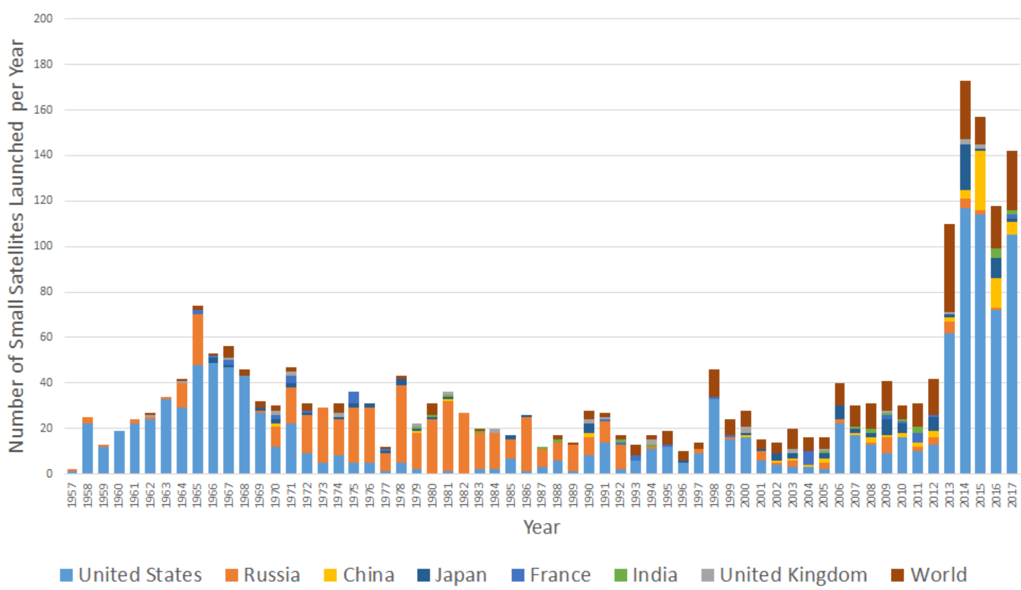
Table A-1. Interviews by Organization Type

Organization Type	Organization Name	Point Person	Interview Date
Academic/Other	Aerospace Corporation	Rich Welle	10/18/2016
	Aerospace (Space Quality Improvement Council)	Marilee Wheaton	01/12/2017
	APL	Bill Swartz	09/01/2016
	Cornell	Mason Peck	10/11/2016
	LASP	Tom Woods	09/02/2016
	MIT	Paulo Lozano	08/30/2016
	Montana State University	David Klumpar	10/31/2016
	SDL	Pat Patterson	08/26/2016
	UC Berkeley	Ned Wright	08/30/2016
	University of Michigan	M-BARC Team	10/12/2016
	University of Keio	Seiko Shirasaka	02/09/2017
	University of Tokyo	Shinichi Nakasuka	02/09/2017
Industry, Foreign	Arianespace	Aaron Lewis	12/13/2016
	Axelspace	Yuyu Nakamura	02/09/2017
	Berlin Space Technologies	Tom Segert	10/21/2016
	Clydespace	Pamela Anderson	11/17/2016
	GomSpace	Igor Alonso Portillo	10/19/2016
	Infostellar	Toyo Kobayashi	02/09/2017
	KSAT	Stig-Are Thrana	10/28/2016
	NEC	Koichi Kishi	02/09/2017
	NESTRA, Orbital Engineering	Koji Yamaguchi	02/10/2017
	OneWeb	Mike Lindsay	12/21/2016
	SSTL	John Paffet	12/06/2016
Industry, U.S.	Accion	Natalia Brikner	10/26/2016
	Blue Canyon Tech	John Carvo	12/08/2016
	Busek	Peter Hruby	12/12/2016
	Chandah	Helen Reed	11/03/2016
	Cubecab	Adrian Tymes	01/04/2017
	Draper Labs	Seamus Tuohy	12/09/2016

Organization Type	Organization Name	Point Person	Interview Date
	Ecliptic	Rex Ridenoure	10/20/2016
	ExoTerra Resource	Mike Van Woerkom	12/07/2016
	Hawkeye 360	Chris DeMay	10/31/2016
	NovaWurks	Talbot Jaeger	11/03/2016
	Phase Four	Umair Siddiqui	03/15/2017
	Planetary Resources	Peter Marquez	11/21/2016
	Pumpkin	Andrew E. Kalman	12/16/2016
	Rocket Crafters	Sid Gutierrez	01/04/2017
	Rocket Lab	Peter Beck	01/26/2017
	Space Systems Loral	Al Tadros	04/26/2016
	Spaceflight/BlackSky	Peter Wagner	11/08/2016
	SpaceX	Matt Dunn	11/01/2016
	Spire	Peter Platzer	11/01/2016
	Terra Bella	John Fenwick	11/28/2016
	Tyvak	Dave Williamson	12/08/2016
	VALT/USRA	Dan Mosequeda	10/26/2016
	York Space Systems	Dirk Wallinger	10/13/2016
NASA	NASA Ames	Bruce Yost	09/22/2016
	NASA Goddard - Roundtable	Round Table	09/02/2016
	NASA HQ	Jason Cruzan	10/24/2016
	NASA HQ	Richard French	02/03/2016
	NASA HQ	David Pierce	11/07/2016
	NASA HQ	Michael Seablom	08/24/2016
	NASA HQ	Garrett Lee Skrobot	10/28/2016
	NASA HQ	Ellen Stofan	09/14/2016
	NASA Johnson	Daniel Newswander	11/03/2016
	NASA JPL	Charles Norton	10/05/2016
	NASA JPL - Roundtable	Round Table	10/24/2016
	Formerly NASA	Lori Garver	01/30/2017
Other Government	AFRL	David Voss	11/29/2016
	NOAA	Steve Volz	11/02/2016
	JAXA	Yasuaki Iwabuchi	02/10/2017
	NSF	Thyagarajan Nandago	11/29/2016
	NSF	Therese Jorgenson	08/29/2016
	FCC	Karl Kensinger	03/21/2017
Venture, U.S.	Bessemer Venture Partners	Sunil Nagraj	10/21/2016
	Lux Capital	Shahin Farshchi	10/25/2016
	Space Angels Networks	Chad Anderson	10/31/2016

Appendix B.
Trends in the Small Satellite Market

The small satellite (smallsat) market has been rapidly transforming since 2013 as new actors have entered the market; new payloads, buses, and technologies have emerged for a growing number of applications, including remote sensing, communications, science and exploration, space situational awareness, technology development and others. This appendix presents a snapshot of the rapidly evolving market with discussion of growth projections for the manufacturing and launch market by application and sector, the global distribution of small satellite market, and finally additional markets served by small satellites (Figure B-1). Unless otherwise noted, projections in this appendix are adapted from a yearly report released by Euroconsult.[1] It is important to note that the projections and historical data in the Euroconsult report and in this appendix include satellites with mass above 200 kg. This is because Euroconsult defines smallsats as satellites below a mass of 500 kg, to include a few additional, mainly defense-oriented, missions (250–500 kg) that are using the smallsat platform.



Source: J. McDowell, June 2017, "Satellite Catalog," http://planet4589.org/space/log/satcat.txt.

Figure B-1. Number of Small Satellites Launched

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[1] Euroconsult, "Prospects for the Small Satellite Market," 2016, http://www.euroconsult-ec.com/research/smallsats-2016-brochure.pdf.

Market Projection Methodology for SmallSat Launch and Manufacturing

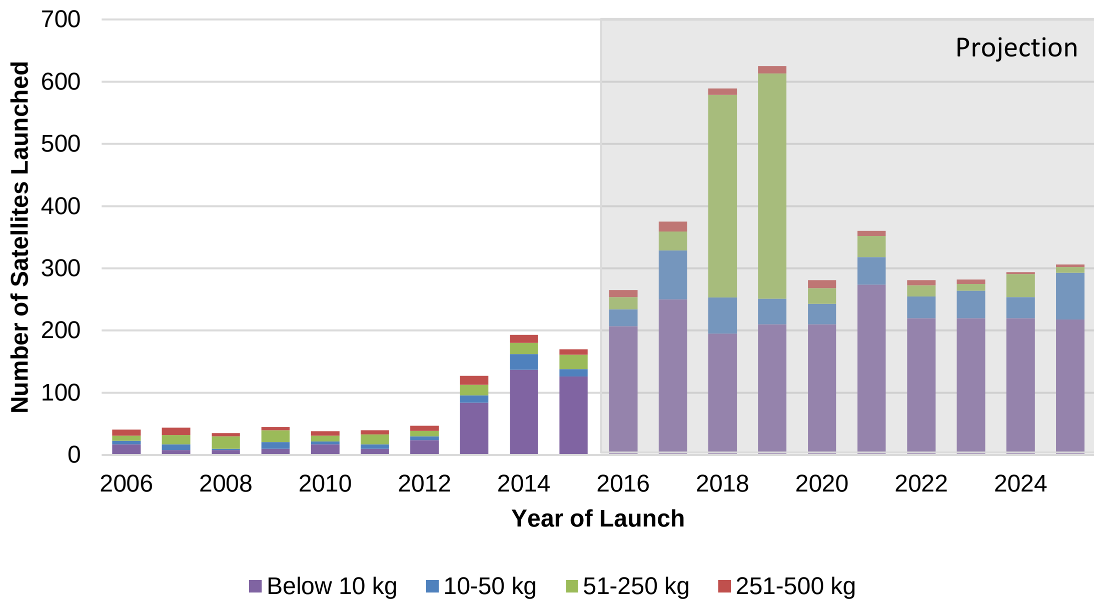
Because the Euroconsult Report of 2016 provides a 10-year projection of the manufacturing and launch markets of small satellites, only upstream processes are included in the market value Euroconsult presents. Despite the absence of midstream and downstream activities, the Euroconsult market analysis provides an overview of trends in the growth of small satellites and their applications, the divide between public and private activity, and the global distribution of operators.

Historical data (2006–2015) is sourced from a database including all satellites launched between the mass of 1 kg and 500 kg. The forecast, covering 2016–2025, is inclusive of commercial, government and academic projects. All current smallsat projects that have been announced are included; replenishment cycles are also accounted for in the estimates. Unannounced government and academic projects, often one-off missions, are projected past 2020 based on models that incorporate historical trends. To prevent skewed data, the analysis does not include proposed SpaceX and Boeing constellations, which would have 4,000 and 2,956 satellites, respectively. Representative of the evolving market, if the two constellations are successful, the manufacturing and launch market values would greatly increase.

Pricing assumptions for the Euroconsult model are estimated against historical pricing from the prior 30 years. Market value includes the cost to manufacture the satellite and to launch into orbit, including commercial insurance. Future manufacturing and launch prices are estimated based on price per kilogram. Estimates could change based on the application of mass manufacturing, commodification of smallsats or the development of new bus, component and launch technologies.

Growth in the SmallSat Market for Commercial and Government Applications

The small satellite industry has grown since 2013 as new actors, from industry, academia, and foreign nation states have capitalized on small satellites as a platform for lower-cost missions (Figure B-2). The deployment of small satellites expanded from 2013 to 2015 as the launch rate of satellites quadrupled, reaching an average of 163 per year. From 2016 onward, the number of satellites manufactured and launched is projected to grow by a factor of almost 4 in the upcoming decade, with 690 launched between 2006 and 2015 and about 3,600 launched between 2016 and 2025. Of the projected 3,600 smallsats, nearly two-thirds would be part of a large constellation; almost all, 97 percent, are planned for launch into LEO orbit; and over 60% would be CubeSats (75% of civil and commercial satellites are expected to be under 50 kg). If estimates of the first generation Boeing (1,400–2,956 satellites) and SpaceX (4,425 satellites) constellations are included, a high end estimate for the total number of satellites launched would reach 11,000, or well over an order of magnitude increase over the prior decade.[2, 3]



Source: Adapted from Euroconsult, "Prospects for the Small Satellite Market," 2016.
Note: Figure does not include number for SpaceX and Boeing constellations.

Figure B-2. Small Satellite Projection: Actual and Projected Satellites Launched

It is important to note here that while the number of small satellites is expected to quadruple from 2016 to 2025, the market value (value of manufacture and launch) is expected to grow by a factor of 1.8, from $12.5 billion to $22 billion (Figure B-3), exclusive of any ground system or downstream application markets. This is understood to be largely the result of the decreasing costs of manufacture and launch. The revenues that are likely to be generated from sale of imagery or other data products are discussed further in the subsections.

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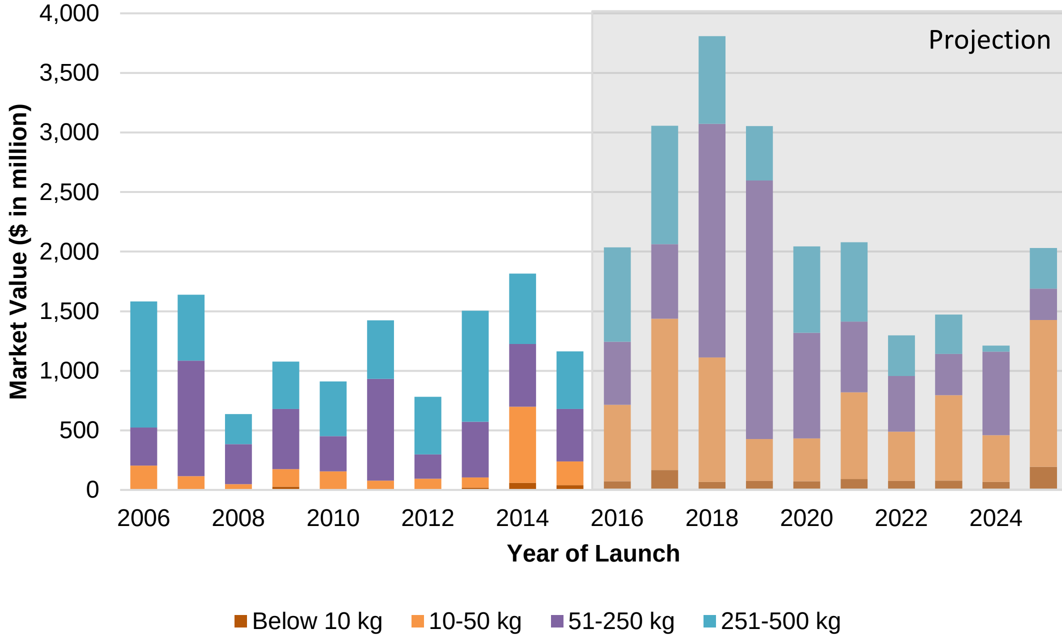
2 Based on FCC filings in November 2016. See D. Mosher, "SpaceX Just Asked Permission to Launch 4,425 Satellites—More than Orbit Earth Today," *Business Insider*, November 16, 2016, http://www.businessinsider.com/spacex-internet-satellite-constellation-2016-11; P. B. De Selding, "Boeing Proposes Big Satellite Constellation in V- and C-bands," *SpaceNews*, June 23, 2016, http://spacenews.com/boeing-proposes-big-satellite-constellations-in-v-and-c-bands/.

3 The success of the various constellations would depend on a variety of factors including, but not limited to, access to space (lower costs or dedicated launch vehicles), private and public investment funding levels, or access to alternative competing platforms.



Source: Adapted from Euroconsult, "Prospects for the Small Satellite Market," 2016.
Note: Figure does not include number for SpaceX and Boeing Constellations.

Figure B-3. Small Satellite Projection:
Actual and Projected Manufacturing and Launch Value

Growth Expected to Continue Across the Public and Private Sectors

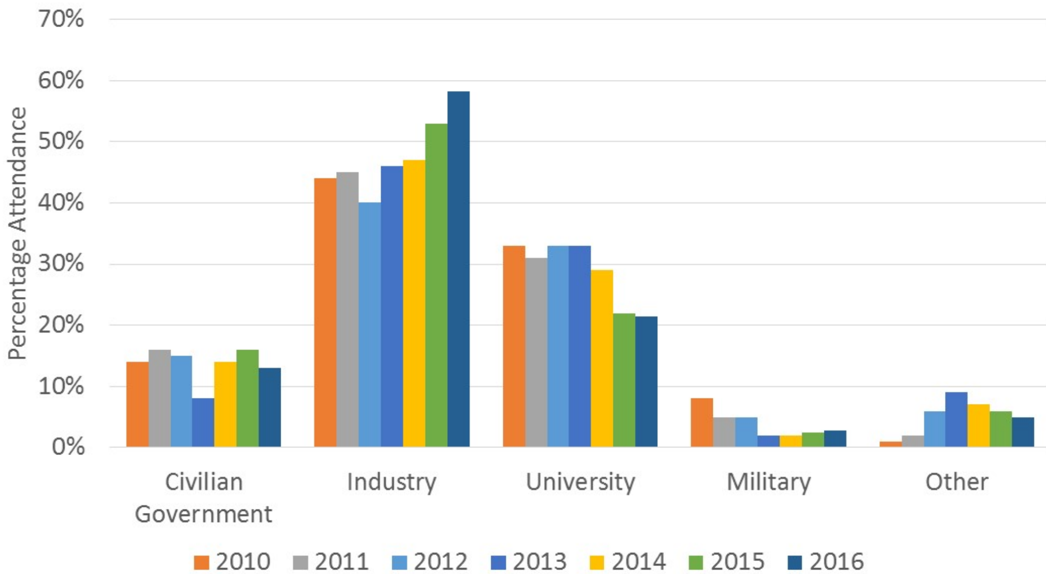
Relative to the prior decade (2006–2015), the projected growth in small satellite launches would be greatest in the commercial sector, growing by a factor of nearly 11. By comparison, the number of civil government smallsats would grow by 25% over the previous decade, and defense-oriented missions would actually decrease slightly (Table B-1). Defense-oriented smallsat missions are projected to remain stable (with a slight decrease); however, these numbers encompass only unclassified missions.

Although the number of launches would be driven by growth in the commercial sector, the total market value for manufacturing and launch would continue to be driven by government (civil and defense) missions. Lower per unit costs in the commercial sector would be driven by commoditized, mass manufactured satellites for constellations (e.g., OneWeb's 720 planned satellites will be mass produced by assembly line). Government missions likely utilize both low-cost platforms, such as the CubeSat, and higher-cost specialized smallsats. See Figure B-4.

Table B-1. Public and Private Sector Activity in the Small Satellite Market

	Satellites Launched (2006–2015)	Market Value (2006–2015)	Planned Satellite Launch (2016–2025)	Expected Market Value (2016–2025)
Commercial	275 (35%)	—	2,972 (81%)	$9.3 billion (42%)
Civil Government	409 (52%)	$8.7 billion (70%)	626 (17%)	$11.0 billion (49%)
Defense Government	96 (12%)	$2.5 billion (20%)	60 (2%)	$2.0 billion (9%)
Total	780 (100%)	$12.5 billion (100%)	3,658 (100%)	$22.3 billion (100%)

Source: Adapted from Euroconsult, "Prospects for the Small Satellite Market," 2016.
Note: Table does not include number for SpaceX and Boeing constellations.



Source: Utah Smallsat conference.

Figure B-4. Attendance at the Utah Smallsat Conference

Commercial Earth Observation and Communications Constellations Drive Growth in the Smallsat Launch and Manufacturing Market

As growth is driven by the deployment of commercial constellations, a number of governmental agencies are expected to benefit as direct consumers of these commercial operators (e.g., Spire recently signed an agreement with NOAA to provide weather data, as part of a pilot program NOAA has initiated that could lead to greater use of data sourced from commercial satellite operators[4]). The growth in the absolute count of small satellites projected to be launched (2016–2025) is expected to be driven by a small number of operators outside government. Approximately 65% of the projected launches would come from six commercial actors. These actors include both broadband satellite communication (SatCom) constellations, such as OneWeb (720 satellites), and Earth observation constellations from Planet (1,000 CubeSats, >230 are launched already), Satellogic (300 satellites), BlackSky (60 satellites), and Spire (260 satellites).

The number of small satellites launched are projected to grow across all application areas except for SSA from 2016–2025 (Figure B-5), but most of the growth is expected in Earth observations and SatCom (Table B-2):

- **Imaging and Earth Observations:** A projected 2,100 smallsats are expected to be launched, mainly for the initial deployment or replenishment of commercial Earth observation constellations. Although 80% of the constellations would be operated by four companies, consumers of the Earth observation data range from commercial actors (e.g., agricultural sector, natural resource managers, maritime tracking, and economic forecasting) to intelligence and defense actors (e.g., NRO), who may be interested in tracking ports, monitoring border activity, and otherwise identifying bad actors, as well as civil government actors (e.g., NOAA), who may be interested in improved weather prediction and disaster monitoring.
- **Satellite Communications (SatCom):** SatCom includes broadband and machine-to-machine communications (either satellite to satellite or satellite to ground). Organizations such as OneWeb, Kepler Communications, and Russian Gonets are using the small satellite platform for SatCom applications ranging from broadband internet, machine to machine communications and government telecom needs, respectively. Excluding SpaceX and Boeing, OneWeb dominates (~700 satellites) the total of 6 constellations that have been proposed for the roughly 800 satellites expected to be launched for SatCom applications.
- **Technology Demonstration:** Growth is further projected for the number of small satellites that are launched for technology demonstration and validation projects. Roughly 560 satellites are expected to be launched for a broad range of missions to test and validate components, subsystems and buses. A majority of the missions, over 90 percent, are under 50 kg. Some of these missions come from countries or university programs developing small satellite technologies,

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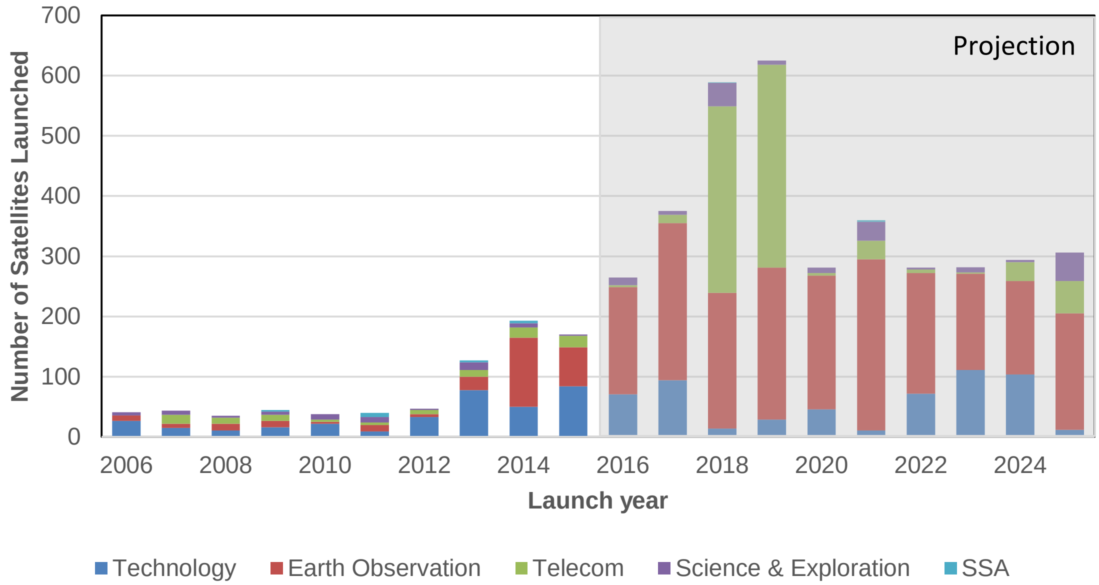
[4] J. Foust, "Two Companies Win First NOAA Commercial Weather Contracts," *SpaceNews*, September 15, 2016, http://spacenews.com/two-companies-win-first-noaa-commercial-weather-contracts/.

and some are testing new technological developments, such as active debris removal or on-orbit servicing of large satellites.

- **Science and Exploration:** This category includes small satellite platforms used for scientific endeavors (astronomy, heliophysics, planetary sciences, and micro-gravity experimentation etc.). Civil governments (through space agencies and other academic institutions) and academic institutions would continue to dominate the science and exploration application sector. Over 160 satellites are projected to be launched for various science missions. A majority of these missions would likely continue to be one-off missions to support R&D and academic ventures. While small satellites are traditionally considered to be LEO-specific, some interplanetary science projects move beyond LEO and even beyond Earth orbit.
- **Space Situational Awareness (SSA):** SSA refers to space surveillance and tracking, near-Earth object monitoring, electrical intelligence (ELINT) and space weather. SSA satellites would continue to be defense-inclined projects conducted by or alongside government entities. Numbers reported do not include recent plans that are expected to be announced by commercial actors such as Chandah Space. More information on this company can be found in Appendix G.

As the commercial sector drives the growth in smallsat launches, government would remain an important player in science, exploration, national defense and in nations that are new to the small satellite field. Overall, small satellites in the next 10–15 years in the commercial sector are projected to skew towards lighter and cheaper options, while small satellites in the government sector are projected to remain relatively larger and higher cost to account for specific mission needs not met by the commercial sector (yet still orders of magnitude below the cost and size of large satellite options).



Source: Adapted from Euroconsult, "Prospects for the Small Satellite Market," 2016, http://www.euroconsult-ec.com/research/smallsats-2016-brochure.pdf.

Note: Figure does not include number for SpaceX and Boeing Constellations.

Figure B-5. Small Satellites Launched by Application Area

Table B-2. Smallsats by Application

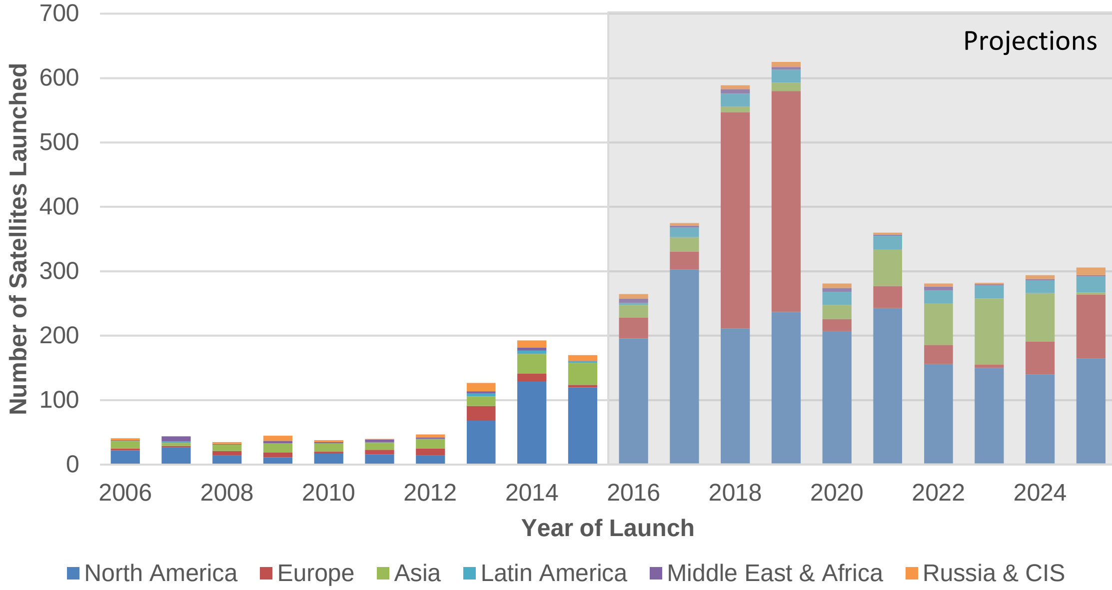
Application	Number Launched (2006–2015)	Number Projected to Launch (2016–2025)	Percentage Growth (%)	Number of Units by Major Actors (2016–2025)
Earth Observation	259	2,070	+700%	Planet (1,000) Spire (260) BlackSky (60) Satellogic (300)
Satellite Communications	97	862	+789%	OneWeb (720) XinWei (32) Gonets (12)
Science & Exploration	62	168	+171%	NASA (13) Lockheed Martin (4) ESA (3)
Technology Development.	345	564	+63%	United States Air Force (19) Argentina National Space Activities Commission (CONAE) (4)
Space Situational Awareness	17	4	–76%	China National Space Administration (CNSA) (3)

Source: Adapted from Euroconsult, "Prospects for the Small Satellite Market," 2016.

Global Distribution

Of the total number of smallsats expected to be launched from 2015–2025, a majority are projected to be launched (55 percent) by the United States (Figure B-6). The global distribution and type of missions supported by region are as follows:

- **North America**: The region is dominated by the United States, with a few projects in Canada projected. A majority of the smallsats are expected to be below 50 kg, and would be used for a host of applications. A few constellations, including Planet, Spire, and BlackSky (part of Spaceflight), are included.
- **Europe**: The region includes Europe, exclusive of Russia. Of the roughly 1,000 projected smallsats, approximately 720 would be launched in the OneWeb broadband constellation. Academic missions encompass a majority of the remaining projected launches.
- **Asia**: The region is also exclusive of Russia. Of the roughly 390 projected smallsats, nearly 60% would be for technology demonstrations and the remaining for academic missions.
- **Latin America**: Two projects dominate the region, including the Earth observation constellation proposed by Satellogic (~300 smallsats) and the SARE technology demonstration project.
- **Russia, Middle East, and Africa**: Inclusive of Russia, this region only has roughly 60 smallsats projected. 12 of the satellites will be launched to augment the Russian Gonet Satcom telecommunications constellation, using smallsat civilian technology derived from the military Strela-3 satellite system. A majority of these missions would be one-off, and focused on technology development and science missions.



Source: Adapted from Euroconsult, "Prospects for the Small Satellite Market," 2016.
Note: Figure does not include SpaceX and Boeing constellations.

Figure B-6. Launches by Global Geographical Region

Growth in Markets beyond Manufacturing and Launch

As a growing number of smallsats are launched, the ubiquitous, higher resolution imagery and broadband internet that are enabled would influence markets downstream. As discussed further in Appendix F, a number of applications would be enabled by the proliferation of smallsats. As a result, markets downstream that are both traditionally (e.g., weather modeling and prediction) and non-traditionally (e.g., agriculture, international banking and resource management) dependent on data sourced from space would be further enabled.

Earth Observation Markets for Data and Insight

Based on a report released by Frost and Sullivan,[5] as overall cost of space assets decrease (i.e., more small satellites replacing larger satellites), the cost for satellite imagery data products is projected to also decrease. Decreased cost may lead to increased competition, especially in the medium-resolution market that smallsats would be capable

[5] Frost & Sullivan, "Assessment of the Small-Satellite Market," September 28, 2015, http://www.frost.com/sublib/display-report.do?id=9AB0-00-21-00-00.

of serving. Thus, the current smallsat imaging market,[6] in 2015 valued at $15 million, is expected to reach a value of $164 million by 2020, increasing by an order of magnitude and at a compound annual growth rate of 49 percent. Web-based analytics platforms and customized analytics algorithms, sourced from space and other data-intensive industries, are expected to continue to bring in new non-space consumers.

Growth in the small satellite imagery marketplace is expected to be driven by industries such as agriculture, urban planning, and maritime (among many others). Customers would include terrestrial decision-makers interested in data-driven decision-making practices, which can be gleaned from the small satellite imagery. Models for new business models, that could begin to be tested in the marketplace as soon as 2019, would include the sale of on-demand imagery to personal devices (e.g., cuing smallsats through applications on smartphones and tablets) and a pay-per-image model to “democratize” the industry, allowing anyone access to use services.

Additional Markets to Continue to Grow Outside of Earth Observations

New and emerging applications, in the past few years, have opened new markets for small satellites. Beyond Earth observations, a number of organizations have considered the idea of using smallsat constellations for machine-to-machine communications and to deliver broadband Internet. A number of studies have investigated the future projection of this application area, as discussed in Appendix F.

The market potential of proposed broadband constellations, if achieved, could greatly outweigh the current launch and manufacturing market in the next 10–15 years. In the maturing large satellite industry, a significant majority of market value is derived from downstream activity, or the “users”; 98% of the $237 billion market value is split across over 5,000 actors in downstream markets (e.g., satellite TV and radio).[7] Although the full market value is hard to predict, in the absence of any operational LEO smallsat broadband constellations, internal numbers released by SpaceX indicate a similar trend could materialize in the smallsat industry. Internal projections made by SpaceX, acquired by *The Wall Street Journal*, indicate that their broadband constellation alone could reach 40 million subscribers worldwide with a revenue of $100 billion between 2019 and 2025 (Figure B-7).[8] This constellation, alone, would be nearly an order of magnitude greater

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[6] The smallsat imaging market includes all Earth observation data (in the form of imagery or video) that is sourced from smallsat platforms. Consumers include other satellite operators, government agencies, terrestrial industries, etc.

[7] Euroconsult, “Satellite Value Chain: The Snapshot 2016,” http://euroconsult-ec.com/research/satellite-value-chain-2016-brochure.pdf.

[8] R. Winkler and A. Pasztor, “Exclusive Peek at SpaceX Data Shows Loss in 2015, Heavy Expectations for Nascent Internet Service,” *Wall Street Journal*, January 13, 2017,

than the projected launch and manufacturing market value, as discussed above, in the same period.

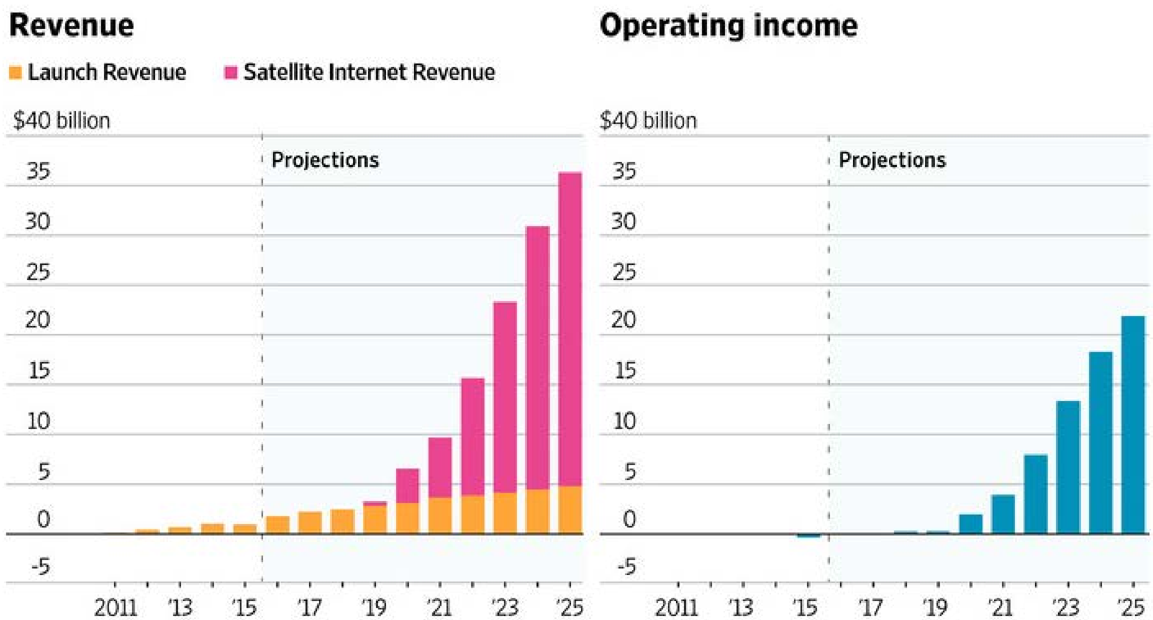

Figure B-7. SpaceX Projected Revenues for Broadband Smallsat Constellation

Further, smallsats in the next 10–15 years would serve markets for SSA and on-orbit activities for servicing, repairing, or monitoring assets in orbit in addition to machine-to-machine communications. One example is the unmanned aircraft systems (UAS) market that has recently expanded.

Driven by the need for persistent intelligence, surveillance, and reconnaissance, UAS projects continue to expand worldwide for both commercial and government actors. Satellites would play an important role, providing satellite communications between UAS and operators. The market could reach nearly $19.9 billion in revenue over the next decade, for satellites. [9] This market could be capitalized upon by small satellites (in competition with larger satellites), if constellations are successful.

As the markets for downstream activity grows, new applications and technologies would augment current markets and enable new markets. For example, current Earth observation markets are providing financial resources for companies such as Planetary Resources and Deep Space Industries that have ambitious, long-term, plans for asteroid

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http://www.wsj.com/articles/exclusive-peek-at-spacex-data-shows-loss-in-2015-heavy-expectations-for-nascent-internet-service-1484316455.

9 J. Van Wagenen, "NSR: Drones Offer $19.9 Billion Opportunity for Satellite," *Via Satellite*, December 14, 2016.

prospecting and mining. Future operations could serve markets for deep space travel (e.g., mining water on asteroids as fuel for propulsion, or mining metals for in-space manufacturing).

Appendix C.
Small Satellite Ecosystem

As the previous appendix on market trends demonstrates, the small satellite sector has grown in the prior decade, with new actors joining the market in both the private and public sector. Drivers for growth include, but are not limited to, the miniaturization of technology for the small satellite platform, increased data processing capabilities, decreased launch costs, the ubiquitous presence of GPS enabling location and attitude determination, improvements in ground system costs and signal processing capabilities and finally the deployment of inexpensive COTS parts.[1]

Innovation and investment in the U.S. and international space sector has nurtured a small satellite ecosystem that shares features with the large satellite industry, and is dynamic enough to capture the interest of new actors (e.g., non-space industries and venture capital).[2] As new nations are breaking into space-based activities, countries that previously could not afford space missions are using small satellites (i.e., CubeSat) for low cost space missions and research. Access to space provides opportunities globally for education, workforce development, and access to new insights to inform decision-makers.

In this appendix, we present an overview of the actors and their function in the smallsat ecosystem. To do so, the STPI team assembled a database of organizations that actively engage in the small satellite industry. We also compiled case studies of a small number of private sector entities in the United States and abroad (see Appendix G). Due to the rapidly changing nature of the sector, this list is extensive but not comprehensive. However, it provides an insightful overview of the smallsat sector. The database includes

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1 B. Lal, et al., *Global Trends in Space, Volume 1: Background and Overall Findings.* IDA: Alexandria, Virginia. IDA Paper P-5242. June 2015. https://www.ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2015/p5242v1.ashx.

2 A smallsat ecosystem would be defined for this report as an innovation system "in which a variety of actors interact in a bounded 'interaction space' where socio-economic value is created through research, novelty creation and traditional market activities. The network consists of customers, subcontractors, infrastructure, suppliers, competencies and functions and the links or relationships between them." See M. Mazzucato and D. K. R. Robinson. *Market Creation and the European Space Agency: Towards a Competitive, Sustainable and Mission-Oriented Space Eco-system*. http://esamultimedia.esa.int/docs/business_with_esa/Mazzucato_Robinson_Market_creation_and_ESA.pdf.

over 660 entities engaged in 12 types of activities.[3] As ODNI investigates general trends leading to future end-states, all aspects of both the larger space and the smallsat ecosystems should be considered, although this report only addresses the smallsat ecosystem.

Actors within the Ecosystem

New actors and start-ups are taking advantage of the growing small satellite market as technology advances and the cost of launch decreases. Pairing business models that allow for relatively low upfront costs with access to capital (through angel investors, venture capital, and corporate venture capital, in the U.S. or through government and commercial contracts abroad), new space companies have emerged throughout the ecosystem.

Within the small satellite ecosystem, actors exist in both the private and public sector. The various types of actors are detailed in Figure C-1. A significant overlap exists between the four actor types; individuals move across the actor types and common missions and goals support partnerships. For example, a number of new smallsat ventures rely upon a workforce of leaders that developed expertise while working at NASA. As the commercial sector grows, actors are becoming less dependent on government money and missions to operate, although government remains a reliable customer and investor in areas where commercial investment is lacking.

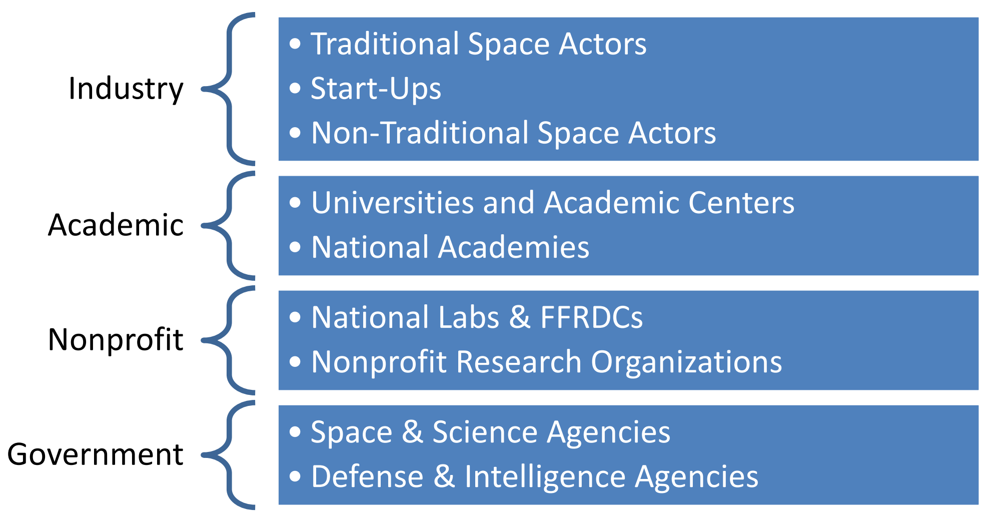

Figure C-1. Actors in the Small Satellite Ecosystem, by Type

3 The database was assembled using purchased sources, such as Euroconsult data ("Prospects for the Small Satellite Market," 2015), discussions with attendees and exhibitors at the Small Satellite Conference 2016, and publicly available documents such as the annual Satellite Industry Association (SIA) *State of the Satellite Industry Report*.

Traditional Space Actors

A large fraction of the growth in the small satellite ecosystem has occurred within the private sector. Whereas some traditional space actors are active in the smallsat market, many new and emerging start-ups and non-space companies have also joined. Traditional space actors include large aerospace companies, like Lockheed Martin, who are applying their expertise developed in prior large satellite missions to develop and sell small satellite buses and components. Other traditional space actors are capitalizing on the growing ecosystem through the acquisition or operation of subsidiaries; for example, UK-based small satellite supplier Surrey Satellite Technology Ltd. (SSTL) operates within the Airbus Defense and Space Group.

Private Start-Ups

As the ecosystem has grown, new space companies have emerged. Start-ups have emerged that are developing new technologies and applications for small satellites. Although new by name, many of the start-ups rely upon leadership strengthened by either experience in the space field and industry or technical expertise. Many start at academic institutions, where initial ideas are developed, such as the propulsion start-up Accion that is commercializing the founder's research at MIT as a graduate student, or the Danish company GomSpace, based in the technology hub of Aalborg, Denmark with leadership connected to Aalborg University. Further, other entrepreneurs leverage experience in the government, as with the former NRO experts who lead the global intelligence company Hawkeye 360 or former NASA JPL engineers at the satellite imaging radar company Capella Space; while others leverage experience of major defense contractors, as seen with the prospective satellite launch company Firefly's appointment of a Lockheed Martin spacecraft design lead to chief technology officer.

To provide further detail on the formation of these small satellite startups, an example is provided in the following sidebar on leadership heritage in European startups. Further information on select startups are provided in Appendix G.

Leadership Heritage of European Start-Ups

A growing number of small satellite start-ups have emerged in various ESA member state countries in the recent decade. Similar to U.S.-based start-ups, a majority of these organizations rely upon leadership with a wealth of technical expertise and business savvy.

A number of start-ups formulate out of ideas and technologies developed by motivated students and academics who gained their expertise from academic missions. For example, a number of companies form as spin-offs of academic projects: the founders of the Dutch company Innovative Solutions in Space (ISIS) met while working on the Delfi-C3 smallsat project at TU Delft;* the founders of Denmark-based company GomSpace met while developing one of the first European CubeSats at Aalborg University.† Further, academic institutions may serve as an innovation hub, even without explicit space programs; for instance, the founders of French-based smallsat manufacturer and services company, 4skies, met at University of Lyon.‡

Additional small satellite start-ups have leadership heritage and ties to larger space primes. For example, the smallsat manufacturer Clyde Space was formed by a senior expert of the major prime SSTL in the UK. Further, the propulsion start-up NanoSpace was formed out of the large prime Swedish SSC, and was recently acquired by GomSpace in October of 2016. Start-ups that begin out of larger primes are often supported by the resources that are at easy disposal (i.e., testing facilities), but then may be sold off (in the case of NanoSpace) when economically favorable.

Many European-based start-ups that we identified in the database relied upon early funding sourced from either government grants or contracts or contracts with private industry. Whereas some organizations depend on funds from early-TRL public innovation funds (i.e., 4 skies, early funding sourced from the National Innovation Agency, Chamber of Commerce and Industry, and Réseau Entreprendre), others depend on investments made by their founders and subsequent contracts (i.e., GomSpace). Although a venture capital community exists in Europe, their growth has been limited relative to the community in the United States.

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*J. Rotteveel, "Launch Results from the QB50 Pre-cursor Launch Campaign Flight Qualification of the QB50 Launch System." Innovative Solutions in Space (ISIS), Presentation, 2014 CubeSat WorkShop, Logan, Utah.

† See case study (Appendix G).

‡ 4skies, "Our Story."

Non-Traditional Space Actors

Finally, in the private sector, the New Space industry has attracted new companies into the ecosystem. Companies that are not traditionally thought to be engaged in the space sector are investing in new and emerging organizations in hopes of accessing new markets. Large international corporate actors are investing in global broadband projects to access new clients, such as Coca Cola in OneWeb's broadband constellation, a company started by a handful of Google employees; media organizations are utilizing insights gained from satellite imagery to inform their work, as seen in partnerships between the New York Times and image analyzer BlackSky Insight to gain insight on the Turkish Coup in 2016 or Google's acquisition of Skybox imaging[4] to incorporate new data analytics with smallsat imagery; technologies, previously not developed for space, are being integrated into small satellite systems, such as the integration of Intel computer chips. Further, methods and technologies from non-space industries are being integrated into New Space companies; one interviewee is adapting parallax algorithms, similar to ones developed for automobile collision avoidance systems, to do smallsat proximity operations.

Academia and Nonprofit

Beyond the private sector, the small satellite platform has been widely used in the academic communities. Universities and academic centers have used the small satellite platform to test new technologies, run micro-gravity experiments, and engage in basic science research. Given the relatively little time required to deliver a small satellite mission from conception to launch (a few years as opposed to a decade for large satellites) engineering universities, such as MIT, the University of Michigan, University of Surrey, and TU Berlin have widely used the small satellite platform to complete research studies, while educating a future workforce.

National academies across the world, from the Chinese National Academies to the Polish Academies of Sciences, have further invested in research and development activities in their nations to promote engagement in space and develop new technologies. Further activity in not-for-profit organizations, drive research and development investments, including organizations like the Laboratory for Atmospheric and Space Physics (LASP), Space Dynamics Lab (SDL) and Draper Labs.

A growing number of non-governmental organizations and foundations, not active in the manufacturing and operations of satellites, have become active in the ecosystem as end users and funders. These NGOs use smallsat imagery and derived analytics to support

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[4] Skybox is now Terra Bella, and was recently acquired by Planet (announced in early 2017). As part of the acquisition, Google has signed a deal to retain access to imagery. For more information, see W. Marshall, "Planet to Acquire Terra Bella from Google," Planet.com News. February 3, 2017, https://www.planet.com/pulse/planet-to-acquire-terra-bella-from-google/.

mission needs related to climate adaptation, disaster preparedness and response, resource and human trafficking, food security, and other social concerns. For example, NASA-backed data analytics provider Raster Foundation has developed algorithms, using Planet imagery, to support the efforts of the Gates Foundation to monitor and track social issues globally. The Foundation itself hosted a Thought Leaders Summit in early 2017 in an effort to develop and launch a platform to harness the large amount of data being produced, and expected to be produced, by satellites large and small;[5] this summit was hosted shortly after the Foundation completed a project that used satellite imagery (not only from smallsats) and mobile phone data to map poverty in Bangladesh.[6]

Government

Governmental organizations have begun to use the small satellite platform for missions within LEO and beyond. Traditional actors, such as major space agencies NASA, ESA, and JAXA, have used the small satellite platform both for technology development missions and greater scientific projects.[7] The low-cost smallsat platform has allowed for new governmental actors to emerge, including Argentina's CONAA, Gabon's AGEOS, Costa Rica's first space missions, and other missions by Turkey and Iran, among others.[8] Increasingly, other governmental agencies are using the platform to inform weather predictions and models (e.g., NOAA's Commercial Weather Data Pilot[9]), to develop technologies and basic research endeavors (e.g., see the National Science Foundation [NSF] Program Solicitation NSF 14-535[10]), or to monitor natural resources (i.e., KSAT's efforts to support Australia's efforts in curbing illegal fishing). Finally, the defense and intelligence sector has invested in small satellite technologies to serve mission goals, including the Defense Advanced Research Projects Agency (DARPA) Phoenix technology development program, which has brought out new modular plug-and-play satlet systems,[11] and the partnership of National Geospatial-Intelligence Agency (NGA) with Earth

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5 P. Totaro, "The Billionaire Philanthropists Intent on Using Satellites to Save the World," Reuters, February 27, 2017, http://www.reuters.com/article/us-technology-satellites-humanitarian-idUSKBN1661KH.

6 W. Tate, "Data from the Heavens: A New Push to Learn More from Satellites," *Inside Philanthropy*, March, 13, 2017, https://www.insidephilanthropy.com/home/2017/3/13/gates-and-omidyar-team-up-behind-an-online-archive-of-satellite-data.

7 Additional information on international activities is provided in Appendix E.

8 Euroconsult, "Prospects for the Small Satellite Market," 2016.

9 NOAA, "Commercial Weather Data Pilot," Office of Space Commerce. http://www.space.commerce.gov/business-with-noaa/commercial-weather-data-pilot-cwdp/.

10 NSF, "CubeSat-Based Science Missions for Geospace and Atmospheric Research," Program Solicitation NSF 14-535, https://www.nsf.gov/pubs/2014/nsf14535/nsf14535.pdf.

11 DARPA, "Phoenix," http://www.darpa.mil/program/phoenix.

observations image provider Planet.[12] Further, the platform has enabled missions for Ministries of Defense in other nations including Israel, Italy, and Turkey.[13]

STPI's Ecosystem Database: A Global Distribution of Actors

In the absence of a uniform database of small satellite actors, the STPI team developed a database to track non-government and government actors engaged in the small satellite industry. Given the rapid evolution of the industry, with new actors entering and leaving the market, the database represents only a snapshot of the various types of organizations involved in the industry rather than an exhaustive list. As such, one should focus on the orders of magnitude rather than the exact numbers.

The United States continues to dominate the industry; in our database of 664 unique organizations, about half (43 percent) base their operations in the United States (Figure C-2). Significant activity by industry is driven by technology developers and manufacturers as well as operators involved in Earth observations. Key players outside the United States include Europe and Asia (25 percent and 22 percent of identified organizations, respectively), based in key research and development hubs in Germany, the United Kingdom, Russia, Japan, China, South Korea, India, and Singapore.

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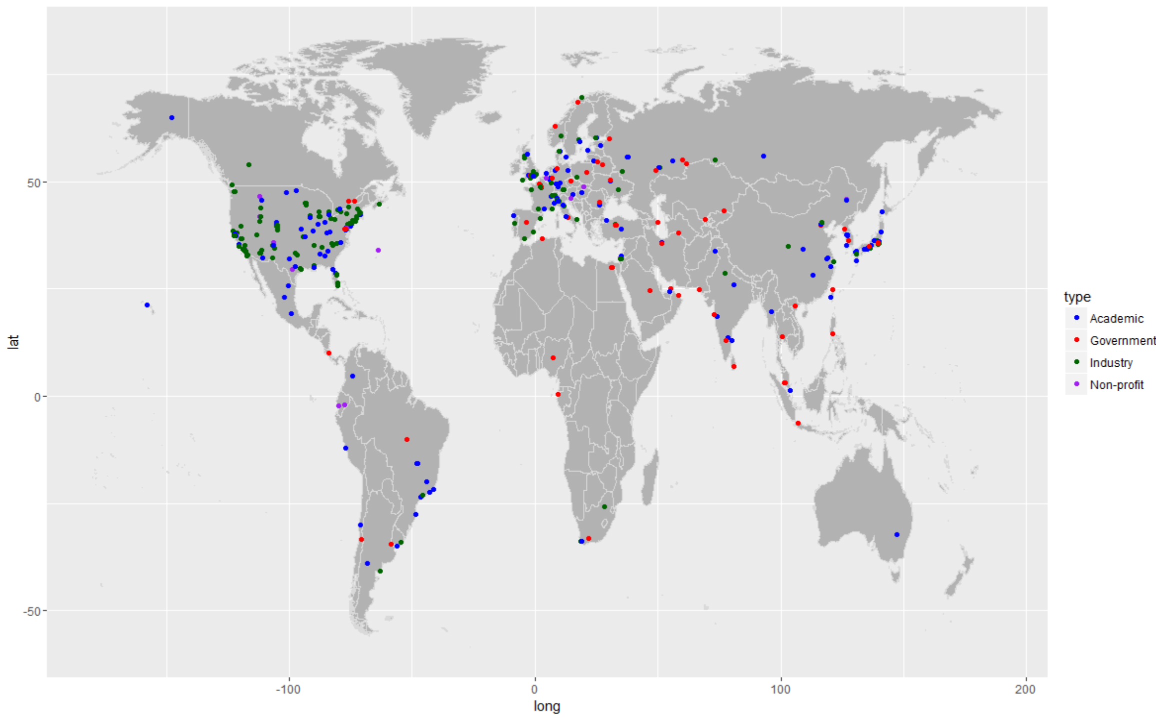
[12] NGA, "NGA Introductory Contract with Planet to Utilize Small Satellite Imagery," https://www.nga.mil/MediaRoom/PressReleases/Pages/NGA-introductory-contract-with-Planet-to-utilize-small-satellite-imagery.aspx.

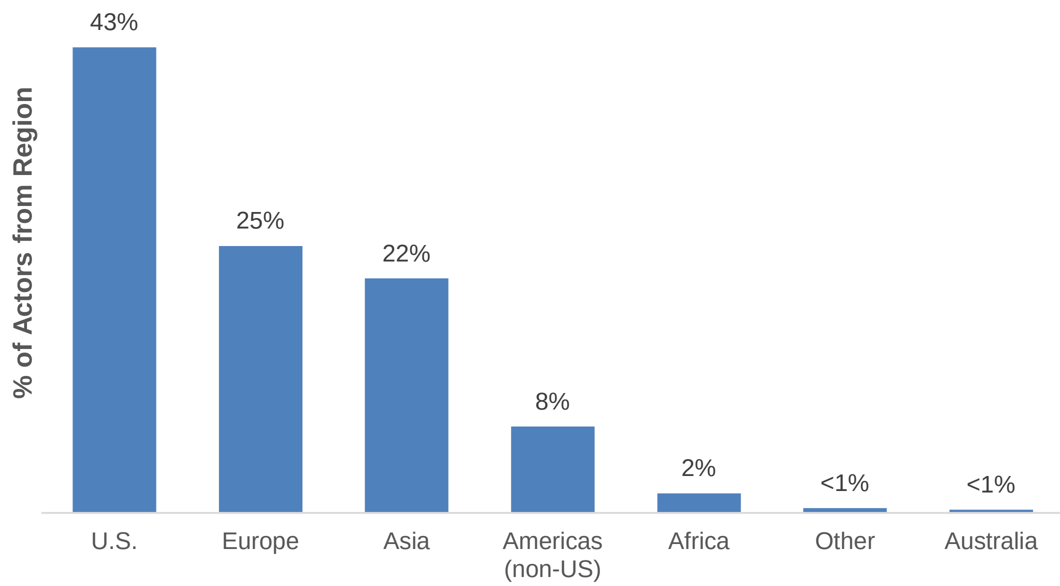
[13] Euroconsult, "Prospects for the Small Satellite Market," 2016.



Note: The distinction between government and academic actors in foreign nations is approximate; in certain nations the separation between academic and government institution may not be distinguishable. Further, there are numerous government actors active in the smallsat ecosystem in the United States; they are consolidated on this figure.

Figure C-2. Global Distribution of Smallsat Actors, Based on Indicated Headquarters (*n* = 664)

Although there is a concentration of activity in the regions specified above, many other countries are involved in the small-satellite ecosystem as well. Of the 70 countries identified, 27 were identified as having only a single organization involved in the small satellite ecosystem (mostly government or academic actors). Figure C-3 provides an overview of the regional breakdown of the organizations that were identified. For nations with small satellite actors, the greatest number had government actors, closely followed by academic; countries were found to generally enter the small satellite field through government or academic work, followed by industrial development (Figure C-4). Finally, 29 space agencies and 15 defense agencies were identified as being active in small satellites at the time of writing.



Note: In the database, Russia is classified as “Europe” and Middle Eastern countries are classified as “Asia.”

Figure C-3. Global Distribution of Smallsat Actors

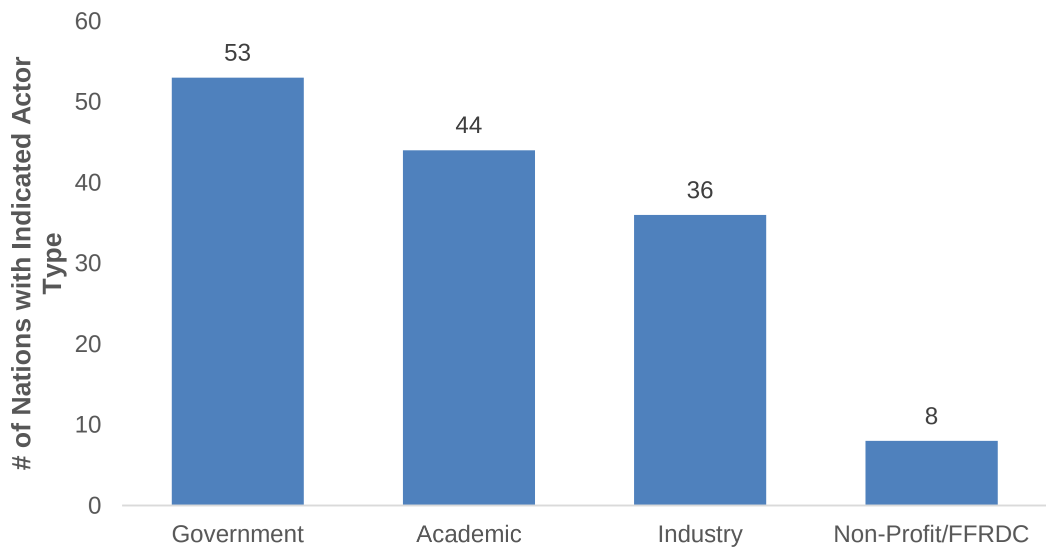


Figure C-4. Number of Nations with Actors in Each Type

In the course of developing this database, we found that many of these organizations rely upon global supply chains. For example, the Denmark-based small satellite manufacturer GomSpace has opened offices in both the U.S. and Singapore in hopes of securing defense contracts and access to emerging Asian markets in the respective countries; the company has secured both public and private contracts globally, in countries in North and South America, Asia, and Europe. Major commercial actors are supporting new global markets; emerging space nations are using the CubeSat standard to launch their first space activities (i.e., Costa Rica partnered with GomSpace to develop their first Space project, IRAZU[14]). Further, other nations are investing in small satellite companies in hopes of becoming technology development "hubs." U.S.-based asteroid mining company Planetary Resources has plans to open offices in Luxembourg after the nation invested money in the company. More information on these organizations can be found in Appendix G.

Globally, we identified a greater number of commercial institutions than any other actor type; in the United States alone, the breakdown skews further towards industry (Figure C-1). The 15 nations with the greatest number of organizations identified as active in the smallsat ecosystem are shown in Table C-1.

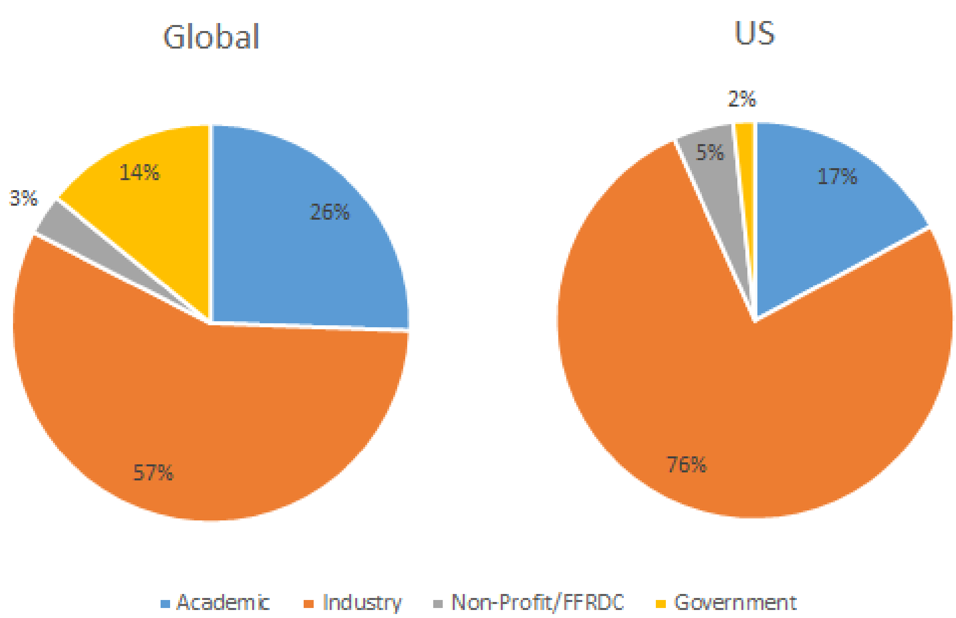


Figure C-1. Distribution of Actors by Type, All Countries

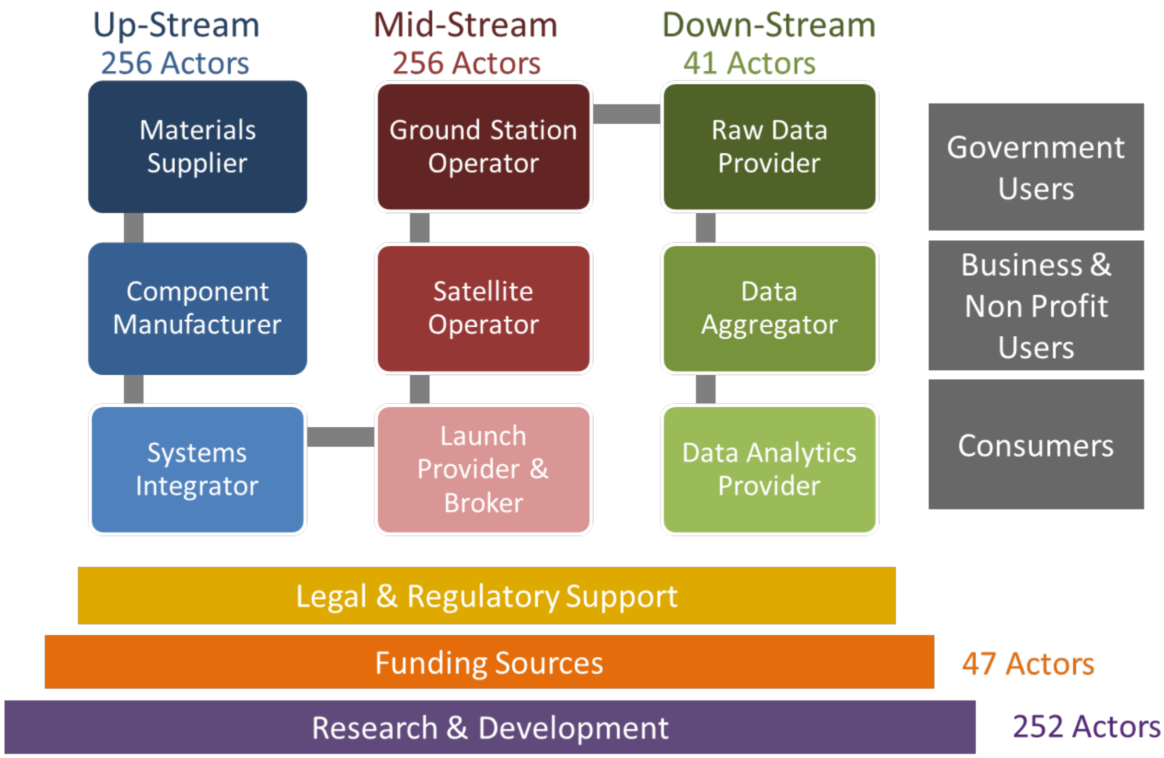
[14] M. G. Jenkins et al, "Irazú: CubeSat Mission Architecture and Development," September 2016, https://www.researchgate.net/publication/308804145_Irazu_CubeSat_Mission_Architecture_and_Development.

Table C-1. Countries with the Most Smallsat Actors (Top 15 Nations)

Nation	Academic	Government	Industry	Nonprofit, FFRDC	Total
United States	49	5	217	14	285
Japan	21	5	22	-	48
Russia	9	9	13	-	31
China	8	7	10	2	27
United Kingdom	2	2	20	1	25
Germany	7	1	12		20
Canada	2	2	15	-	19
Italy	4	3	8	-	15
Brazil	7	4	2	-	13
France	2	3	7	-	12
India	6	2	2	-	10
Spain	2	1	7	-	10
South Korea	7	1	1	-	9
Israel	1	2	5	1	9
South Africa	2	1	4	-	7

Smallsat Ecosystem Model

The STPI team developed an ecosystem model to identify and understand the relationships between the various actors engaged in the small satellite industry. The model is shown in Figure C-6, including the number of U.S. actors that were identified in our database. A second visualization is shown in Figure C-7; the figure provides an overview of the terminology used throughout this appendix to illustrate the ecosystem. The ecosystem is divided into three categories: the value chain, users and consumers, and foundational actors. The first category includes the value chain, with three sectors (upstream, midstream and downstream) that are broken down further into nine subsectors. The second category includes the users and consumers of small satellite data and services (gray boxes). Finally, a third category includes actors that provide the foundation necessary for the ecosystem, including research and development, funding sources and legal and regulatory support.



Note: Numbers are approximate, based on the STPI database. Actors can engage within one of the subsectors, or work across several subsectors (e.g. one actor may be counted towards both the up-stream and down-stream sectors).

Figure C-6. Small Satellite Ecosystem, by Subsector

The model itself is meant as a framework for understanding a rapidly growing and evolving industry. The level of activity varies across the ecosystem by actor. Whereas some actors are vertically integrated and engage across sectors by focusing their production (upstream) and operational (midstream) activities in-house, others focus on specific subsectors of the ecosystem (horizontal integration). Also, actors in the small sat ecosystem are not complacent in the evolving market. Companies are seeking new markets as they evolve and open into new subsector activity.

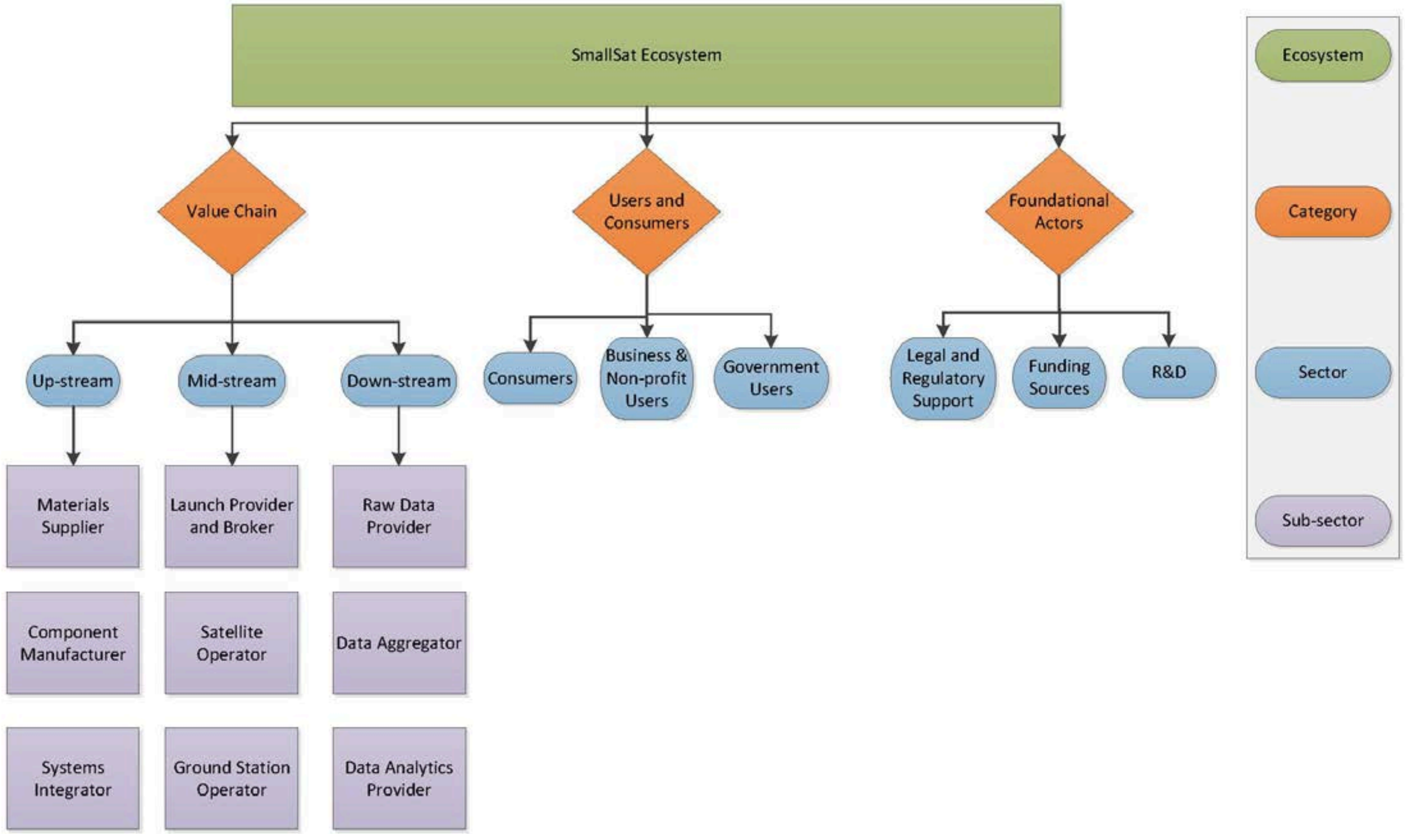


Figure C-7. Overview of Smallsat Ecosystem

The following section provides an overview of the interactions between the three categories of activity. To illustrate these relationships, the value chain is split between the upstream, midstream and downstream sectors. Subsequently, an overview is provided for the key funding mechanisms that are relevant to this ecosystem and the global distribution of activity.

Upstream Sectors: Creation of the Small Satellite

Upstream actors include material, component, subsystem, payload, bus and satellite (final integration) manufacturers and integrators. They are the organizations that design and manufacture small satellite systems, but do not necessarily operate them. Approximately 144 U.S. organizations were identified as active in this sector. Further discussion of the state of art of the technologies being developed can be found in Appendix D. Upstream activity is separated into the following subsectors:

Materials, Components, and Subsystem Suppliers

These actors develop and test input materials and components that go into payloads and satellite buses. Historically, most satellite materials were developed to withstand long-term exposure to radiation; however, given the prevalence of short-term missions in LEO (where radiation is not a major concern over the life of a mission), a number of vendors we spoke to are capitalizing on materials mass-produced for other terrestrial markets as inputs for building their small satellites. This can be seen in the activity of both veteran space companies, such as Nobel Aerospace Coatings, and non-traditional space suppliers, such as Poco Graphite, a materials company that is joining the space industry for the first time by manufacturing cheaper optics based on terrestrial products. Given increased demand from commercial operators for cheaper small satellites, a number of manufacturers are using commercial off-the-shelf (COTS) parts as inputs for their systems (i.e., computer hardware, cell phone batteries, and GoPro cameras); the PhoneSat CubeSat is one demonstration of how smallsat manufacturers are leveraging cheap consumer electronics from non-traditional space materials and component suppliers.[1] Another emerging trend is the "virtualized" or "software defined" satellites from companies such as Galactic Sky. Galactic Sky is developing a virtualized platform that could be used for operators to test different satellite designs and potential issues that may arise during the life of the satellites before the satellite is built, reducing the time traditionally required to take a satellite from a design concept to flight.

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1 Phonesat.org, "Phonesat," http://phonesat.org/.

Manufacturers

Manufacturers develop subsystems, buses, and payloads.[2] In addition to the hardware, numerous manufacturers develop software for the operation of satellites and their payloads (e.g., operating systems, data aggregation algorithms etc.). Throughout the data collection process, we identified a few unique business strategies for small satellite manufacturers; both provide benefits and limitations for companies in question. The two extremes are:

1. Horizontal integration: Organizations seek to develop market control across the manufacturing subsector, developing SOTA components and buses or low-cost commoditized parts and systems.
2. Vertical integration: Organizations whose operations span across up-, mid-, and downstream sectors, building, operating, and managing missions in-house.

A growing number of actors are specializing in the manufacturing sector alone, seeking horizontal integration within the smallsat market. In the commercial sector, there are a growing number of actors that are currently or planning to supply both commodity (e.g., Novawurks' Hyper-Integrated Satlet, a modularized uniform building block that houses power, thermal, and attitude determination and control subsystems) and specialized (e.g., GomSpace's development of unique sensor payloads for Hawkeye 360) components and subsystems. Many manufacturing start-ups emerge by developing and commercializing specific components and technologies (e.g., Accion and propulsion units), and then grow by expanding their portfolio of subsystem and platform technologies. For example, Blue Canyon Technologies began by developing and commercializing an ADCS system with an SBIR from the Air Force, and now the company has used the expertise they successfully developed and attracted to sell a wider array of smallsat products to increase revenue. (See the case study on Blue Canyon Technologies in Appendix G.)

Through the modularization and growing accessibility of space technology, countries no longer need homegrown development capabilities to operate in space.[3] Actors such as ISIS, Pumpkin, and Clyde Space publish catalogues of components and subsystems accessible to any actor, from a principle investigator at a University to an emerging space nation, which can be used to support missions. For example, small-satellite manufacturer Surrey Satellite Technology Ltd. (SSTL) designed, built, and launched a constellation of Earth observation satellites for their China-based client Twenty-First Century Aerospace

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[2] Subsystems are inclusive of all systems that are essential for the functionality of a smallsat (e.g., communications hardware, power, housing and shields, star trackers, magnetometers, computer and operating systems etc.). Payloads are separate instruments that are integrated into smallsats (e.g., sensors).

[3] Lal, et al., *Global Trends in Space, Volume 1*.

Technology.[4] Further, manufacturers like Denmark-based GomSpace are not only providing catalogues of components and systems, but are also providing systems design and management consultation for operators new to the space sector, allowing for actors and nations with no technical background to launch smallsat missions.

Finally, a growing number of smallsat operators are developing and manufacturing bus and subsystems in-house. Vertically integrated organizations provided a number of rationales for building in-house including reduced costs and increased control over product reliability and capabilities. We use Planetary Resources as an illustration of vertical integration in the sidebar below.

Planetary Resources

Planetary Resources is a vertically integrated company. The company develops most components, subsystems and buses for their needs in-house.

The motivation for developing in house includes the following:

- Lower cost: if a technology would be bought in high quantities, it is beneficial to build in-house if the costs of development are outweighed by the marked-up price of alternate commodity options
- Less reliance on supply chains: by building in-house, the company is less susceptible to fluxes in the supply chain (i.e., do not have to worry that a supplier would go out of business)
- Quality assurance: the company has control of the product from conception to completion, and thus can enact internal quality assurance methods; further it is easier to identify and solve component malfunctions for future missions

In the short-term, the company has developed a business plan to use and develop their asteroid prospecting technology to meet current Earth observation and SSA markets. The added income allows for the company to retain enough revenue to develop technologies in-house.

System Integrators

System integrators in the smallsat ecosystem incorporate components, payloads, and bus infrastructure into a final product (entire small satellite or larger subsystem) while also

4 P. B. De Selding, "Surrey to Build Three Optical Imaging Satellites for Chinese Firm," *SpaceNews*, June 29, 2011, http://spacenews.com/surrey-build-three-optical-imaging-satellites-chinese-firm/.

ensuring that subsystems function together properly. Actors in this subsector may conduct final testing and operation of the integrated system.

In the space community, integrators historically have been large primes that provide heritage and have the infrastructure in place, such as testing facilities and clean rooms, to support larger mission development (e.g., Airbus D&S and SSTL). While some of these large primes active in the large satellite community have shifted towards the smallsat ecosystem (e.g., Lockheed Martin through their contract with NASA to build and integrate the Lunar Imaging CubeSat[5]), a growing number of new or emerging actors are filling this subsector, becoming competitive against larger primes. For example, Clyde Space, a company with fewer than 100 employees, has onsite environmental testing, simulator technologies, and clean rooms capable of testing entire CubeSat systems up to 12U for clients.[6] Further, for vertically integrated companies, a number of actors are integrating and testing in-house or with close partners (e.g., OneWeb building, integrating and testing their smallsats through OneWeb Satellites, a partnership between OneWeb and Airbus).

Midstream Sectors: Operation of Small Satellites

The **midstream** actors include organizations that operate or own small satellites, are launch providers or brokers or are ground station operators.[7] Approximately 85 U.S. organizations were identified as active in this sector. Activity in the sector includes:

Launch Providers and Brokers

The smallsat launch subsector includes both launch vehicle operators and launch brokers that serve as the mediator between the launch vehicle operators and smallsat operators. This section examines the actors in the launch sub-sector and their role in the smallsat ecosystem.

Launch options for small satellites are currently dominated by the established markets and technologies that have been designed for large satellites and payloads. Small satellites launch options include rideshare, cluster launch, and piggyback launch. The rideshare and cluster launch missions launch a group of satellites of similar characteristics and orbit requirements on a single vehicle, while the piggybacking option allows a satellite to ride

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5 Lockheed Martin, “Picture Perfect: Lockheed Martin Finalizes Contract for NASA Lunar Imaging CubeSat,” August 8, 2016, http://www.lockheedmartin.com/us/news/press-releases/2016/august/ssc-080816-smallsat.html.

6 Expert interview.

7 The Tauri Group defines an active operator as one who has orbiting satellites, announced funding, signed launch contracts/agreements, or a NOAA license. See Satellite Industry Association (SIA), *State of the Satellite Industry Report*, September 2016, http://www.sia.org/wp-content/uploads/2017/03/SSIR-2016-update.pdf.

as secondary with a large primary payload, who controls the launch schedule and delivery orbits.

Rideshares and piggybacking missions are more economical for small satellites than dedicated launches, however, impose restrictions in terms of integration and launch schedule, orbit destination and subsystems incorporated in the small satellite (i.e., restrictions on type of propellant carried, available payload volume, etc.). Small satellites can get to orbit for a fraction of the cost of a full launch service because they do not need to procure a dedicated launch vehicle. Large launchers, such as ULA with the ESPA ring[8] and Spaceflight Industries with SHERPA (to be operational in 2017),[9] have developed multiple rideshare interface capabilities to accommodate small payloads on heavy and medium lift rockets. Launch brokerage companies, such as Spaceflight Industries, ECM space, TrySept, Tyvak and Innovative Solutions in Space (ISIS), have emerged to facilitate the launch process for smallsat rideshares[10] and leverage existing relationships with launch providers (e.g., help with integration, paperwork, interaction with the launcher, etc.). There are brokers, such as Spaceflight Industries,[11] who might buy their own rocket to avoid launch schedule and orbit restrictions imposed by a primary payload. Spaceflight Industries also have developed online platforms to expedite the process and reach more customers; the site provides basics such as pricing estimates, available launch vehicles, mass thresholds, and orbits.[12] Current small satellite launch options, although more economical than dedicated rides, cannot offer on-demand service.

[8] In the early 2000s the ESPA ring was developed, with support from the AFRL and DOD Space Test Program, allowing the integration of satellites up to 180 kg in mass as secondary payloads on the Atlas V and Delta IV rockets. Moog, "ESPA: The EELV Secondary Payload Adapter," accessed February 20, 2017, http://www.moog.com/literature/Space_Defense/Vibration_Control/MCSA_ESPA.pdf.ULA offers multiple rideshare interface capabilities for spacecraft ranging from 1 kg to 5,000 kg to ride on their family of launch vehicles (the Atlas, the Delta YY and the Delta IV). K. Karuntzos et al., "United Launch Alliance Rideshare Capabilities for Providing Low-Cost Access to Space," In Aerospace Conference 2015, IEEE, 1–9..

[9] Spaceflight Industries produces SHERPA, a custom ESPA Grande ring outfit with custom payload adapters and dispenser systems, designed for hosting secondary payloads. SHERPA operates on one of three nodes: as a non-propulsion free flyer spacecraft, as a propulsive free flyer spacecraft and as a non-separating payload adapter. (http://www.spaceflight.com/sherpa/).

[10] See Appendix C.

[11] Spaceflight purchased a SpaceX Falcon 9 and sold 80 small payload slots to the community.

[12] Spaceflight, "Schedule and Pricing," accessed February 20, 2017. http://www.spaceflight.com/schedule-pricing/.

CubeSats could also be deployed from the ISS by a dispenser operated by NanoRacks[13] or JAXA, after being transported to the station via ULA, SpaceX, JAXA, and Orbital ATK cargo flights (Atlas V/Cygnus, Falcon9/Dragon, Antares/Cygnus or H-IIB/HTV). China continues working on the establishment of a permanent space station,[14] which could offer low-cost or even free deployment of CubeSats in the future**.** The deployment from a space station has advantages: it is cheaper than rideshares, the smallsat can be stored in the space station and launched whenever needed, and the vibration tests that they need to pass are less rigorous than when piggybacking due to the way they are packaged on the cargo spacecraft.[15] However, the deployment orbit is limited to the altitude and inclination of the space station, which has an impact on the CubeSats life (typically 2-3 months). CubeSats made by student teams and university researchers are launched for free as secondary payloads on Federal Government launches.[16] In addition, ULA sponsored a program in 2016 offering universities the chance to compete for six CubeSat launch slots on two Atlas V launches aiming at eventually offering free rides on any of its launches.[17] CubeSats can rely on a larger variety of economical options for launching when compared with larger smallsats although still subjected to orbit and schedule restrictions.

The United States launched over 60% of the satellites between 2013 and 2015[18] weighing less than 50 kg and 25% between 50 and 500 kg. China, Russia, and India all together launched 30% of satellites less than 50 kg and 66% of the ones between 50 and 500 kg (Figure C-8). U.S. small satellites are currently banned from launching from China, Russia and India, although petitions are considered on a case-by-case basis.[19] Many operators use non-U.S. launchers due to attractive price and availability. Parsing the data differently, over 90% of small satellites weighing less than 50 kg, and 63% of small satellites weighing between 50 kg and 500 kg were launched by commercial entities. All

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[13] As of March 2016, over 350 payloads have been launched from the ISS via NanoRacks services http://nanoracks.com/wp-content/uploads/NanoRacks-Release-48-NanoRacks-Deploys-Over-100-CubeSats-From-ISS.pdf

[14] Xinhuanet, “China’s Space Activities in 2016,” http://news.xinhuanet.com/english/china/2016-12/27/c_135935416_3.htm

[15] https://www.nasa.gov/mission_pages/station/research/benefits/cubesat.

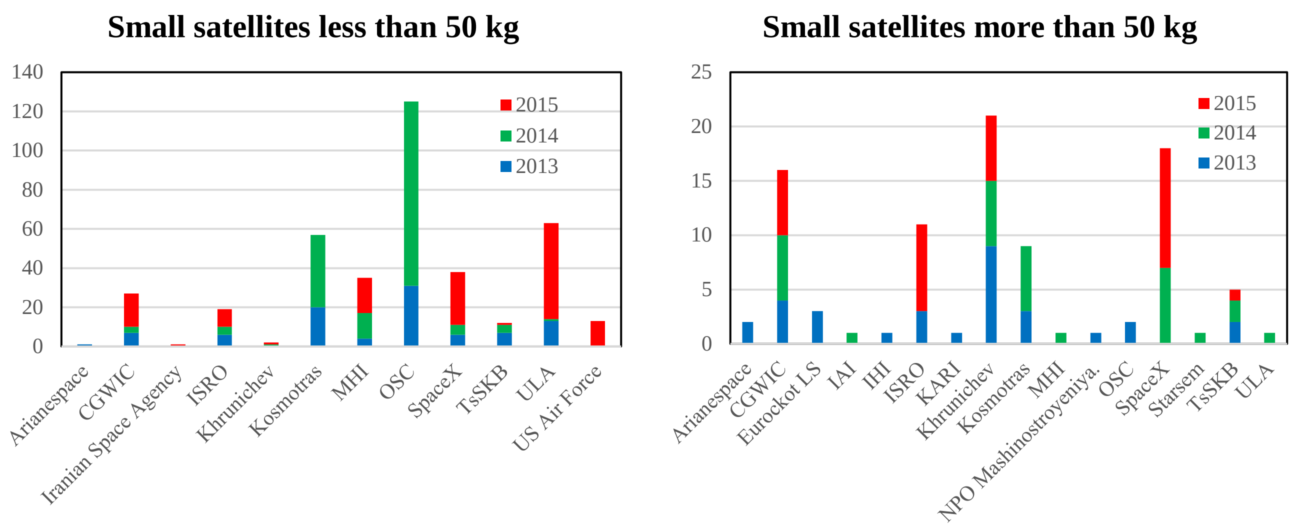
[16] A. K Nervold, J. Berk, J. Straub, and D. Whalen, “A pathway to small satellite market growth,” Advances in Aerospace Science and Technology, 2016, 1, 16-20.

[17] ULA, “United Launch Alliance,” http://www.ulalaunch.com/.

[18] Around 64% of the small satellites launched between 2006 and 2015 were launched between 2013 and 2015.

[19] In February 2017, an Indian rocket launched 88 CubeSats for Planet and 8 were CubeSats for Spire; previously Indian rockets have launched Terra Bella and Spire satellites. http://indianexpress.com/article/india/isro-satellite-rocket-launch-live-updates-video-cartostat-planet-4525639/.

the launches were as rideshares or secondary payloads so all of these small satellites were subjected to the restrictions described in this section.



Source: Euroconsult, “Prospects for the Small Satellite Market,” 2016.

Figure C-8. Main Launch Service Suppliers for Small Satellites between 2013 and 2015

One of the challenges for small satellites with regard to launch is the lack of on-demand access to space. This concerns mainly constellations because they might depend on fast access to space for replenishment when satellites fail or when technology refresh is required,[20] to continue providing services.[21] Thirty-four companies and government institutions (13 are domestic and 21 are international[22]) are developing small satellite launchers to LEO[23] to address the anticipated high demand for small satellite launches over the next ten years. Twenty-two of the 34 companies are planning to become operational between 2017 and 2021 and span a wide range of Technology Readiness Levels (TRLs), with the Pegasus XL having extensive flight heritage (TRL 9), the Electron from Rocket

20 Assembled from various sources including C. Niederstrasser, “Small Launch Vehicles—A 2015 State of the Industry Survey.” 29th Annual AIAA/USU Conference on Small Satellites, 2015; D. Lim, “Small Launcher Market Survey—Where Are We and Where Are We Going?” Room, October 2016; D. Messier, “A Plethora of Small Satellite Launchers” Parabolic Arc, October 2016; and company websites.

21 Hughes faces capacity constrains due to delay in the launch schedule for their next upgrade. “Satellite Internet in the Mobile Age”, Hanson, W.A., Stanford University. 2016

22 Twelve in Europe, three in China, two in Russia, two in Japan, one in Canada, and one in Argentina.

23 All the companies are focused on LEO orbits. Based on the Euroconsult report, 2016 97% of small satellites planned over the next ten years would be operating in LEO. There is very limited market demand for GEO small satellites.

Lab with extensive ground tests and getting ready for flight tests (TRL 5-6),[24] and the SABRE engine from Reaction Engines on early stage design at TRL 3 and TRL 4 for some components.

Smallsat Operators

Small satellite operators include the owner or principle investigator associated with a smallsat mission. A large number of operators span across the public sector (e.g., defense and civil government agencies, academic institutions) and the private sector. Operators use the smallsat platform for a variety of applications including remote sensing (Earth Observation and Situational Awareness), technology demonstrations, science and exploration, communications, and space situational awareness. As expressed by Tauri Group's Carissa Christensen.

> There's not one sensor, not one constellation, that's going to answer all of our problems. It's going to take a portfolio of technologies and a portfolio of providers.[25]

This combination of sensors and constellations provides a wealth of insight and solutions and has attracted the interest of commercial terrestrial market actors (e.g., global product distributors like Coca-Cola) and civil and defense actors (e.g., those in weather or signals intelligence). These applications are discussed further in Appendix F.

We identified a range of operators, each with different business plans and revenue sources. In addition to academic and government missions focused on research and development, there is a wide variety of commercial operators. They include VC-backed start-ups with ambitious ideas, companies currently developing new technologies and applications, and established organizations that are operating small satellites and generating revenue. Operators either focused their efforts entirely in the operating subsector (horizontal integration) or were active across multiple subsectors (partial to full integration); an example of two companies at each extreme is shown in Figuer C-9.

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[24] C. Henry, "Rocket Lab Declares Electron Ready for Test Flights," December 19, 2016, Space.com.

[25] J. Foust, "Big Data a Big Market for Small Satellites," *SpaceNews*, November 22, 2016, http://spacenews.com/big-data-a-big-market-for-small-satellites/.

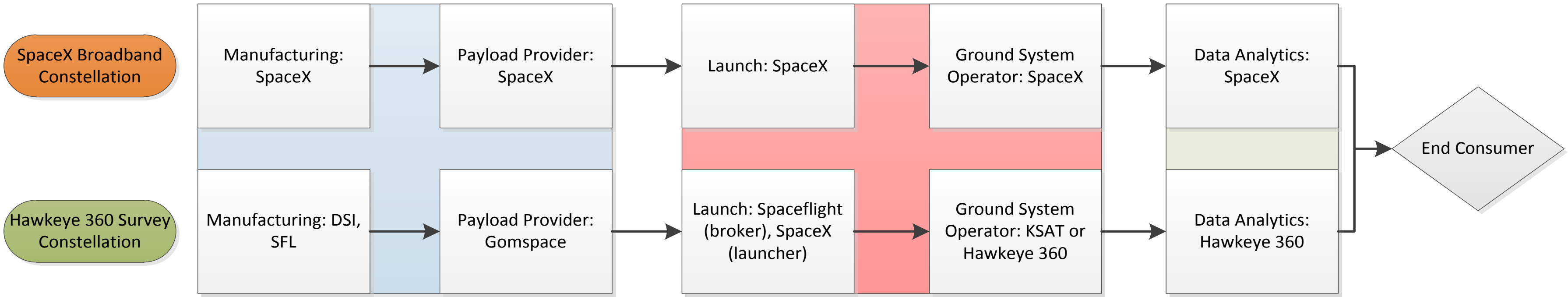
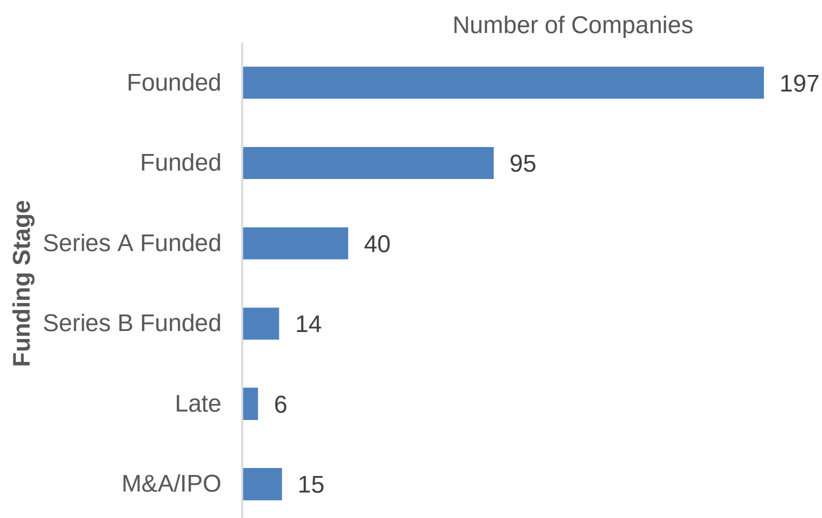


Figure C-9. Example of Vertical and Horizontal Integration

The growth of VC investment in the New Space sector, has supported a growing number of start-ups in the smallsat ecosystem, particularly in the operator subsector. The following discussion about the various development stages for start-ups, although specific to operators, is representative of broader trends in the smallsat ecosystem across other sectors and subsectors.

Many operators in the smallsat ecosystem begin as start-ups with ambitious ideas on paper; the organizations operate off money sourced from VC and angel investors, funds from the founders, or contracts with government or private organizations. Although there are a large number of these actors globally, there is a high attrition rate as numerous entrepreneurs are unsuccessful in developing promised technology and capabilities, capturing additional investments and contracts, or meeting market needs (Figure C-10).



Source: Adapted from Tracxn, "NewSpace Sector Report 2016," December 2016, https://blog.tracxn.com/tag/newspace-sector-report-2016/.

Figure C-10. High Attrition Rate of New Space "Start-Up" Companies; First Commercial Deals Are Made at the Series A and B Funding Stages

The growth of the Earth observations operator, Terra Bella, illustrates the stages of development. The company, then called Skybox Imaging, was developed by four Stanford students in 2009. As is typical for many Silicon Valley smallsat start-ups, the company began by securing early funding (Series A) from early investors (Khosla Ventures) to implement and prove the feasibility of their business plan with the development of technology and code; after going through additional funding rounds (Series B and C), the company launched its first satellite in 2013. The company continued to grow, launching more assets and securing a contract with satellite manufacturer SSL, and then was acquired by Alphabet in 2014 and then Planet in 2017.[1] A company often becomes commercially viable after securing Series A and B funding, although still continues to rely upon contracts, grants, and other revenue streams to remain active in the smallsat ecosystem.

Once operator start-ups have secured early stage funding, companies continue to prove their technologies but more importantly identify downstream consumers; the markets served, downstream, may fluctuate with the demands of terrestrial markets. Planetary Resources provides a unique example of a company with a long-term business plan, to prospect and mine asteroids, which they had planned to support by working in the short term in Earth observations, where there is current demand. The company had been developing an Earth observations constellation to both test its sensor technology and secure additional revenue from EO data consumers, but has recently decided to focus on its deep space mission.[2]

Ground Station Operators

Ground station operators provide monitoring services (telemetry, tracking, and command services), data download and acquisition services, and other satellite-ground communications services. Additionally they maintain the associated ground station infrastructure. Ground station operators are often the main consumers or producers of the relevant operation software.

Current ground station operators that serve the smallsat community include both large actors, that have adapted existing infrastructure, and emerging start-up actors. Ground station providers that have traditionally supported larger satellites, such as KSAT, are now moving into the smallsat market. For example, to remain cost-competitive, KSAT has altered its network to create a KSAT Lite network. Using this network, once they fulfill a few technical standards, smallsat operators have the option to either have an expensive fixed 24/7 connection with their assets (traditional) or a new shared service (fluctuating connection speeds based on loading in the region and time of day; the smallsat is also not in constant connection with the ground station).

Additional start-ups have emerged, developing ground systems for smallsat constellations. For example, Italian start-up Leaf Space, after securing $1.1 million in funding from Italian investors, is developing a 20-station global smallsat ground network.[3]

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[1] Terra Bella, “Our History,” accessed February 20, 2017, https://terrabella.google.com/?s=about-us&c=about-history.

[2] https://ac.arc.nasa.gov/p1sgypdg9d6p/?launcher=false&fcsContent=true&pbMode=normal&proto=true

[3] C. Henry, “Leaf Space Raises $1.1 Million for Dedicated SmallSat Ground Station Network,” *Via Satellite*, July 11, 2016, http://www.satellitetoday.com/publications/st/2016/07/11/leaf-space-raises-1-1-million-dedicated-smallsat-ground-station-network/.

A Japanese start-up, Infostellar, is developing a brokering system to connect operators with under-used ground station networks.[4] Additionally, a few satellite operators, including Spire and Planet, have developed their own ground systems. The subsector is growing through the re-use and re-configuration of old ground station infrastructure and the development of low-cost alternatives (both in-house and externally; for example, BCT is operating one of their satellites from a single antenna installed on the roof of their headquarters).

Downstream Sectors: Bringing Satellite Data to the Market

Downstream actors bring small satellite data to both space and non-space markets, and often integrate small satellite data with other data sources. Approximately 35 U.S. organizations specifically working with smallsat data were identified as active in this sector. Subsectors are presented as mutually exclusive to illustrate the various *activities* occurring in the downstream sectors; however, many organizations in the downstream sectors currently engage in a number of these activities, and thus are often active in more than one of the three presented. These sectors include:

Raw Data Providers

Raw data providers are the source for minimally processed small satellite data; after collection, raw data is subsequently sold directly to the end-consumer or processed further by downstream actors. Raw data is typically in the form of imagery and video (hyperspectral, multispectral, IR, Vis), radar (e.g., synthetic aperture radar), or other signals (radio-occultation [RO], radio frequency [RF], and Automatic Identification System [AIS]). Additionally, some operators allow customers to directly task satellites to secure specific data sets (e.g., Twenty First Century Aerospace Technology allows clients to task their constellation of EO smallsats). Additionally, commercial raw data providers typically provide or sell access to archives of their data, particularly imagery (e.g., Planet has Planet Archive, which shares all the images collected by Planet satellites).

Actors include operators, who provide data directly from their satellites to downstream data analytics organizations (e.g., operator Planet sells imagery directly to NGA[5]), and data brokers, who serve as a third party to deliver raw data from operators to interested clients for further analysis (e.g., Orbit Logic, through its SpyMeSat smartphone

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[4] T. Romero, "Japan's Airbnb for Satellites—InfoStellar," Disrupting Japan, October 11, 2016, http://www.disruptingjapan.com/japans-airbnb-satellites-infostellar/.

[5] NGA, "NGA Introductory Contract with Planet."

application, allows end-consumers to request and task satellites to take an image of a specific region[6]).

Data Aggregators

Data aggregators collect and integrate data from a range of different sources, for subsequent analysis. Data sources may include numerous small satellite operators, or actors outside the smallsat ecosystem that provide data from large satellite and hosted payloads, unmanned aerial vehicles, planes, and social media feeds. In most cases, aggregation is a precursor to analytics, as the examples below illustrate.

A number of companies that aggregate data that were identified work entirely in the realm of satellite data. Companies such as the Vancouver-based UrtheCast, currently aggregate data from multiple satellite sources to develop their geospatial analytics-based platform;[7] this proof of concept would enable the company to secure further funding to deploy a planned constellation of Earth observation smallsats, which would use a modified version of their current analytics-based platform.

Further, a growing number of actors that previously worked with satellite or non-satellite data are now turning to data sourced from smallsats to supplement their data sets. For example, Descartes Labs, a data analytics company that aims to provide agriculture crop-yield projections, aggregates data from large government satellites and smallsat operators such as Planet.[8] Further, government intelligence agencies such as NGA and civil agencies such as NOAA are integrating commercial smallsat data sources to augment data-sets and models.[9]

Finally, other data aggregators are aggregating smallsat data with non-satellite data streams (social media feeds, UAV imagery, LiDAR, etc.) to provide insights to clients. For

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[6] Currently the satellites that can be tasked are only large satellites, however based on an interview with a representative from the company, the service could easily use data from small satellites, especially as the number of operators and smallsat assets in-orbit increase. As this company is collecting data from multiple satellites, they could also be regarded as a data aggregator. More information is available at http://www.spymesat.com/.

[7] UrtheCast, "A New Kind of Earth Observation," accessed February 20, 2017, https://www.urthecast.com/.

[8] Medium, "This Company Is Using Satellite Imagery & Deep Learning to Predict a $67B Corn Market," December 21, 2015, https://medium.com/planet-stories/this-company-is-using-timely-satellite-imagery-and-deep-learning-to-predict-a-67-billion-u-s-7346bd0f3643#.lpfj3at41.

[9] White House, "Harnessing the Small Satellite Revolution to Promote Innovation and Entrepreneurship in Space," October 2016, https://obamawhitehouse.archives.gov/the-press-office/2016/10/21/harnessing-small-satellite-revolution-promote-innovation-and.

example, U.S.-based BlackSky is currently integrating data from smallsats operated in-house with data from social-media feeds to provide insights on socio-political trends.[10]

Data Analytics Providers

Data analytics providers convert small satellite data (or aggregated data) into useful insight for end-consumers. Various analytical methods are employed, including machine learning, predictive modeling, and change detection algorithms. Insight products range from 3D maps of terrains, to asset telemetry and tracking, prediction of political and military conflicts, economic or crop forecasting, and others. Data analytics companies may source raw data or aggregated data internally, or rely upon other providers through contracts.

A variety of organizations are engaged in this subsector. For example, BlackSky Global, that plans to deliver products directly to end-users, analyzes aggregated data (from satellites, unmanned vehicles, and social media) with proprietary algorithms to develop reports for multinational corporations on political and social stability in a given region. Another organization, Terra Bella, before being acquired by Planet, planned to convert satellite data into business insights, indicating the size, location, or change in an asset of interest. Additionally, organizations such as the Norwegian company KSAT are directly supporting government agency needs, using satellite imagery for resource management, monitoring and enforcement (e.g., tracking illegal fishing off the coast of Australia).Companies such as Orbital Insight provide a web-based geo-analytics platform for users to mix and match various satellite data types to extract global trends. Lastly, the U.S.-based company Spire will be utilizing GPS-RO data to inform weather predictions, and AIS to track marine assets.

Funding Mechanisms for Emerging Companies and Missions

This section examines the funding mechanisms that have led to the growth of the smallsat ecosystem. Similar to trends examined in the prior discussion of the value chain (up-, mid-, and downstream actors), new and existing actors have joined the smallsat ecosystem as funders. These funders, both in the private sector and public sector, have been paramount in the development of technology to aid in up-, mid-, and downstream activities and to provide the capital necessary to manufacture, launch and operate smallsat missions and constellations.

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[10] Expert interview.

A Conceptual Framework for Understanding the "New Space" Funding Mentality

The evolution of the smallsat ecosystem has been driven by changes in the greater space industry as new public and private mechanisms have emerged to enable space activities. Historically, space activities were funded by major government bodies like NASA and ESA or large institutional bodies like defense contractors Lockheed Martin and Northrup Grumman. These missions were characterized by highly specialized and risk adverse systems that resulted in high per-unit mass and costs; markets were driven by contracts between business and government or between space firms.[11]

Recently, with the emergence of the "New Space" era, this paradigm has shifted. Large investments by private sources (e.g., Google, Coca Cola) paired with mass production methodologies have driven down mission costs, while the market has shifted to focus on relations between businesses and customers as space firms have paired with big data firms to deliver data to meet the needs of terrestrial markets.[12] Within the satellite industry, the emergence of the smallsat, particularly the CubeSat standard, has been one driver to this new paradigm. In the Earth observation market, venture-backed start-ups have launched constellations of satellites, enabled by technologies developed internally (e.g., Planetary Resources' sensor technology) and through government-funded SBIRs (e.g., Blue Canyon's state-of-the-art ACDS subsystem developed through an AFRL SBIR). The market has paired space firms and operators (e.g., Planet, Digital Globe) with big data firms (e.g., Google) to deliver data for terrestrial needs ranging from agricultural to business insights.

To understand the funding mechanisms that serve as a foundation to the smallsat ecosystem, two cycles would be examined, the cycle of technology development and the cycle of a company's life. In the evolving smallsat ecosystem, these cycles are not mutually exclusive. For example, the early years of many smallsat start-up operators are "high risk" due to the need to develop technology to meet mission needs (e.g., Planetary Resources developing sensor technology to eventually meet their asteroid mining mission needs).

The first cycle, of technology development, can be understood against the well-developed concept of technology readiness levels (TRL) which designates the state of a technology's development.[13] In the smallsat sector, early stage research (approximately TRL 1-3) is often funded by governmental institutions like NASA and DOD in the United States and like ESA and JAXA internationally; this is a result of long development cycles

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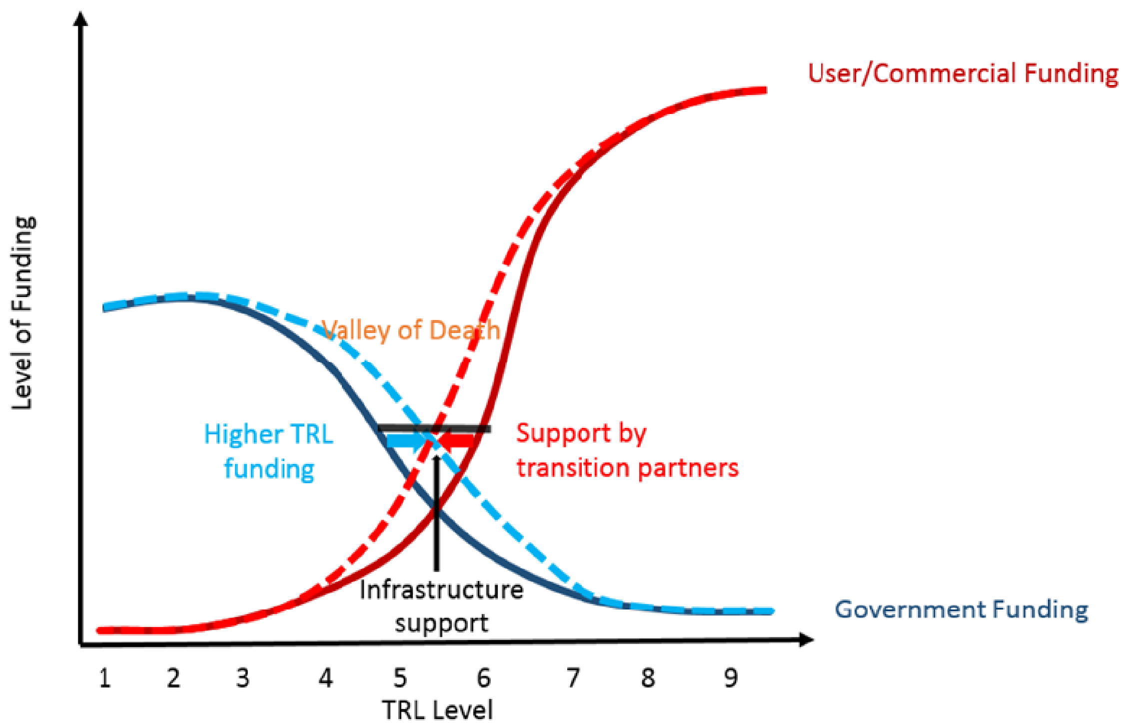
[11] Mazzucato and Robinson. *Market Creation and the European Space Agency*.

[12] Mazzucato and Robinson. *Market Creation and the European Space Agency*.

[13] B. Lal et al., "Trends in Small Satellite Technology and the Role of the NASA Small Spacecraft Technology Program," March 2017.

for technologies that do not have immediate commercial potential.[14] A conceptual model for commercial and government funding across TRL stages, is shown in Figure C-11.



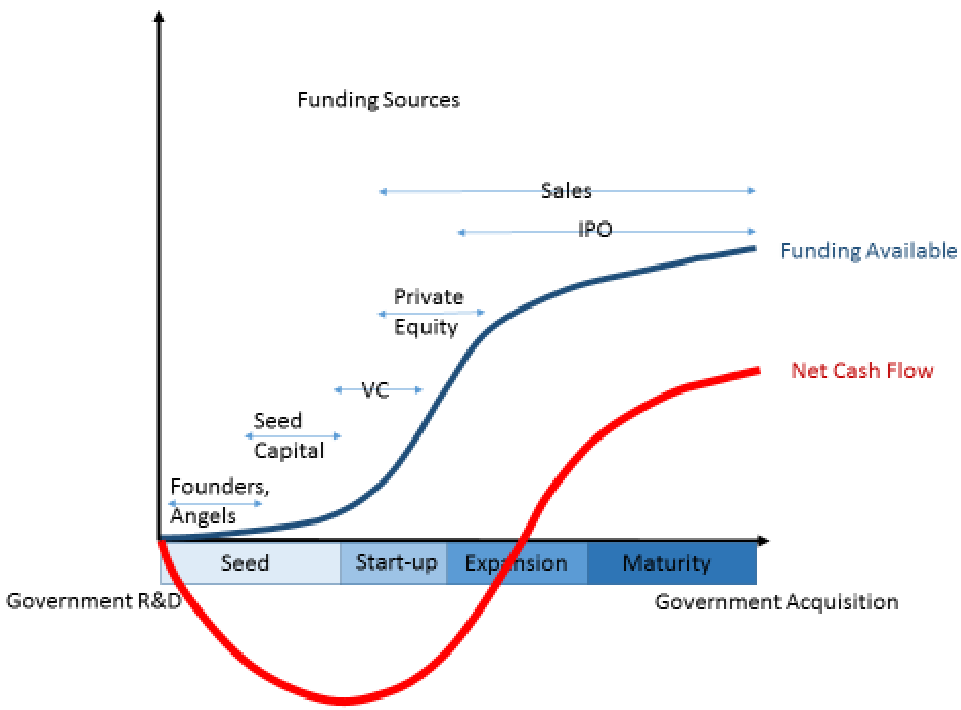
Source: Adapted from NSF Engineering Research Centers, "Building an Innovation Ecosystem," November 4, 2012, http://erc-assoc.org/best_practices/53-building-innovation-ecosystem.

Figure C-11. Conceptual Diagram of Public and Private Investment in Technology R&D

Illustrated in the example of Terra Bella, discussed in the prior section in the overview of the operator subsector, the second cycle encompasses the lifecycle of commercial "start-up" actors. To develop as an organization, start-ups depend on a number of different funding sources as illustrated in Figure C-12. The early years of an organization depend on early "seed" money from either government R&D contracts and grants, or private investors (i.e., money sourced from the founders or angel investors). As the organization develops and expands, additional resources sourced from venture capital (VC) and private equity support capital expenditures (i.e., office space, manufacturing facilities or additional staff) that allow the organization to secure contracts with interested clients. Once organizations reach a positive cash flow, companies would either continue to increase operations and sales, maybe even acquiring or partnering with other start-ups to expand operations (e.g.,

[14] B. Lal et al., "Trends in Small Satellite Technology and the Role of the NASA Small Spacecraft Technology Program," 2017.

GomSpace's acquisition of propulsion start-up Nanospace[15]) or may "go public," through an initial public offering (IPO), often to secure further funds for expansion (e.g., GomSpace becoming publically traded in early 2016 to gain capital for investment in technology development, building new facilities, doing M&A operations, and starting subsidiaries[16]).



Source: Adapted from D. Taylor, "The Next Wave of Space Investors," *Space News*, August 29, 2016, https://www.spacenewsmag.com/capital-contributions/the-next-wave-of-space-investors/.

Figure C-12. Funding Mechanisms for New Companies in the New Space Industry

This section provides an overview of various funding mechanisms and actors across the public and private sector. Table C-2 provides an overview of the types of investors active in the smallsat ecosystem.

15 Swedish Space Corporation (SSC), "NanoSpace Becomes Part of GomSpace," October 17, 2016, http://www.sscspace.com/news-activities/all-news-archives/2016/nanospace-becomes-part-of-gomspace.

16 See the GomSpace case study in Appendix G for more information.

Table C-2. Investors Engaged in the Smallsat Sector in the Public and Private Sector

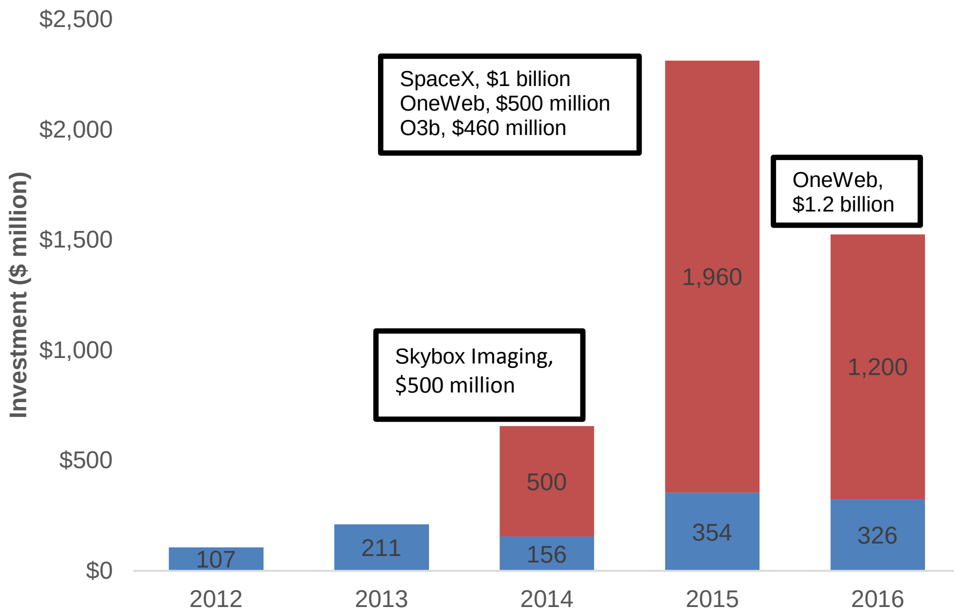
	Type of Investor or Mechanism	Overview of Investor	Example (Investor, Company)
Private Sector	Angel Investors	Often high-wealth investors that invest early in a company's life.	Elon Musk, SpaceX; Space Angels, Accion Systems
	Venture Capital (VC)	A dedicated group of investors that identify high-risk, high-return companies to invest in; usually based off a managed fund	Bessemer Venture Partners, Spire
	Corporate Venture Capital and Investors	A subset of VCs; may support relevant R&D efforts of interest to the company, or to develop strategic partnerships	Coca Cola and Bharti Enterprises, OneWeb
	Private Equity Investors	Large investment houses that often invest in relatively established companies, either through equity or debt financing.	Google and Fidelity, SpaceX
	Public Markets	Companies raise money once they "go public" (IPO), allowing for a portion of the company to be owned publically.	Public Market (Nasdaq First North Premier), GomSpace
	Internal Funds	Funds secured through contracts, non-equity partnerships and other means.	SpaceX, proposed broadband constellation
Public Sector	Grants (e.g., SBIRs in the United States)	Grants are awarded by government institutions to support both private and public (e.g., academia) endeavors	Air Force SBIR, Blue Canyon Technologies
	Contracts and Public-Private Partnerships	Contracts are often awarded by governmental and academic actors to companies across all sectors.	NGA, Planet
	Internal Funds	Internal funds (e.g., IR&D) are used within public agencies to support technology and mission development	NASA IR&D funds, NASA Centers
	In-direct support (e.g., tax incentives)	Governments support actors through in-direct investments including subsidized launch options and tax incentives for manufacturing facilities	India (subsidized launch), Berlin Space Technologies (potentially opening manufacturing plant in India)

Notes: Additional information on funding mechanisms can be found in the following reports related to private funding mechanisms and U.S. public funding mechanisms in the smallsat ecosystem respectively: Tauri Group, *Start-Up Space: Rising Investment in Commercial Space Ventures*, January 2016, https://brycetech.com/downloads/Start_Up_Space.pdf; B. Lal et al., "Trends in Small Satellite Technology and the Role of the NASA Small Spacecraft Technology Program," March 2017.

Private Sector Funding Mechanisms

This section examines the role served by the different types of private funders, outlined in Table C-2, in the smallsat ecosystem. In the private sector funding is either sourced from investment vehicles, often in the early stages of a company's life, or contracts and internal funds. Figure C-13 provides an overview of recent private investments in the

New Space industry; a majority of funds were invested in a small number of smallsat companies.



Source: Adapted from CB Insights data, accessed December 2016. https://www.cbinsights.com/

Figure C-13. Venture Investment in New Space Start-Ups, 2012–2016

Private Investment Vehicles Drive the Early Stages in an Organization's Life

The recent activity of private investors in the smallsat industry has enabled a number of companies in the smallsat ecosystem to advance in their business efforts. Over the next 10–15 years, the continued growth of the ecosystem could continue to attract additional investment, as described below by angel investor Dylan Taylor.

> Even though the NewSpace industry has a long way to go before it sees venture capital interest on par with software and other hot technology sectors, the groundwork has been laid that would lead to another wave of investors likely entering the industry in the next few years. Namely, private equity sources.[17]

Beyond capital investment from these investors, start-ups benefit from strategic guidance, facilitated discussion and introductions to other investors, and access to both technical and financial expertise.[18] Investors invest in a portfolio of companies, expecting

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[17] D. Taylor, "The Next Wave of Space Investors," *SpaceNews Magazine*, August 29, 2016, https://www.spacenewsmag.com/capital-contributions/the-next-wave-of-space-investors/

[18] Expert interview.

high margin returns on only a small portion of the companies they invest in; multiple interviewees gave a success rate of 10% of the portfolio as one benchmark.

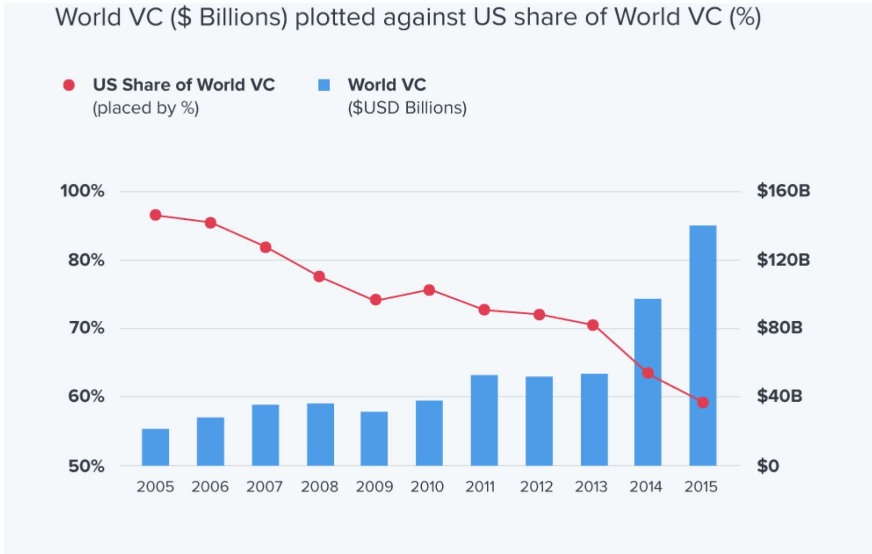
Angel, seed and venture capital investors invest early in companies. Start-ups of interest are often led by entrepreneurs seeking to commercialize innovative technologies, ideas and business plans. Investors place particular interest in companies that are seen as potential "disrupters," companies that, upon commercialization, could shift or open new markets and industries, thus having a high return on investment.

To determine whether or not a company is viable and realistic, one interviewee provided a step-wise framework that investors utilize. The following questions are asked.

- Does it work? Particularly of interest in the space industry, a preliminary technological analysis is completed to understand the feasibility of proposed technology (e.g., can the technology actually be developed without breaking basic laws of physics?)
- Does anyone want it? One examines, simply, whether or not the company's product is desired by any consumers.
- Are there a lot of those people? One examines the size of the market demand, whether current or projected, for the company's product. (e.g., are there enough customers, consistently, to purchase the product or service?)
- Can you find them? If there is a demand and a market, this step is crucial for examining whether or not the product can be commercialized. Strategies for bringing the product to market, the amount of marketing necessary to connect to identified customers, and other basic supply-chain economics are examined.
- Is timing realistic? Particularly relevant in the space industry, companies are examined to see if they are capable of becoming profitable, but not necessarily fully operational, within a reasonable timeframe (5–7 years).

Overview of the VC Community

In the overall VC community (inclusive of "New Space" actors), although a majority of venture capital remains in the United States, recent trends indicate that foreign VCs are becoming more prevalent as the field overall grows (Figure C-14). Whereas most American VC capital is focused to Silicon Valley and other domestic innovation hubs, foreign VC investments are distributed across various nations and regions. One major benefit for foreign VC firms, outside the United States and Canada, is that they are likely to be focused on the global market given that there currently is no single market that compares in size to the United States, thus most start-ups, say Argentina's Satellogic, are thinking about markets outside their nation in order to attract foreign investors (who may not be as knowledgeable on local economies and markets).



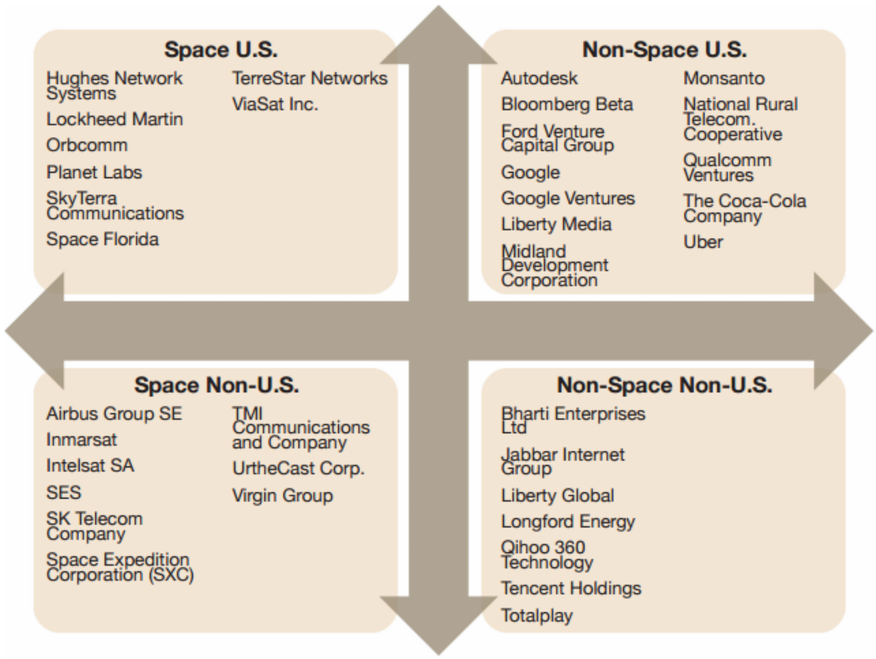
Source: C. Steiner, "International Venture Capital would soon Pass That of United States," Funders Club, August 30, 2017, https://fundersclub.com/blog/2016/08/30/international-venture-capital-will-soon-pass-united-states/.

Note: The figure provides an overview of the Venture Capital market generally, and is not specific to space.

Figure C-14. U.S. Share of World Venture Capital

An interesting exception is China. According to Bloomberg, China's government has dedicated a pot of $339 billion to start-ups in the nation. The United States still has more start-ups (128 start-ups valued above $1 billion relative to China's 52), but China far surpasses any other single nation; the United Kingdom comes in third with only 11 start-ups valued above $1 billion. Overall, foreign VC firms and individuals may have a nationalistic motivation to invest in their home region or countries.

Based on interviews with experts, many VC investors in the New Space industry are seeking a return on their investments in 5–7 years (with some exceptions based on the company of interest). There are some notable examples of companies that have raised funds and successfully achieved favorable profits for investors (e.g., Planet, Terra Bella and SpaceX), however if future start-ups are incapable of meeting ambitious timescales (e.g., new policy regimes or a catastrophic event that inhibits manufacturing and launch) the VC community may decide to shift away towards other non-space sectors that have promise of returning investments at a quicker rate. However, even given this uncertainty, a growing number of corporations are investing in equity ("corporate venture"), for a number of New Space actors (Figure C-15).



Source: Tauri Group, Start-Up Space: Rising Investment in Commercial Space Ventures.

Figure C-15. Major Corporate Actors Engaged in the New Space Industry

Various corporate actors either invest right off the balance sheet, or through a dedicated venture capital fund; many of the CVC funds are based in Silicon Valley, where numerous start-ups initially begin. Investment made by corporate actors spans across the investment stages either for early stage-development (venture funds) or later-stage development (equity investment, acquisitions or through contracts).

Beyond a return on monetary investment, corporate investors invest in start-ups for strategic reasons. Through investments, companies are able to access new markets opened by start-ups (e.g., Coca Cola's investment in prospective smallsat broadband provider OneWeb), geographic expansion or to innovate on internal business strategies or technologies. Examples of corporate investors in the smallsat ecosystem include the following:

- Coca Cola's investment in OneWeb: The company is investing in an organization that would eventually support their operations; global broadband would potentially open up new markets in regions that are currently under-connected, easing the delivery of Coca Cola's distribution systems globally.

- Google and Fidelity invested $1 billion in SpaceX (not specific to smallsats): The investments benefits the investor's business goals and is seen as a potential high-return equity investment.[19]

Illustrated in the example of SpaceX is another private investment mechanism—private equity. When a start-up reaches positive net profit flow, more traditional equity investors become interested. "Most private equity firms specialize in moving profitable companies from one stage of growth to another."[20]

Private (non-investment) Funding Sources

A number of organization representatives that we interviewed, especially foreign organizations, indicated that a majority of current revenue is sourced from contracts with both private and public actors. Particularly in the private sector, some of these contracts are for commodity products, thus not fueling further technology development. For example, actors including Clyde Space and Blue Canyon Technology sell catalogues of products, often making only minor modifications to meet the needs of their clients. However in the smallsat ecosystem, basic R&D efforts, particularly in sensor technology and downstream technologies, are also being funded through private contractual agreements. For example, Hawkeye 360 has partnered with GomSpace to design, develop and build a new specialized sensor technology.

Further, a number of actors are investing internal funds for basic R&D to support mission needs. This subsect of actors, however, are often limited to larger companies who have high profit margins or access to other internal funds, such as SpaceX, Boeing and Honeywell. However, with the growing use of COTS parts and other low-cost options, start-ups such as Planet and Planetary Resources, are developing specialized technologies for mission needs.

Public Sector Funding Mechanisms

In the public sector, a growing number of public actors are engaging in the small satellite ecosystem using a variety of mechanisms. Below are a few examples of public mechanisms. More information on public investment by international actors is provided in Appendix E. Further, an overview of current investment completed by U.S.-actors is provided in a separate STPI report completed in 2016.[21]

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[19] G. Smith, "Google, Fidelity Make $1 Billion Bet on Elon Musk's SpaceX," *Fortune*, January 19, 2015, http://fortune.com/2015/01/20/google-seen-close-to-1-billion-bet-on-elon-musks-spacex/.

[20] D. Taylor, "The Next Wave of Space Investors."

[21] B. Lal et al., "Trends in Small Satellite Technology and the Role of the NASA Small Spacecraft Technology Program," March 2017.

- **Government contracts and grants for *R&D efforts***: defense, intelligence and civil agencies are supporting research for technologies and applications (e.g., DARPA and NASA STMD engage in early stage research; NASA's CubeSat Launch Initiative provides low-cost access to space for academic R&D projects; SBIRs)
- **Government contracts and grants for *data***: defense, intelligence and civil agencies are purchasing remote sensing data to inform efforts (e.g., Australia's contract with KSAT to track illegal fishing)
- **Government contracts and grants for *acquiring assets***: defense, intelligence and civil agencies are acquiring technologies and buses to support mission needs (e.g., NASA's acquisition of Clyde Space technology for use and integration into smallsat missions)
- **Government grants for general innovation (public "VC" funds):** publically funded organizations provide innovation hubs for emerging start-up companies; these innovation hubs provide access to capital, testing facilities and technical expertise (e.g., Japan's impACT program and Innovation Network Corporation of Japan).

Global Distribution of Actors, by Sector

As part of the database effort, we analyzed the global distribution of organizations by sector. Organizations were categorized into the categories listed below; some organizations were double counted if they are active in multiple parts of the ecosystem.

- **Upstream:** actors engaged in the materials supplier, component manufacturer, or systems integrators subsectors.
- **Midstream:** actors engaged in the launch provider and broker, satellite operator, or ground station operator sub-sectors.
- **Downstream:** actors engaged in the raw data, data aggregator, or data analytics subsectors.
- **R&D:** actors engaged in R&D across the up-, mid-, and downstream sectors. All academic institutions and a majority of government actors are categorized under this category.[22]

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[22] Although a number of academic groups and public research labs operate smallsats, many of these institutions are supported by investment from outside organizations and undertake missions for general R&D efforts. Therefore, all small sat projects undertaken by academic groups and public research labs are classified more generally in our analysis as R&D organizations.

- **Funding**: all funding sources, outside government agencies, which fund smallsat actors. We focused on identifying prominent VC and equity firms.

Globally, industry is mainly engaged in upstream and midstream activities (Figure C-16), indicative of the incomplete proliferation of smallsat technology into downstream markets to date. Further, a majority of R&D occurs outside industry, dominated by government and academic institutions (Figure C-17).

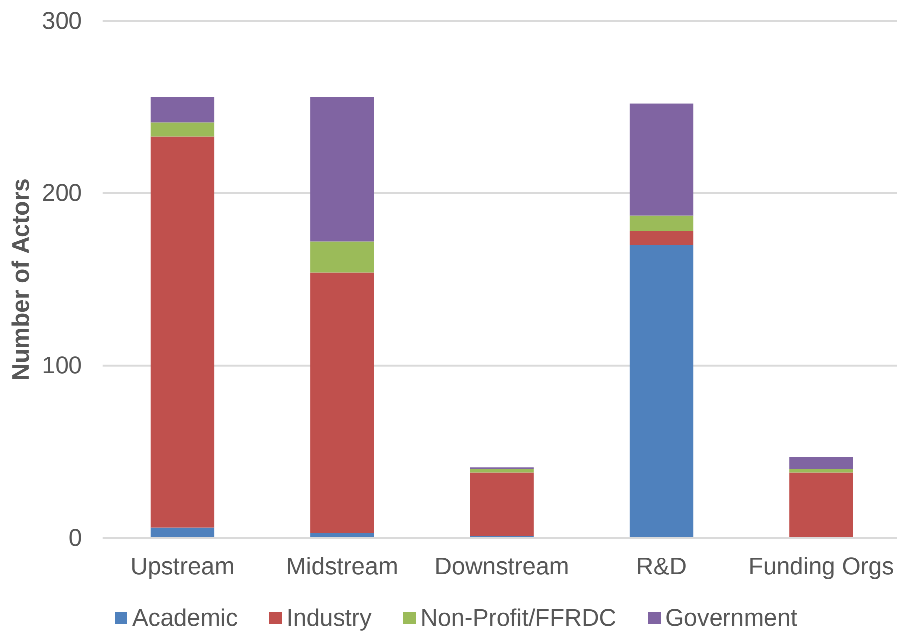

Figure C-16. Global Distribution of Function by Sector

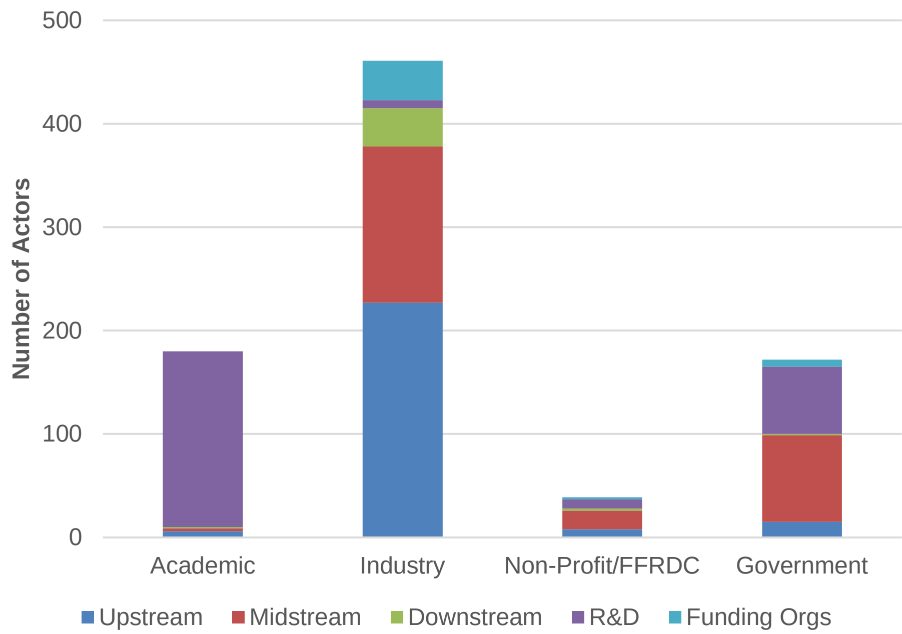

Figure C-17. Global Distribution of Sector by Function

Challenges for Characterizing the Small Satellite Ecosystem

- The ecosystem model provides a snapshot of the current structure of the small satellite industry. However, as the industry expands, consolidates or brings in new actors and customers, the model may evolve.
- Each application area and actor may have different technological needs and demands. The level of acceptable risk varies greatly, for example, between a constellation of OneWeb satellites (short lifespan, COTS components) and a NASA science mission (e.g., high precision for attitude and control, high resolution for imaging devices).
- A wide variety of activity is occurring across the commercial space industry. Defining success and determining whether a company would succeed or not is a challenge not only for researchers but also investors within the industry. Organizations that have had relative success in the industry, although successful for a diversity of reasons, successfully access finance (contracts or private investment), employ an experienced workforce (both technical and business), and have commercialized new technologies (technologies are actually being flown on missions).

Takeaways

Ecosystem is R&D and Industry-Heavy; Global

- Commercial sector is growing, and becoming less dependent on government money/missions; industry is also global, however ITAR restrictions do limit some activity (SAR), most venture capital and start-ups are based in the United States.
  - About half the organizations classified as industry; majority of planned launches are driven by industry. Component manufacturers/suppliers and operators are the majority of industry
  - Mass manufacturing a general trend that interviewees emphasized as being a potential game changer; decreased cost and commodification with the on-set of mass constellations
  - Satellite communications and Earth observations are the dominant applications for industry; however, insights would be pulled from an intersection of inputs (SAR, hyper spectral, UV/IR/Vis; social media feeds; drones and other unmanned aerial vehicles etc.)
- R&D is being driven by non-industry actors. About half the organizations identified in our analysis, are involved in R&D.

United States Dominates but Global Presence

Small number of countries currently dominate the landscape

- The top 10 countries represent over 74% of the smallsat organizations worldwide
- Industry dominates the United States and Europe; in other countries not a strong distinction between government, industry and academia. Growth continues occurring outside the United States and Europe in technology hubs such as Japan and Singapore

Concurrent Consolidation and Fragmentation in the SmallSat Ecosystem

- Functional modularization in the industry is occurring. Various actors are specializing in different sections of the ecosystem, thus providing operators and consumers with various opportunities for engagement.
- However even with fragmentation, given the incomplete commodification of the small satellite bus and associated components, numerous actors are focusing on consolidation and vertical integration (building, operating and selling data in-house).

Appendix D.
State-of-the-Art Small Satellite Technology

The content in this appendix is drawn primarily from two sources, the *Small Spacecraft Technology State of the Art* (NASA/TP–2015–216648/REV1, December 2015), and a National Academies of Sciences, Engineering, and Medicine, *Achieving Science with CubeSats: Thinking Inside the Box* (Washington, DC: National Academies Press, 2016). Other sources are cited as footnotes.

Technology Areas—Payloads

Definition

This very general category encompasses all technologies used to perform a smallsat's "mission." Currently, common payloads for smallsats generally fall within two categories: those used for Earth observations, and those used for communications. In the former category, we include technologies such as optical, full motion video, hyperspectral, multispectral, microwave, and thermal infrared sensors, and synthetic aperture radar. In the latter category, we include technologies used for satellite communications, optical communications, RF communications, radio occultation, and signals intelligence. As smallsats become increasingly used in other application areas (to perform novel science missions, for example), payload technologies specific to these missions are likely be included as well.

Payload technologies are, of course, heavily dependent on other technologies onboard the spacecraft (the platform technologies); for example, the use of thermal infrared sensors (payload) for data collection would rely on effective thermal control systems (platform). There is also overlap of specific technologies across application areas—for instance, an optical communications system could be considered a "payload" if the smallsat's mission is to provide a high speed communications network, but could also be considered part of the platform if the high speed communications facilitate the smallsat's performance of a different mission.

State of the Art and 10-Year Trends

For smallsats, typical instruments and sensors must be scaled down while still maintaining the capability to take useful scientific measurements. Already, there have been several missions demonstrating scaled-down versions of traditional sensors; for example, the energetic particle detector in the Colorado Student Space Weather Experiment is a miniaturized version of the REPT instruments on Van Allen Probes.

However, there are physical limits on how effectively an instrument can be miniaturized. In general, for a given scaling factor R, an instrument's sensitivity is scaled down by $1/R^2$ or $1/R^3$. Due to these reductions in sensitivity, scaling heritage instruments is not necessarily the solution for smallsat instruments and sensors. These challenges can be overcome by developing new technologies entirely or by combining the capabilities of several smallsats in formation.

Avalanche photodiodes can detect very low-intensity signals of a single photon, enabling the small aperture size typical of many smallsats. Building sensors with multiple alloys results in very precise thermal measurements.

Constellations of antennae and the coordination of the information they acquire is a method of artificially increasing aperture size, but requires advances in other areas besides instrumentation, including data handling, attitude and orbit control, and propulsion. The state of the art in constellations and formation flight is addressed in detail in a subsequent section on constellations.

Over the next decade, the trend towards miniaturization for smallsat instruments and sensors would continue, likely enabled by developing novel technologies rather than by scaling down current large satellite instruments. Additionally, the use of smallsat constellations would likely become more prevalent, enabling multipoint data gathering. This approach may be more viable (both from a cost and physics standpoint) than merely scaling down instruments to engineer a smallsat capable of replacing a traditional spacecraft.

Key players in this arena would be principally NASA SMD, which would continue to require more precision in its sensors than other directorates at NASA (e.g., HEO, which also would utilize smallsat payloads, but has not expressed needs for further precision), users in academia, and industry operators moving into new application areas for smallsats or designing large constellations.

Technology Areas: Platform

Attitude and Orbit Determination and Control

Definition

Attitude determination, attitude control, orbit determination, and orbit control are four closely linked areas that draw on an array of overlapping technologies.

Taken together, attitude and orbit provide information on a satellite's station and where it is pointing relative to Earth—knowledge and control of these parameters is essential both for effective communication links between the satellite and ground station and for successful completion of the spacecraft's mission (e.g., Earth observations would require precision in sensor pointing). Attitude refers to an object's orientation with respect to an inertial reference frame, in this case the Earth (often given in terms of the geocentric inertial coordinates). Orbit refers to the specific path a satellite takes around the Earth, defined by the parameters inclination, eccentricity, right ascension of the ascending node, and altitude. Satellites use sensors to determine their attitude and orbit, and employ pointing and/or propulsive technologies to control their position and maintain their station. In order to comply with debris mitigation standards, satellites also rely on their orbit control systems to either deorbit or raise to a graveyard orbit at the end of their missions. In smallsats, the technologies employed in these areas are for the most part extremely similar to those used in traditional spacecraft.

State of the Art and 10-Year Trends

There are several different sensors for attitude determination currently available—the different types are summarized in Table D-1. One commonly employed sensor is a *star tracker*, which compares a digital image captured onboard with a CCD or CMOS sensor with a star catalog stored onboard in order to determine which way the satellite is pointing. This is a well-established technology in satellites, and there are several models available that are small enough for use on smallsats, including the Rigel-L and Procyon from Surrey Satellite Technology, and the ST-16 from Sinclair Interplanetary. These are all at TRL 9 and have accuracies ranging from 25 to 75 arcsec.

A similar concept in attitude determination is employed by *sun sensors*, which provide an estimate of the Sun's location in relation to the satellite, which can then be used to calculate the satellite's attitude. There are both coarse and fine sun sensors on the market. Coarse sensors can provide only a non-directional cosine reading of the sun's location, so a minimum of six would be required onboard in order to fully determine attitude. Fine sensors provide a 2-axis measurement of the Sun's location, and a minimum of four would be required. Both coarse and fine sensors are available at TRL 9 for smallsats from vendors including New Space Systems, Adcole, and Space Micro. Their masses range from 0.0141 to 0.068 kg, and their accuracies range from 0.1 to 5° (reflecting the difference between fine and coarse sensors).

A third sensor type for attitude determination is the *Earth sensor*. These rely on various indicators to sense where a satellite is in relation to Earth's surface. They can be simple devices containing infrared horizon crossing indicators, or rely on more advanced thermopile sensors to detect temperature differences between the Earth's poles and the equator. Both types are available for smallsats at TRL 9, from vendors such as Maryland

Aerospace and Servo. Masses are between 0.033 kg and 0.050 kg with accuracies ranging from 0.25 to 0.75°, depending on which technology is used.

Table D-1. Summary by Type of State-of-the-Art Sensors Commercially Available for Attitude Determination

Technology	Manufacturer	Pointing Knowledge	Mass
Star trackers	Surrey Satellite/Sinclair Interplanetary	0.4°/1.2°	2.2 kg/0.12 kg
Sun sensors	Space Micro/New Space Systems	5°/0.1°	0.0141 kg/0.035 kg
Earth sensors	Maryland Aerospace	0.25°	0.033 kg
Magnetometers	New Space Systems/PNI Corp/Surrey Satellite	6.5/15/10 nT resolution	0.2 kg
Gyroscopes	Analog Devices/Northrop Grumman/Surrey Satellite	N/A	0.016/0.75/2.8 kg

Magnetometers can be used for attitude determination as well. These devices take measurements of the local magnetic field, and this information can be used to determine a satellite's orientation with respect to the Earth. As with star trackers, magnetometers have a long history of use in traditional spacecraft, and there are several available that meet the size restrictions of smallsats. Manufacturers like New Space Systems, PNI Corporation, and Surrey Satellite Technology all produce TRL 9 magnetometers under 0.2 kg, with resolutions ranging from 6.5 nT to 15 nT.

A final method available for attitude determination is the use of *gyroscopes*. Gyroscopes as a tool to measure angular velocity date back hundreds of years, but those used on smallsats generally are one of two specific types: microelectromechanical system (MEMS) gyroscopes or fiber optic gyroscopes (FOGs). MEMS gyroscopes, which rely on small vibrating structures to determine rate of rotation, are inexpensive and widely available, and are commonly found in consumer electronics and airbag systems. Surrey Satellite Technology and Analog Devices both produce 3-axis MEMS gyroscopes suitable for smallsats, with masses of 2.8 and 0.016 kg, bias stabilities of 10 and 35° h^{-1}, and random walks of 0.6 and 2.0 $hr^{1/2}$, respectively. FOGs rely on the Sagnac effect, based on the interference of light passed through a coil of optical fiber, to detect changes in orientation. FOGs are generally higher performance than MEMS gyroscopes (with better bias stability and lower rates of random walk), but are also more costly and massive. Northrup Grumman produces a TRL 9 3-axis FOG for smallsats, with a mass of 0.75 kg, bias stability of 1° h^1, and a random walk of 0.1° $hr^{-1/2}$.

Attitude control requires the use of actuators or of a propulsion system. A common type of actuator used on smallsats is a miniaturized set of *reaction wheels*. Reaction wheels consist of electric motors attached to flywheels—when the rotation speed of the flywheel is changed, the spacecraft would counter-rotate around its center of mass due to the conservation of angular momentum. Complete attitude control abilities would therefore require a set three reaction wheels, though they often come in sets of four in order to provide fault tolerance. Smallsat reaction wheels at TRL 9 are available from manufactures including Surrey Satellite Technology and Sinclair Interplanetary, with masses from 0.185 to 2.6 kg, peak torque provided ranging between 0.002 Nm and 0.11 Nm, and momentum capacity from 0.04 Nm/s to 1.5 Nm/s—in general, greater peak torque and storage capacity comes with a mass penalty.

A second type of actuator available is the *magnetorquer*, which creates a magnetic field using a set of electromagnets that interacts with the Earth's magnetic field to produce torque. They can only produce torques perpendicular to the Earth's field, but they are commonly used in satellites in combination with reaction wheels to remove excess momentum. TRL 9 magnetorquers for smallsats are available from companies like Surrey Satellite Technology, ZARM, and Spaceflight Industries, with a wide range of masses and peak dipoles: 0.003–0.727 kg and 0.1–15 Am^2. As with reaction wheels, a larger peak dipole comes with a larger mass.

Finally, a smallsat's *propulsion system* can be used for attitude control. The state of the art and future directions of propulsion systems are described in more detail in a later section.

Orbit determination systems can rely on magnetometers as well. In addition, they can incorporate *GPS receivers* in onboard systems, or rely on ground-based radar tracking (the results of which can be uploaded and paired with an appropriate propagator to calculate the spacecraft's position at later times). There are many options for GPS receivers available for smallsats at TRL 9 from vendors like Surrey Satellite Technology and Novatel. Their masses range from 0.021 to 0.95 kg, and their accuracy ranges from 1.5 to 10 m. The accuracy of GPS receivers depends on the precision of the civilian-use GPS data (provided with free access by the U.S. Government) as well as on the propagation variance through the exosphere as the satellite orbits Earth.

Orbit control systems can rely on magnetorquers as the satellite moves through Earth's magnetic field. They also depend heavily on the spacecraft's propulsion system, which is discussed in a subsequent section on mobility and propulsion.

There are several concurrent trends in the direction of attitude and orbit determination and control that should shape technology over the next 10 years.

The first trend is simply improvement on the technologies already available. In general, attitude and orbit determination and control systems are readily adaptable from those found in traditional spacecraft, and the technologies listed above are mature. These traditional technologies would continue to get both smaller and more accurate over the next ten years—for example, Blue Canyon has developed a precision star tracker that allows for pointing knowledge of 8 arcsec, beating the previous state of the art, which was flown in the MinXSS mission at the end of 2015. In the coming months they expect to achieve star tracker precisions of 2 or 3 arcsec. The trend towards increased precision would be driven by the needs of new applications; optical communications systems, for example, would require precision attitude determination and control.

A second driver for change would be as propulsion systems develop, as they can be used for both attitude and orbit control, in deorbit technologies, and in integrated units for performing both attitude/orbit determination and control functions. Compared to the technologies discussed above, propulsion for smallsats is low in readiness, yet also sees substantial investment from NASA and industry. The needs and potential directions for propulsion systems are discussed later in the section on mobility and propulsion.

A third trend would be an increased focus on deorbit technologies. Currently, novel deorbit technologies are relatively immature. The NASA Orbital Debris Program office specifies that spacecraft must deorbit within 25 years after the end of their mission, or be placed into a graveyard orbit following that time. Smallsats have a greater need for additional de-orbit techniques than do traditional spacecraft, given that they often do not have a propulsion system to use.

Deorbit technologies can be categorized as either active or passive. Active deorbit technologies have been identified as a need or area of interest, but have not been given much attention—their need for excess propellant and maintenance of attitude control over the spacecraft makes them more difficult. For example, a commonly proposed active deorbit system, a *steered drag sail,* would require a functioning attitude control system during the post-mission disposal period. The continuous operation requirements of active deorbit systems make them more costly than many smallsat missions would be able to afford—though this might change as autonomous operations become more feasible and common.

There are some passive deorbit technologies currently being developed. These include variations on a *deployable drag sail* or *boom*. A drag sail was successfully demonstrated to deorbit a 3U spacecraft (FASTSAT) in 2011, and another smallsat currently in orbit (CanX-7) would also deploy a drag sail to deorbit at the end of its mission. Two other technologies, the Roll-Out DeOrbiting device (RODEO) from Composite Technology Development, Inc. and the Aerodynamic End-of-Life Deorbit system (AEOLDOS) from Clyde Space and the University of Glasgow rely on lightweight membranes attached to roll-out boom structures to multiply a smallsat's surface area and increase drag in the upper atmosphere. These technologies range from TRLs 7-8, and further demonstration would be needed before they are considered fully mature.

Another proposed concept is the use of an *electrodynamic tether* for passive deorbiting. An electrodynamic tether works by deploying a length of conductive wire (insulated or uninsulated) that generates an electromagnetic force as it moves relative to the Earth's magnetic field with the motion of the satellite's orbit. Tethers Unlimited has developed a Terminator Tape module, which deploys an electrodynamic tether up to 250 m long using a burn-wire release mechanism.[1] These modules are currently flown on Aerocube-V CubeSats, and more are scheduled for launch in 2016. The technology is currently considered to be at TRL 8/9, and again, further demonstration is needed before it can be widely adopted.

Finally, another trend in the development of attitude and orbit determination and control would be the increased production of *integrated units*, which combine multiple attitude and navigation components described above into a compact unit available off the shelf to fulfill all or most of a smallsat's determination and control needs. For example, a single unit may combine reaction wheels, magnetometers, magnetorquers, GPS receiver, and star trackers into a ½U box. Maryland Aerospace and Blue Canyon Technologies have developed integrated units at TRL 6, but none have flown yet. Demand for these off-the-shelf integrated units would increase as mass-manufacturing of smallsats (perhaps for large constellations) becomes more prevalent.

Communication

Definition

The communications system of a spacecraft performs several functions: it transmits data to Earth, receives commands from ground stations, and relays and receives data to and from other spacecraft. Technologies in this area are generally either transceivers or transponders. A transceiver both transmits and receives signals. A transponder also transmits and receives signals, but also derives the transmit frequency from the received signal, which allows for the provision of range and speed information (either spacecraft-to-spacecraft or spacecraft-to-Earth) to an interrogating station.

State of the Art and 10-Year Trends

Because CubeSats have not been flown beyond LEO, they have thus far skirted the need for highly focused transmissions that would necessitate the use of a large dish antenna

[1] Tethers Unlimited, "The Terminator Tape and Terminator Tether Satellite Deorbit Systems: Low-Cost, Low-Mass End-of-Mission Disposal for Space Debris Mitigation," accessed February 20, 2017, http://www.tethers.com/TT.html.

and precise attitude control. Instead, they have been able to employ *whip*, *tape*, or *patch antennas*. These antennas have low directionality and can maintain a communications link with Earth even when the satellite is tumbling. Whip and tape antennas are easily deployable and are often used in the VHF and UHF bands (30 MHz to 3 GHz), while patch antennas do not require deployment and are often used in the UHF through S bands (300 MHz to 4 GHz) on CubeSats. Another option currently in development are *deployable helical antennas*, such as the quadrifilar helical antenna by Helical Communication Technologies and deployable helical antenna by Northrop Grumman.

The current state of the art for smallsat communications is in the use of the *radio frequency band* (30 MHz to 40 GHz).

In the *VHF and UHF bands*, there are many transceivers at TRLs 8 or 9 available for smallsats from several manufacturers, including Astronautical Development LLS, BitBeam Inc., Clyde Space Ltd., GOMSpace ApS, Haigh-Farr Inc., ISIS B.V., and L3 Communications Inc. Many of these transceivers, especially those built for CubeSats, are whip or patch antennas (see above).

In the *L-band*, smallsats often take advantage of existing space communications networks (e.g., Iridium) by employing network-specific transponders. This removes the need for dedicated ground station equipment. Several network-specific transponders at TRLs 8 and 9 are available for smallsats from Iridium Communications, Inc., NearSpace Launch, Inc., and sci_Zone, Inc.

In the *S-band*, several companies have commercially available TRL 9 transceivers and/or transponders, including Astronautical Development LLC, Clyde Space Ltd., Haigh-Farr Inc., Innoflight Inc., IQ Wireless GmbH, ISIS B.V., Helical Communication Technologies, and Vulcan Wireless. These antennas include variations on the *patch antenna* as well as a lower-TRL deployable *quadrifilar helical antenna*. Some CubeSats have also flown with *commercial off the shelf land-based technologies designed for the unlicensed Industrial, Scientific, and Medical bands* used for inter-satellite communication.

In general, smallsats can benefit from higher data rate capabilities, and the next ten years would likely see developments working to enable this.

In the future, there would likely be further advances in the use of *higher carrier frequencies*, especially in the X through Ka bands (8 to 40 GHz). There is more bandwidth available in these higher frequencies, which are not yet subject to crowding from cell phones, which means higher data rates are more easily achievable.

The *X-band* has been a recent area of focus, following the commercial availability of Monolithic Microwave Integrated Circuits (MMICs). Smallsat-compatible X-band antennas (including patch antennas for CubeSats) have been developed by Antenna

Development Corporation, Syrlinks, and Surrey Satellite Company. JPL developed an X-band transponder for CubeSats in deep space missions, and CU Boulder and Goddard developed an X-band SDR.

Within radio frequency communications, one development of interest is *software defined radio* (SDR), which can be tuned for use in multiple bands without changing the hardware, merely by uploading new settings from a ground station.

An area where smallsats need work is in precise pointing capabilities and/or in the development of alternatives to the traditional dish antenna. Larger spacecraft use dish antennas because they can focus transmissions into a precise beam, necessary for transmitting over long distances. However, this is difficult for smallsats because their pointing ability is less precise, and dish antennas are physically large (and therefore difficult to integrate with some smallsats). One solution would be to continue to improve smallsats' *attitude control abilities* (see attitude control section above). Another solution is to develop alternatives to the traditional dish antenna. An *inflatable dish antenna* is one such proposed concept.

Another issue with smallsats (particularly CubeSats) is that sometimes deployable solar panels are infeasible, and there is therefore limited surface area to generate power. In these cases, *optically transparent antennas* are desirable so as to not interfere with solar cells. There are some prototypes available but none have yet been flown.

Some have proposed using *commercial off-the-shelf wireless systems* such as Bluetooth-compatible hardware for communication between satellites and/or for wireless networking on a single satellite (i.e., instead of relying on wired connections between subsystems, using Bluetooth connections). Testing these systems in space has been limited but may be more prevalent on CubeSats going forward.

A developing communications area is in *lasercom*, which includes concepts both for satellite-to-satellite communications, where the smallsats themselves host lasers, and for those involving an asymmetric optical link, where the laser is on Earth and the satellite hosts a modulating retroreflector. Aerospace Corporation is in the process of launching CubeSats in its AeroCube Optical Communication and Sensor Demonstration (OCSD) program, which would demonstrate inter-satellite lasercom, and Fibertek is also working on developing a 6U lasercom system. SPAWAE and NASA Ames are both currently working on versions of an asymmetric lasercom system.

Finally, an area of interest in smallsat communications generally is in technologies to support *inter-satellite communications*. If data can be relayed reliably between spacecraft (for example, for the maintenance of precise positions in a coordinated constellation or flight formation), smallsat missions would be less reliant on the coverage of ground stations. It would also enable deep space missions, as smallsats could save on the high power requirements of transmitting and receiving data to and from Earth, and instead relay it through a mothership. It is likely that the communications hardware itself would not be very different from the transponders already used in smallsats. The use of transponders in networked swarms has not yet been demonstrated, and more work is required on the systems and software engineering than on the hardware itself. Demonstrations of networked operations using CubeSats are upcoming.

Mobility and Propulsion

Definition

Propulsion systems in satellites are used for maintaining or changing a satellite's position on orbit when necessary, for performing pointing maneuvers (i.e., performing attitude control functions), and for raising and lowering a satellite's orbit as required to reach their operational orbit and by end of life procedures for debris mitigation. Propulsion systems can generally be classified as using chemical, electric, or propellant-free propulsion. A complete "propulsion system" includes the propellant, propellant storage, feed systems, thrusters, and Power Processing Units (for electrical systems; this does not include the electrical power supply). There are a wide variety of propulsion systems available for spacecraft in general, but miniaturizing them for smallsats has been difficult.

State of the Art and 10-Year Trends

Propulsion systems can be assessed along several metrics, including thrust levels, mass, power requirements, specific impulse, total impulse per unit system wet mass, total impulse per unit system volume, and thrust-to-power ratios.

Among chemical propulsion systems, the use of *hydrazine propellant* has a long heritage in traditional spacecraft, and some of the systems built are small enough to be adapted to smallsats. These include small thrusters that would have been used for precision maneuvers and/or attitude control on larger spacecraft, and that are large enough to serve as the primary propulsion system on smallsats. Because of hydrazine systems' long flight history, system components (for example, individual thrusters) are available commercially off the shelf from companies like Airbus Defense and Space, Aerojet Rocketdyne, and Moog ISP. For smallsats, hydrazine systems are at TRL 6, with thrust levels of 0.5-4 N available, and specific impulses of 150-250 s. In general, developing hydrazine systems for smallsats is difficult because they must be closely temperature-controlled, which requires active thermal control systems as well as adequate power onboard.

Because hydrazine is toxic and requires stringent safety measures for handling, there has been interest in recent years in developing propulsion systems for *non-toxic propellant*. Most of these propellants are still in development, with TRLs of 5-8. Some non-toxic propellant systems have already been successfully flown (e.g., Ecological Advanced Propulsion Systems, Inc.'s (ECAPS's) High Performance Green Propulsion system in the

PRISMA mission in 2010), and many others are in the process of being integrated. Aerojet Rocketdyne, ECAPS, the U.S. Air Force, Tethers Unlimited, Inc., and Busek are all working on systems in this space. Thrust levels range from 0.2 to 26.9 N, and specific impulses from 204 to 258 s.

Some of the cheapest and simplest options for smallsat propulsion systems use *cold and warm gas* (e.g., gaseous nitrogen, butane, etc.) expelled through a thruster or set of thrusters. They are very simple systems with non-toxic propellants, and as a result are quite robust. Systems using nitrogen or butane are available from Marotta, NanoSpace, and Surrey Satellite Technology Ltd. at TRL 9. Systems using other fuels (Argon, R134a) are also in development but are at slightly lower TRLs (6–8). Thrust levels and specific impulses for cold and warm gas propulsion systems are lower than those of more traditional chemical propellants: 0.01 mN to 2.36 N, and 32 to 80 s.

A final type of chemical propulsion system currently available for smallsats involves the use of solid fuel. *Solid motors* consist of solid or powdered propellant enclosed in casing, an igniter, and a nozzle—they are very simple and were widely used before the advent of liquid propellant, and still can be found in model rockets. If an electrical control system is incorporated, the system can be restarted and provide some steering capabilities. Currently, solid fuel systems are available from Industrial Solid Propulsion, Orbital ATK, and Digital Solid State Propulsion LLC. Their thrust and specific impulses varies widely depending on the design, from 0.3 to 258 N and 187 to 900 s. Solid motors for smallsats are at TRL 6–8.

Electric propulsion systems are on the whole less mature for smallsats than chemical propulsion systems, and most of them would require more development over the coming years. One comparatively mature electrical propulsion system is the *resistojet*, which provides thrust by heating a non-reactive propellant (e.g., xenon or nitrogen) using electricity, which causes the expanded gas to be expelled through a nozzle to produce thrust. It is a relatively simple technology that has been used on satellites since the 1960s (however, the vast majority of those that have been flown in the past have used hydrazine). For smallsats, Surrey Satellite Technologies, Ltd., CU Aerospace, and VACCO have all developed resistojets that have flown in smallsat missions. Thrust levels can reach up to 100 mN, and specific impulses up to 99 s depending on the propellant used. Power requirements range from 30 to 50 W.

Over the next ten years, the development of propulsion systems for smallsats would continue to attract considerable attention. Experts interviewed agreed that electric propulsion systems provide the most promising path forward. The remainder of this section details propulsion systems currently at low TRL for smallsats that would likely see further development.

Electrosprays are an electric propulsion system that uses electrostatic acceleration of propellant droplets (usually a low-volatility ionic liquid) to generate low levels of thrust. This is a desirable capability for several reasons: very high specific impulses are attainable due to the high velocity of expelled ions, the propellant does not need to be pressurized, and no gas-phase ionization is needed, unlike with other electric propulsion systems. Accion Systems, the MIT Space Propulsion Laboratory, and Busek are all working on electrospray systems that could be applied to smallsats. The technology is currently at TRL 5-6. Thrust levels are low (and scale with power), at 60 µN to 0.7 mN, while specific impulse ranges from 800 to 2300 s. Power requirements and masses are also low, with most systems requiring under 5 W and 1 kg including propellant.

Radiofrequency ion thrusters ionizes propellant (usually xenon or iodine) using a radiofrequency current in a helical coil, then accelerates the ions through an electrostatic field to high exhaust velocities. They are highly efficient (high specific impulse) compared to other electrical propulsion systems, and can offer more robust thrusters since they do not use electrodes and therefore can avoid grid erosion. Systems are being developed by Busek, Airbus, and the University of Tokyo. Most are at TRL 5. The University of Tokyo's combines ion thrusters with cold gas thrusters (both share the same gas feed system), and is at TRL 8 as it has already been successfully demonstrated in space on the Proximate Object Close flyby with Optical Navigation (PROCYON) mission. Thrust levels range from 50 µN to 1.4 mN, and specific impulse can reach up to 3000 s. Power requirements are between 10 and 60 W.

Pulsed plasma and vacuum arc thrusters are two types of plasma-based propulsion. Pulsed plasma thrusters trigger a high voltage discharge between two electrodes to produce an electric arc that ablates a solid state material, and produces a self-generated magnetic field to accelerate propulsion particles through the thruster head. Vacuum arc thrusters consist of two metallic electrodes separated by a dielectric insulator, wherein one of them is used as solid metallic propellant that is consumed as the thruster operates. These plasma-based thrusters are simple enough that their miniaturization has presented less of a challenge than for other electrical propulsion systems. They are desirable in smallsats as the trigger pulse of the discharge can be finely adjusted, allowing for their use in attitude control and other precise pointing maneuvers. Mars Space and Clyde Space, GWU and the U.S. Naval Academy, NASA Ames and GWU, and Busek have all developed thrusters of this type, with TRLs ranging from 5 to 8 depending on the extent of the flight testing. Power requirements are 1.5–14 W, thrust levels are 1 to 90 µN, while specific impulse varies widely from 536 to 3000 s.

Another plasma-based propulsion technology, this one developed by the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory, is being commercialized by the company Phase Four. In addition to building upon miniaturized high-power density electronics, the technology is being developed for the CubeSat standard and uses magnetic fields to shape and direct plasma, eliminating exposure and erosion of metal parts (which is an important failure point in current plasma-based propulsion technologies). The system could be capable of providing 1 km/s delta-V (for a 3U CubeSat) but is still in development; on-orbit testing is planned for 2017 (see Appendix G for additional information).

Hall-effect thrusters are another form of electric propulsion system, where electrons are trapped in a magnetic field and used to ionize propellant (usually xenon, though many other propellants could be used as well), which is then accelerated to produce thrust. Their mass utilization efficiencies are quite high. The concept for use on larger spacecraft has been given considerable theoretical and experimental research since the 1960s, and have been flying operationally on spacecraft since the early 1980s. Their large power requirements and the difficulty of miniaturizing some of their components makes their maturity for smallsats lower, though there are some companies working on compatible systems. Rafael, Aerojet Rocketdyne, JPL, UCLA, Busek, Sitael Aerospace, and the University of Toronto's Space Flight Laboratory all have Hall-effect propulsion systems for smallsats at varying stages of development. Power requirements are relatively high, at 175–200 W, while thrust ranges from 5–15 mN and specific impulse ranges from 1139–1390 s. The various systems are at TRL 4–8 (Busek's is at the high end, as it has been successfully flight tested already).

Finally, many smallsat mission designers are interested in propellant-free propulsion systems, due to their potential to reduce complexity and mass onboard. *Solar sails* are the most well-established concept in this regime, and have been demonstrated on larger systems in the past. For smallsats, NASA Ames and Marshall Space Flight Center have collaborated on the launch of the NanoSail-D2 as a technology demonstration mission in 2010. That sail was fabricated from a material called CP-1, had a 10 m^2 deployed surface area, and a mass of 4.2 kg. More recently, the Planetary Society demonstrated the use of a 32 m^2 solar sail on a 3U CubeSat in 2015, and plans to perform another demonstration with additional maneuvers in 2016. Solar sails for smallsats are at TRL 6–7.

Many other new propellants and technologies are currently being developed, many incorporating completely novel components and systems not drawing on previous propulsion systems in traditional spacecraft. They are at TRL 4 and below.

Electrical Power Generation and Storage

Definition

The power system of a spacecraft commonly takes up one-third of the spacecraft's total mass, and is essential for supplying electrical power to all necessary components like the mission's instrumentation, thermal control (when active), communications systems, and propulsion system. It includes both the generation of power and its storage and management/distribution.

State of the Art and 10-Year Trends

By far, the most common type of power generation on smallsats is the collection of solar power. There are several technologies currently ready for use on smallsats. Photovoltaic cells use thin layers of semiconductors to produce electric current when they are exposed to light via the photoelectric effect. Photovoltaic cells can either use a single layer of material, or combine multiple materials with different bandgaps in multi-junction cells to utilize a larger spectrum of solar radiation and therefore increase efficiency. Adding additional junctions adds to the cost of the cell. *Single- to triple-junction solar cells* are currently the state of the art for smallsats. Space-qualified cells are available from Azurspace, Spectrolab, EmCore, and SolAero, with efficiencies ranging from 16.9% to 33% (higher vs. lower efficiencies correspond to the number of junctions in the cells). Cells from these manufactures come in both standard and customizable sizes.

Assembled solar panels and deployable arrays take the solar cells previously described and assemble them into arrays ready for flight as “plug and play” components. TRL 9 systems are available from SolAero, DHV Technology, GomSpace, Clyde Space, and Spectrolab. Efficiencies range from 26–30%, and they are available in many sizes (often standardized for CubeSats) or are customizable (Table D-2).

Table D-2. State-of-the-Art Smallsat-Compatible Solar Arrays

Array	Power output	Mass-to-power ratio	Stowed power density	Size
SolAero COBRA	Up to 600 W	7 g/W	30 kW/m^3	Customizable
DHV	2.24 W	17 g/W	N/A	100x100mm (1U)
DHV	8.48 W	15 g/W	Unknown	3U (deployable)
GomSpace NanoPower	6.2-7.1 W	Unknown	N/A	
Clyde Space	Varies	~75 g/W (deployable type)	Unknown	0.5U-12U (mounted and deployable types)
Spectrolab	Varies	5.28 g/W	N/A	30 cm^3
MMA Design HaWK	36 W	7.7 g/W	99 kW/m^3	3U-12U (deployable)

In situations where solar power is not readily available, spacecraft operations depend on stored power, normally from batteries. *Secondary type batteries* (differentiated from primary type batteries by their electrochemistry) are commonly used in space missions because they are longer-lived. For smallsats, state of the art is in secondary Li-ion and Li-po batteries. In many cases, they are able to take advantage of technologies designed for traditional aerospace missions or even terrestrial applications, as some of these batteries are quite small already. Manufacturers such as EaglePicher, SAFT, and ABSL have long histories of supplying the aerospace industry, and several of their systems are available commercially off-the-shelf. In addition, other manufacturers such as GomSpace and Clyde Space are producing batteries specifically designed for smallsats or CubeSats. A list of available batteries and their energy densities is listed in Table D-3.

Table D-3. SOTA for Batteries

Battery	Energy Density
EaglePicher Rechargeable Space Battery	153.5 Wh/kg
SAFT Li-Ion	126–165 Wh/kg
ABSL COTS 18650 Li-ion	90–243 Wh/kg
LG ICR18650 B3 Li-ion	191 Wh/kg
Panasonic 18650B Li-ion	243 Wh/kg
Canon BP-930s	132 Wh/kg
Clyde Space Li-Po	150 Wh/kg
GomSpace NanoPower BPX	157–171 Wh/kg
Vectronic Li-Ion Battery Block VLB-16	Unknown

In the next 10 years, technology advancements would likely occur in two areas: improvement of solar cell efficiency, and in miniaturization of fuel cells, RTGs, batteries, and other traditional sources of power on larger spacecraft.

Already, there is substantial work being done on *multi-junction solar cells*, which improve the efficiency from the triple-junction solar cells described earlier. Terrestrial applications drive the progress in this area, and smallsats may be able to take advantage of the improvements. Fraunhofer Society is currently developing a four-junction solar cell (46% efficiency) and Boeing Spectrolabs are working on 5- and 6-junction solar cells (up to 70% efficiency)—these developments are still in the lab, and power-to-weight might not be comparable to current triple-junction cells. In the short term, these technologies are too expensive to justify the improved efficiency over triple-junction cells in smallsat missions, but this may change in the course of the next decade.

Another technology currently under development is the *flexible and thin-film solar cell*, which has a photovoltaic layer of only one micron in thickness (compared to traditional cells, with layers 350 microns thick). In addition to making them extremely flexible, the use of less photovoltaic material also brings manufacturing costs down. However, at their current stage of development, efficiency is lower (8–20%). As this technology develops further, it may be of interest to the smallsat community as it could open up new possibilities for deployable systems while remaining low cost.

The use of *organic or plastic* materials provide another avenue toward low-cost solar cells. These photovoltaics use organic electronics or organic polymers and molecules, a small quantity of which can absorb a large amount of light. As a result, they offer the potential to be cheaper and more lightweight than traditional photovoltaics. However, they are currently at very low efficiency (4% or less).

The second trend would be in the development or miniaturization of non-solar power sources, usually adapted from those used on traditional spacecraft.

Fuel cells are one commonly used power source for both space and terrestrial applications (they have been flown on every U.S. manned space mission since the Apollo program). A fuel cell is an electrochemical device in which the chemical energy is directly converted into electrical energy. In the cell, hydrogen and oxygen react to form water and electrical power and heat (the reversed electrolysis reaction). It is similar to a battery, which also consists of a positive and negative electrode and electrolyte. However, while a battery is essentially an energy storage device, a fuel cell supplies power as long as there is a supply of fuel and oxidant. *Hydrogen fuel cells, including regenerative fuel cells*, are garnering some interest for smallsat applications, as they would help enable planetary missions that may have to operate out of sunlight. None have yet been flown.

Radioisotope thermoelectric generators (RTGs) are commonly used on outer solar system science missions. They convert the thermal energy given off by a decaying radioactive source (Plutonium-238 is the isotope of choice in the United States) using static thermoelectric elements to generate usable power. Because of the long half-life of Pu-238 and the elimination of moving parts, RTGs can reliably provide power for longer periods of time than solar panels or batteries, possibly up to decades. Up until this point, RTGs have been too expensive and massive to feasibly be incorporated into smallsat missions. However, some have expressed interest in the development of *lightweight RTGs*, which could be integrated into interplanetary smallsat missions. The required shielding would likely make RTGs too massive for many applications, but for larger smallsats used for planetary missions, they could offer a promising way forward.

A similar, though less tested, technology of possible interest to smallsats is the *thermophotovoltaic battery*. They also rely on radioisotope fuel as a thermal emitter, but rather than using thermoelectric couples as convertors, they use infrared-tuned photovoltaic cells. The advantage of this approach is an increase in specific power. There are, however, technical challenges due to the fact that a substantial amount of waste heat must be rejected between the fuel source (>1000 K) and the thermophotovoltaic cells (which operate most efficiently at < 350 K).

Alpha- and beta-voltaic systems are another type of radioisotope power system. Instead of using the nuclear radiation to generate heat, which is then converted to electricity, alpha- and beta-voltaics use a non-thermal conversion process. They rely on semiconductor junctions to produce electrical particles from the emitted alpha or beta particles. As with other radioisotope power systems, they would provide long-lived and consistent levels of power. However, they are still in the development and testing phase for spacecraft applications, and may be too massive and expensive to be feasible for smallsats in the coming years.

All of these "next generation" power systems would likely only see adoption in the smallsat community when the smallsat market grows significantly. The cost of developing miniaturized nuclear energy sources, for example, is well beyond what the industry can currently support, although it is technically feasible.

Thermal Control

Definition

Thermal control refers to the technologies and subsystems dedicated to maintaining an appropriate temperature onboard the spacecraft, usually to ensure that the instrumentation and bus subsystems continue to function properly. Thermal control technologies can either be passive or active systems. Because passive technologies traditionally rely on large surface areas from which to radiate heat, and active technologies are often heavy and power intensive, the adaptation of traditional techniques to suit the needs of smallsats is not straightforward. Many promising technologies are still at lower TRLs.

State of the Art and 10-Year Trends

In passive thermal control, several technologies are ready or close to ready for smallsat flight. The simplest is the use of *multi-layer insulation (MLI) and thermal coating*, which takes the form of blankets, tape, and paint which can both block incoming solar radiation and also mitigate heat dissipation from the spacecraft. These techniques have a long heritage on traditional spacecraft and do not require any modifications for use on smallsats, so they are at TRL 9. However, their performance on smallsats is often compromised, as the effectiveness of these materials often decreases when they are compressed to a small surface area. Companies that produce MLI blankets and thermal control paint or tape include Dunmore Aerospace, AZ Technology, MAP, Astral Technology Unlimited, Inc., Lord Techmark, Inc., Sheldahl, and Akzo Nobel Aerospace Coatings. These companies are not smallsat-specific and have all produced MLI and thermal coating for traditional aerospace use, but have had their products demonstrated on smallsat missions.

Another passive thermal control method that should soon be available is the use of *sunshields*. Sunshields offer shading of a spacecraft from solar radiation to prevent overheating. They have long been employed on traditional spacecraft, but must be adapted to unfold from a much smaller form factor when used on smallsats. Sierra Lobo has developed one such deployable sunshield, currently at TRL 8, that would be demonstrated on a smallsat this year.

There has also been interest in developing *thermal straps* for use on smallsat missions. Thermal straps are another passive thermal control technology commonly used on traditional spacecraft. They are flexible strips of metal foil or other fibers of any length used to passively transfer heat along a set path. Thermal Management Technologies has developed aluminum and copper thermal straps designed for smallsats, which have been tested but not yet flown. Thermacore has developed straps using k-Core encapsulated graphite with greater thermal conduction efficiency, which have also been tested but not flown. The use of Graphite Fiber Thermal Straps (GFTS) from Technology Applications, Inc. shows promise for smallsats given their low masses and high efficiencies, but they have not been yet demonstrated or tested on smallsats. One thermal strap currently flying is Thermotive Technology's Two Arm Flexible Thermal Strap (TAFTS), which is used in JPL's Portable Remote Imaging Spectrometer (PRISM) instrument—although this particular instrument has not flown on a smallsat, similar infrared cameras have. Thermal straps for smallsats are currently at TRL 8.

A final passive thermal control technology nearly ready for use on smallsats is the *thermal louver*. Traditionally, thermal louvers have been active technologies, serving as "blinds" that can be raised or lowered over external radiators or between internal spacecraft surfaces. However, these traditional louvers are too massive and power intensive to make them feasible for use on smallsats. Instead, Goddard Space Flight Center has been developing passively controlled thermal louvers for smallsats using bimetallic springs (which expand when heat in the spacecraft rises) to control the flaps. This technology has not yet been demonstrated and is at TRL 8.

Active thermal control methods are those that rely on some level of input power to run. They are more precise (i.e., they can maintain set temperatures) and are generally more effective. However, there are fewer active thermal control techniques that have been successfully miniaturized for use on smallsats. Currently, the only active thermal control technology commonly used on smallsats is the *electric resistance heater*, which is controlled by a temperature sensor and typically employed to regulate battery or biological payload temperature when the satellite passes into the cold portions of its orbit. Minco Products, Inc., manufactures TRL 9 flexible strip heaters that have been flown on several smallsat missions.

In the coming years, there would be some further development on certain passive thermal control technologies for smallsats, as well as an increased focus on miniaturized active thermal control systems (the move into active systems would be necessitated as smallsats begin to move into novel application areas or carry advanced payloads requiring more cooling, such as miniaturized infrared cameras).

There are several lower-TRL passive thermal control technologies currently being developed. The first is the *deployable radiator*, which would expand a smallsat's surface area in order to radiate away more heat. A passively deployable radiator would work similarly to the passive thermal louvers discussed above, with an actuator consisting of a shape memory alloy and a bias spring to move the radiator from its stowed position when cold to its deployed position when hot. This design was proposed and tested by a collaboration between Kaneka Corporation and JAXA, while a similar concept has been designed and tested by Thermal Management Technologies. It is currently at TRL 6. Another concept, from Thermotive, is the Folding Elastic Thermal Surface (FETS), which could be applied either to individual smallsat instruments or to an entire small spacecraft and is currently at TRL 4/5.

Heat pipes are another passive thermal control technology currently under development. Heat pipes are an established technology in larger spacecraft and other applications, and rely on a closed loop system of liquid flow with an evaporator and a condenser, which quickly transports heat from one end to the other. The traditional cylindrical form is not very useful on smallsats, but there have been efforts at JAXA to design and incorporate a flat plate heat pipe on a smallsat, where stainless steel tubing with the working fluid is sandwiched between two aluminum plates. This technology is at TRL 6, though further design modifications would be necessary if smaller platforms like CubeSats are to use it.

Finally, there are further advances in passive *thermal strap* materials and technology still expected. In particular, Thermotive's Pyrovo Pyrolytic Graphic Film straps began flight tests on smallsat missions in 2016. The pyrolytic graphite they use has up to 20x the thermal conductivity of traditional thermal strap materials (copper and aluminum), and the new straps are currently at TRL 6.

There are more areas for further work in active thermal control, as active options from standard spacecraft have been successfully miniaturized to a lesser extent than passive technologies.

Flexible and enhanced active thermal straps (FEATS) are modified versions of thermal straps (described above) that incorporate actively powered heating and conductive elements to provide more targeted heat fluxes (useful for certain electronic instrumentation). Currently, Load Path Aerospace Structures have developed FEATS for smallsats with heat dissipation up to 50 W cm^{-1} and cooling capacity of 35 W, which have been tested but not yet flown.

Several instruments commonly used in spacecraft require cryogenic cooling. For example, high-precision IR sensors benefit from cryogenic cooling as the lower temperatures improve their dynamic range and extend their wavelength coverage. Other instruments like imaging spectrometers, interferometers, and MWIR sensors need cryocoolers to function at the low temperatures required. In general, cryocoolers are associated with longer instrument lifetimes (possibly due to the reduced vibration), high thermodynamic efficiency, and low mass. Cryocoolers have not yet been integrated and flown on smallsats, but several efforts are underway to develop mini-cryocoolers that would be compatible with smallsat missions. Sierra Lobo and NASA collaborated on CryoCubeC-1, the first CubeSat (in this case a 3U spacecraft) to incorporate cryogenic cooling, which is scheduled to perform fluid management and cooling tests on orbit in 2016. In addition to Sierra Lobo, other companies are working to develop smallsat-compatible mini-cryocoolers, currently at TRLs 6 and 7; these include Ricor-USA, Inc., Northrop Grumman, Creare, Sunpower, Inc., and Lockheed Martin Space Systems.

Thermal storage units are another proposed technology for smallsats, which passively stores excess heat (from instruments or from sunlight) until it can be used for future energy use. They have been implemented in the past on traditional spacecraft, usually in conjunction with cryocoolers, but have not yet been used on smallsats. There are two designs for smallsat thermal storage units, both at TRL 5, currently in development at Thermal Management Technologies and Active Space Technologies.

Finally, another active thermal management concept involves the use of *fluid loops* to regulate heat transfer. Usually, fluid loops use mechanical pumping mechanisms to circulate fluid, transferring heat to different places on the spacecraft via forced convective cooling. However, these designs are not portable to smallsats because of their relatively high mass and power requirements. Instead, smallsat operators have shown interest in alternative designs based on lightweight circulator mechanisms. Lockheed Martin is currently developing a smallsat-compatible fluid loop (TRL 3) based on a closed cycle Joule Thomson cryocooler, which has a mass of 0.2 kg and power requirements of 1.2 W, yet can manage 40 W of spacecraft power as a single-phase loop or up to hundreds of Watts as part of a two-phase loop.

Deployable Systems

Definition

This category includes hardware innovations that make more space available within the small satellite and allow for higher performance of other technological subsystems. This could be the result of clever structures freeing up space within the smallsat for instruments or the result of deployable structures unfurling and providing the smallsat with expanded capabilities.

State of the Art and 10-Year Trends

Space-saving structures include *monocoque construction, modular frame design, and card slot systems*, all of which provide shorter time-to-flights for smallsat designers. *Deployable systems* are currently used for solar array panels and antennae. Access to many solar array panels allows the satellite to generate its own energy and not rely on miniaturized batteries. Antennae larger than the standard smallsat size allow for longer range communication. Large deployable gossamer structures can be used as *solar sails* to augment drag and then drive or deorbit the satellite. The NEA Scout concept takes advantage of the CubeSat's constant exposure to sunlight to use a solar sail to push the satellite towards a near-Earth asteroid it can then study.[2]

The NanoSail-D2 CubeSat successfully used a solar sail to deorbit in 2011.[3] *Electrodynamic tethers* are another type of deployable used to deorbit satellites. This mechanism must be 100s–1000s of meters long and harnesses the Earth's electromagnetic field to induce drag on the satellite.[4] *Sun shields* were demonstrated as a method of providing thermal control to a satellite by CryoCube-1 in 2016. CryoCube-1's deployable Sun shield is able to cool the nanosat by over 150 degrees.[5] Also included in this category are *solar panel drive actuators* that can rotate solar arrays by 180 degrees and release actuators that can fracture a fastener with little force.

As is the case for many categories of smallsat technology, there has been a trend towards standardization that may continue over the coming years. In this case, the establishment of a *standard bus and chassis* for smallsats smaller than 12U would accelerate time-to-flight for smallsat missions. As additive manufacturing capabilities mature, one can envision printing large antennae or primary structures on-orbit.

Advances in radiation shielding, such as graded-Z shielding, would benefit the smallsat community. The choice of aluminum to build smallsat structures was motivated by weight and volume concerns rather than by radiation shielding. Spot shielding and sector shielding of critical instruments on a small satellite uses up much needed volume. Graded Z-shielding uses multiple polymers with different atomic weights to shield satellite components from protons, ions, electrons, and photons. Shielding from neutrons is still a work in progress.

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[2] NASA. "NEA Scout," accessed February 20, 2017, https://www.nasa.gov/content/nea-scout.

[3] NASA, "NASA's Nanosail-D 'Sails' Home—Mission Complete," November 29, 2011, http://www.nasa.gov/mission_pages/smallsats/11-148.html.

[4] NASA. "NEA Scout."

[5] J. Berg, "CryoCube-1: A Cryogenic Fluid Management CubeSat." KSC Engineering and Technology, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130013661.pdf.

Data Handling, Processing and Autonomy

Definition

This category encompasses all software, both on the satellite and on the ground, required to carry out the satellite's mission. This includes flight software, instrument software, ground systems software, data storage, processing capacity, and ground-based analytics.

State of the Art and 10-Year Trends

The need for standardization has driven some hardware manufacturers such as Clyde Space to provide flight software that is compatible with their subsystems. Still others have moved towards open source code. General purpose CubeSat flight software called CubedOS is in the process of being developed.[6] The most common source of memory for a CubeSat is *SRAM*, which stores 4MB; *Flash* is more popular for mass data storage, storing 128–256 Mb. On-board computing is provided by *microcontrollers*, *field programmable gate arrays (FPGAs)*, *smartphone-based processing*, and some *open-source platforms*. Along those lines, these open source platforms often also come with open source operating systems such as Linux.

As sensor capabilities increase, on-board computing is increasingly necessary, not only for flight systems but also for onboard data processing to handle some of the data, as sending all of the data back to ground stations becomes a significant drain on power and bandwidth. Basic forms of onboard processing, particularly for video, simply remove individual frames at a set rate before sending data back, which lowers the amount of data to be transmitted while reducing data quality across the board. NASA lists their current data reduction for Earth Observation satellites as 5% as of 2015.[7] Hyperscout, a commercial hyperspectral imager designed for demonstration in December), has onboard data processing at Level 2.[8]

Ground data systems are trending towards *turnkey capabilities* as the numbers and capacities of small satellites increase, and amateur ground stations are no longer able to handle the desired volume and quantity of data. Companies such as Kongsberg Satellite Services provide access to their network of ground stations for small satellite operators,

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6 Vermont Technical College CubeSat Laboratory, "CubedOS: Project Overview," http://www.cubesatlab.org/CubedOS.jsp.

7 NASA, "NASA Technology Roadmaps TA 11: Modeling, Simulation, Information Technology, and Processing," July 2015, https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_11_modeling_simulation_final.pdf.

8 Cosine, "Product Specs," accessed February 20, 2017, http://hyperscout.nl/product/.

allowing them to receive data without developing their own network. Satellite to satellite communication also has the potential to reduce the communication and storage burdens on small satellites by allowing small satellites to transmit data to larger communications satellites and thereby use larger satellites storage and then communication systems to transmit data to the ground.

Processing of small satellite data varies to some degree on the type of data collected—IR, LiDAR, AIS, GPS-RO, and visual imagery, to provide a few examples, all require different types of processing in order to extract data, but this processing, as these sensors have been available for some time, is less of a stumbling block to analytics. And as many satellites capture multiple bandwidths (for example: hyperspectral sensors), or carry multiple sensors, many operators have multiple sources of data.

A variety of approaches exist to analytics beyond this basic processing, while some companies pursue individualized analytics packages, others incorporate COTS modeling packages, and others pursue a combination of both; similarly, some companies use proprietary systems while others use and provide open source code. For example, Digital Globe recently acquired both HumanGeo, which builds on a range of commercial programs such as OmniDex (Hg) and Tiger to create their MineShaft, ISEAX, and ISEBOX packages,[9] and Timbr.io, which builds on open source python code in order to provide analytics for their satellites.[10] Behind these processing packages, cloud storage and cloud computing are frequently essential to handling the large volumes of data and computations from increasing numbers of satellites.

As satellites often carry multiple signals, and on the ground analytics companies often acquire data from a range of satellites, aggregation of data from across multiple satellites and multiple sensor types is a key analytics challenge. This challenge can also include incorporating data from large satellites, aerial imagery, and other data such as cell phone usage or social media trends. For this reason, *multi-modal data fusion* is a key focus of small satellite analytics. Multi-modal data fusion is not unique to the small satellite field, and therefore this technology builds on a range of developments from other fields which handle multiple data streams, such as human machine interaction or biomedical studies.[11] One example of such data fusion is BlackSky's data interface, fusing satellite imagery and social media, and news data to provide insights and alerts to likely areas of conflict.

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[9] HumanGeo, "Data," accessed February 20, 2017, http://www.thehumangeo.com/solutions.html.

[10] Timbr.io, "Collective Intelligence for Data Science," accessed February 20, 2016, http://timbr.io/.

[11] D. Lahat, T. Adalı, and C. Jutten, "Multimodal Data Fusion: An Overview of Methods, Challengesand Prospects," *Proceedings of the IEEE*, Institute of Electrical and Electronics Engineers, July 23, 2015. Multimodal Data Fusion, 103 (9): 1449–1477, https://hal.archives-ouvertes.fr/hal-01179853/file/Lahat_Adali_Jutten_DataFusion_2015.pdf.

Another example of the interplay between signal sources and of the landscape of small satellite analytics is the issue of 3D modeling, a useful tool across applications. LiDAR data can be used to develop 3D elevation maps,[12] which can be taken alongside imagery data to better understand cities and landscapes. However, often organizations would prefer to be able to work solely from imagery data, and offer analysis varying from determining building height to determining stock levels in oil barrels. Companies such as VRICON even offer full surface 3D models based on archived imagery. A continual push for improvement has led 3D modeling from satellite imagery to be a particular focus of IARPA.[13] The 3D modeling teams competing in IARPA's challenge come from a range of backgrounds, including Army intelligence, surveillance and reconnaissance, economic modeling, and video game programming. This is illustrative of how this field can take advantage of a range of advances in computing and analytics.

At this point, software for large satellites is highly standardized whereas software for small satellites is more haphazard, developed by many separate teams, reliant on testing rather than formal verification, and shorter in code length. Small satellites require standard, reliable code bases, but the rapid pace of change in the field currently hinders their development.

Advances are needed in *autonomy, robustness, extensibility, fault protection (radiation tolerance and protection circuits), and auto-code generation*. Software with dynamic resource optimization would allow the small satellite to use its processors more effectively. High-performance multi-processor architecture would allow measurements to be processed on the satellite and transmitted to the ground, taking up less bandwidth than the transmission of the original measurements themselves, reducing the burden on communications systems.

Such *improvements to on-board processing, in addition to autonomous flight systems and navigation*, reduce the burden on ground systems. This is an ongoing process in industry and government. For example, NASA's technology roadmap has already cited 50% data reduction as a needed capability, with additional goals of moving the proportion of satellite downlink decisions made autonomously from 30% to 100%.[7] Additionally, as on-board processing improves, not only would individual satellite processing and autonomy improve, but the ability for satellites to provide intelligence and guidance more directly to other satellites, "tipping and cueing," for example, an RF satellite directing a nearby imaging satellite to take pictures of a location where a signal has been identified. NASA's technology roadmap sets a goal of moving from their current state of the art, where

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[12] M. Alderton, "More Than Meets the Eye," *Trajectory Magazine*, 2016 Issue 4, http://trajectorymagazine.com/trajectory-mag/item/2274-more-than-meets-the-eye.html.

[13] Intelligence Advanced Research Projects Agency (IARPA), "Core3D," accessed February 20, 2017, https://www.iarpa.gov/index.php/research-programs/core3d.

20% of events identified autonomously at TRL 3, to 100% of events identified autonomously at TRL 7, with onboard decision making.[7] Current limitations for onboard processing for small satellites include cost of high quality chips and the weight and power limitations of small satellites.

Movements to greater turnkey capabilities for ground station data handling, satellite to satellite communication, and increasing drives to higher data rate frequencies, whether through shifts from X band to Ka band, or shifts to lasercomm, would increase the amounts of data moving from satellites to operators.

As the amounts of data available increases, the issue of storage and computational resources, even on the ground, would become a potential hurdle, as companies strive to build more efficient algorithms. This surfeit of data highlights the need for increased automation. Currently human analysts remain a key part of recognizing and distinguishing more complex features, but with increasing amounts of imagery, the amount of data they would need to look at would have to be increasingly pared down, with a likely shift to full autonomous identification. *Automated feature evaluation* is becoming developed and established in some companies with feature analysis of properties or identification of objects such as cars or airplanes. This technology does not just build on satellite analytics but also on Earth-based image recognition systems such as robotics, autonomous vehicles, and facial recognition, which are driven in part by advancements in machine learning, a key developing area for all of these fields. As automated feature identification moves forward, so too would automated tracking, pattern of life detection, and, building from those, predictive analytics.

Key Players

Onboard Computing

Microcontrollers and FPGAs

- GomSpace, ISIS, Pumpkin, Tyvak, Xiphos, Space Micro, NanoSatisfi, Utah State University

Smartphone processors

- SSTL, NASA

Open Source

- Arduino, BeagleBone, Raspberry Pi, Intel[12]

Ground Systems

- Kongsberg Satellite Services, Surrey Satellite Technology Ltd, ISIS, Tyvak, Clyde Space, ASAT[12]

On the ground data analytics

- IARPA, SPIRE, Descartes, Terra Bella, BlackSky, Digital Globe, Hawkeye 360, Kongsberg Satellite Services, Spire

System Integration

Definition

System integration refers to the processes used to incorporate subsystems into a complete bus or satellite. It can be done either by mission designers themselves, or by vendors seeking to sell ready spacecraft buses to be used for a variety of customer missions.

State of the Art and 10-Year Trends

Just as small satellite technology has taken a dual approach to development by both starting with larger technologies and scaling them down and also starting with small buses and growing, small satellite integration companies are evolving from both larger, more traditional satellite companies with lots of experience working with larger satellites as well as small startups that gradually build up from subsystems components suppliers.

One of the major trends is that companies who were once mostly suppliers of several different major subsystems components are now *selling whole spacecraft buses*. Several of these companies started out as suppliers and are working towards assisting their customers with operations as their business and expertise grows. Examples include GomSpace, ClydeSpace, Blue Canyon Technologies, Innovative Solutions in Space (ISIS), and Pumpkin. The Japanese company Canon also is both a parts supplier and seller of fully integrated satellites. As time goes on, these companies are not only offering components and whole buses, they are also transitioning into full operations capabilities for customers.

Some of the companies that have or are planning to operate large constellations are also building their own components and integrating their own buses. Planet and SpaceX are examples, as discussed in the next section.

Other companies are working closely with suppliers to offer greater capabilities to customers. Tyvak has partnered with MMA Design to integrate better deployable structures for better power and communications capabilities. Tyvak's current portfolio is 90% government work, but they are expanding their customer base on the commercial side.

Traditional players in the satellite integration market include Space Systems Loral, Lockheed Martin, Boeing, Airbus, Northrop Grumman, Orbital/ATK, and Sierra Nevada. While these companies have in the past focused on larger satellites and have much expertise in the satellite world, the price points for small satellites may be too low for them to enter the market of CubeSats.

Companies are also trying to reduce the time from mission conception to launch. For large satellites, this time could be on the order of a decade. Companies are now aiming towards 6 months for some simple missions, and no more than 5 years for the most complex constellations.

Due to larger quantities of satellites, companies are also looking to *improve their assembly lines through automation*. Several companies are investing in automation for major subsystems components; while the performance of these automatically assembled subsystems might not reach the state of the art for individual subsystems as described in the previous sections, from a manufacturing and assembly perspective they represent a change in how the state of the art is evolving for lower cost, higher quantity production. This is especially key when it comes to satellite constellations that require many satellites, so companies have an incentive to work on bringing down the cost per individual satellite in unprecedented ways.

Other companies are working on innovative ways to build satellites with "bricks," where modular designs can lead to decreases prices for similar performance. Novawurks is designing "satlets" that serve as platforms with integrated capabilities that just need to be activated in order to work, so all customers receive essentially the same hardware regardless of whether or not they need the extra performance it can provide.

There has also been additional research over the past 15 years in mission concept design selection. While this research is not as valuable to the private sector, since private sector success can be measured with a multitude of cost-based value centric design methodologies, this research is especially useful when benefits are not measured in cash rewards but instead some aggregate utility. These methods are particularly useful when designing constellations given the various tradeoffs between the capabilities of an individual satellite versus the capability of the constellation as a whole.

Constellations

Definition

This category encompasses all missions that require or leverage more than one space-based asset to conduct their primary mission. Satellite constellations require advanced capabilities in many of the above areas depending on their baseline missions. For example, some constellations may require basic propulsion systems to maintain their altitude and physical separation within an orbital plane, while others may require advanced, precise systems in order to conduct formation flight. Other constellations may require no propulsion systems at all because the spacing of the satellites is not critical.

State of the Art and 10-Year Trends

Systems and constellations of small satellites rely on advancements in many of the other technological areas previously discussed. Currently unrealized technologies required for constellations are *bulk and streamlined manufacturing*, *constellation deployment and operations*, and *data management*. Constellation launches are likely to occur on dedicated vehicles, unlike current smallsat launches which are secondary payloads on launch vehicles. Constellations and formation flying would also require software with greater capabilities, especially to enable inter-satellite communication and fleet management. Current science data management does not include more than ten spacecraft.

The current state of small satellite constellations is expected to advance significantly over the next ten years compared to what is considered the state of the art today as many new stakeholders begin to enter the small satellite constellation business. These entities plan to use satellite constellations for Earth observation, signals intelligence, synthetic aperture radar, and global broadband communications.

"State of the art" for satellite constellations can be examined from a number of perspectives, including how small the satellites are in a constellation while still remaining capable of conducting their mission, how much satellites in a constellation communicate with each other to conduct their mission, how fixed, organized, and controlled their orbits need to be to conduct their mission, and how many satellites are in the constellation. While there are a number of advanced communications satellite constellations, such as IntelSat, TDRS, Iridium, Sirius,/XM, DirecTV, and DSCS, these are all composed of large satellites and do not fit within the scope of this study.

In terms of constellation size, Planet (formerly Planet Labs) represents the state of the art of small satellites today. Their constellation of 3U-sized Dove satellites continues to grow, and the time to take an image of the entire globe would shrink from days to hours. However, these satellites do not communicate with each other, so there is no in-space networking.

In terms of how well satellites within a constellation work together, NASA's Nodes mission represents the current state of the art for small satellites. Nodes is an offshoot of the EDSN mission that was destroyed during launch failure in November 2015; Nodes is a smaller system that demonstrates many of the same functions that EDSN intended to demonstrate. Future commercial missions, such as commercial communications constellations and federated satellites, should improve upon these capabilities.

Ongoing research in federated satellite systems could pave the way for future markets where satellites operate as part of a network of independent owners and operators that communicate to share resources such as downlink availability, processing power, and potentially electrical power through microwave beaming (e.g., Kepler Communications (Canada) and Analytical Space (U.S.) are developing constellations to serve as relay in support of large constellations). Individual satellites for missions could be launched that rely on a federated network's excess resources so that some satellites "supply" and others "consume," such that some satellites are intentionally designed to be less capable than their mission requires because they can rely on other satellites that are designed to be over-capable and sell their extra services. A terrestrial example of this is cloud computing, where server down time can be leased out to other users who need the processing power for short bursts of time.

SpaceX plans to launch more than 4,000 satellites into LEO "to provide a wide range of broadband and communications services for residential, commercial, institutional, governmental and professional users worldwide," SpaceX wrote in its FCC application. The constellation would use optical inter-satellite links to relay data around the globe. SpaceX plans to build these satellites in their new Seattle facility.

Hawkeye 360 is planning to operate a constellation of satellites to produce radio-frequency based data analytics. GomSpace would be providing the software-defined radio instruments that would be used as the payload. DSI would be providing the thrusters, which use water as the primary propellant. The University of Toronto Spaceflight Laboratory would be supplying the buses.

Terra Bella (formerly Skybox Imaging) is a Google subsidiary that intended to provide Earth observation data and data analytics. SSL won the contract for building Terra Bella's satellites. The company is not interested in persistent video coverage of the planet, but instead would focus on analytics and data products it can sell from imagery of the planet several times per day.

OneWeb plans to launch about 720 satellites to provide global internet broadband coverage. Airbus and OneWeb have formed a partnership called OneWeb Satellites to build the first 10 satellites in France, but OneWeb plans to build a large factory in Florida building the rest of the constellation and make continuous upgrades to the satellites over time. The satellites would not be interconnected, but would instead be required to be in view of one "gateway ground station," in order to achieve connectivity. OneWeb plans to have 55 to 75 gateways around the world.

Iceye is planning to launch a constellation of small satellites to conduct synthetic aperture radar. The company plans to launch its first satellite in 2017 with Vector Space Systems and has already raised over $5 million through venture capital and the European Union's Horizon 2020 research program.[14] The current design for the constellation would consist of 21 satellites.[15]

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[14] C. Henry, "Iceye Prepares Prototype for 2017 Launch," *Via Satellite*, December 8, 2015.

[15] Gunter's Space Page, "ICEYE," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/iceye.htm.

Aperture synthesis interferometry is one area where small satellites in formation flight could produce imagery with higher resolution than any single large aperture could. This technique is primarily applicable to radio astronomy but could have users in infrared and optical imagery too. Despite the many potential applications of smallsat constellations, none of the organizations interviewed were particularly interested in using them to conduct aperture synthesis interferometry. The complexities of non-Keplerian orbits, inter-satellite communications, and in-space interferometry make this challenge an area that may not be tackled by private companies anytime in the next 10 years.

There is concern that a growing number of satellite constellations would lead to a dangerous increase in the amount of orbital debris. Some of these proposed constellations include more satellites than all the satellites that have ever been launched up to this point in history. Space situational awareness capabilities are improving thanks to better GPS precision and better onboard instrumentation.

Appendix E.
International Small Satellite Activities and Trends

For many countries, launching a smallsat (often a CubeSat) is its first foray into space. Recently, for example, Ireland announced its first satellite in space with the launch of a 3U CubeSat.[1] This appendix addresses the international small satellite community across Asia, Europe, the Middle East, Australia, and Africa, and highlights overarching trends in these regions and across the international small satellite community. See Figures E-1 and E-2.

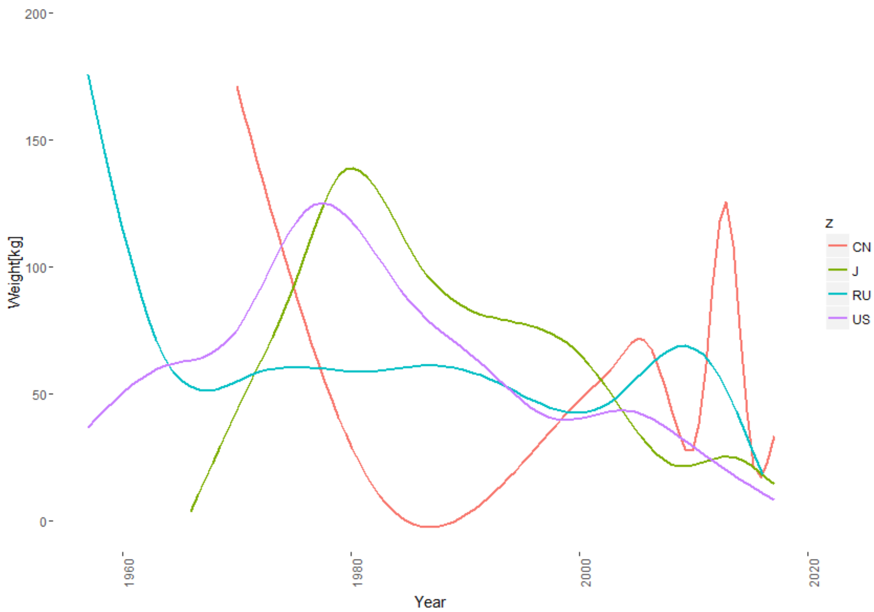

Figure E-1. Trends in Average Small Satellite Mass by Country

1 https://www.rte.ie/news/business/2017/0523/877210-satellite/.

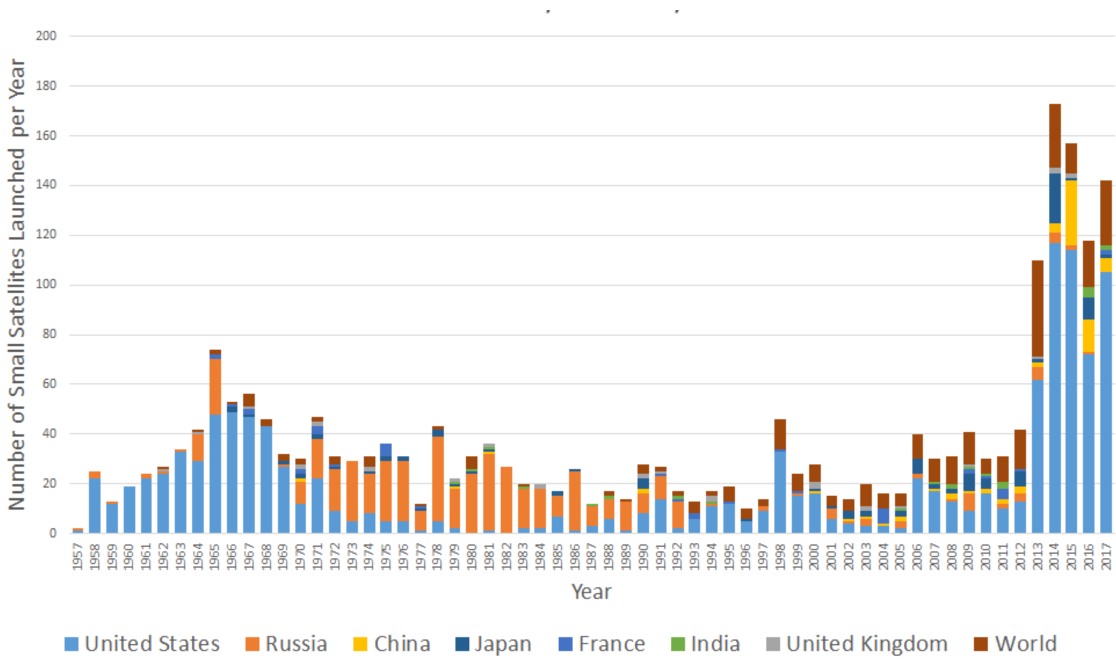

Figure E-2. Small Satellite Launches per Year by County

Overarching Points

- Companies are increasingly international, with offices and manufacturing established in many countries. However, the International Traffic in Arms regulations (ITAR) was cited by many interviewees as a reason companies move development out of the United States or don't move development into the United States. Many companies still find it beneficial to have a U.S. office, especially European companies, indicating the continuing value of the U.S. market.
- Current research and development (R&D) efforts are underway globally to expand small satellite launch options; if global efforts successfully develop new technologies to make space more accessible, access to space could expand to countries without current traditional internal launch capabilities. In the near term, most new space countries are reliant on rideshares, which remains a significant bottleneck.
- Small satellites are becoming cheap enough for emerging countries to buy, regardless of whether they have the internal capabilities to build them on their own. Through contracts or partnerships, emerging countries would be able to train their own workforce or otherwise improve their own internal capabilities.

- Data selling also provides access to space information without access to space itself. The data products of U.S.-based companies or companies with U.S. offices may not remain restricted to the United States.
- Emerging countries still often pursue internal space programs for various reasons (national pride, developing Science, Technology, Engineering, and Math (STEM) workforce, specific technical goals, etc.) but typically take advantage of international partnerships and existing technology in order to increase development and gain access to space. These emerging players typically do not see small satellites as an additional or alternative capability, but as a wholly legitimate means of entering the space world.

Regional Distribution

Key Takeaways

- Asia and Europe are strong players in the small satellite field, noted by stakeholders as having important markets and significant technological development.
- Asia in particular is noted as a growing region in the field, with new startups and increasing availability of launch.
- Government is the primary source of funding in most emerging countries; although there is limited foreign private (venture capital) funding, such funding has not proliferated into the new space industry as widely as has occurred within the United States.
- Countries with a longer space heritage, such as Russia, China, and potentially India, are often perceived as having not fully leveraged their satellite experience for small satellites, with government space programs having placed more emphasis on large satellites. However, this attitude is changing, particularly in China.
- South American countries have demonstrated interest in small satellites given a growing number of government sponsored small satellite missions; Academic institutions are key in developing technologies.

Asia

Key Takeaways

- Japan is seen internally as mostly focusing on keeping small satellite costs low, India is regarded by stakeholders as a place to watch, Singapore is a popular location to have neutrality and as a gateway to the Asian market—the popularity of the location indicates the industry's belief that Asian markets will continue to grow. Singapore is also seen as having well developed technologies and a strong technology workforce.

- Japan and India are becoming sources of expertise and training for new space nations, in Southeast Asia and beyond.
- Other countries newer to the space field, including Bangladesh, Vietnam, Thailand and the Philippines, among others, have also shown interest in small satellites, particularly as they relate to crop and natural disaster monitoring.[2] In part of the region prone to damage from natural disasters—including Japan—this is an application of particular interest.
- Though these sections are broken up as to cover government, academic, and industry institutions, it should be noted that in Asian countries these institutions are often closely tied together. Where possible, connections across sectors have been highlighted.

Japan

Japan has established a strong presence in the small satellite world. 48 of the 664 organizations identified in the STPI database are headquartered in Japan. There is strong involvement in small satellites across government, university, and industry.

According to stakeholders within Japan, small satellites are seen less as a space technology and more as a way to improve life in Japan by having better remote sensing to predict and address disasters. Earth observation, rather than communication, has been a focus. One reason for this focus because Earth observation allows for disaster relief and predictions, such as tsunami warnings, which are a key national interest. Additionally, it is easier to break into the Earth observation market. Data can be sold as soon as a single satellite is on orbit. However, to effectively serve customers, a constellation of communications small satellites is necessary, and in this regard, companies such as SpaceX and OneWeb have a significant lead.

There is less of a focus on pushing the state of the art in small satellite technology and more of a focus on making improvements without increased cost, and moving more

[2] A. Harebottle, "The Big Power of the Smallsat Revolution," *Via Satellite*, http://interactive.satellitetoday.com/via/asia-edition-2017/the-big-power-of-the-smallsat-revolution/?utm_content=buffer38855&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer.

production domestically. Broadly, the market for Japanese technologies in this field is seen as their local region of Southeast Asia, though they build partnerships more globally.[3]

Government

Japan's space agency, the Japan Aerospace Exploration Agency (JAXA), has not been strongly involved in small satellites. Small satellites, rather than being seen as area of space and science research, are largely seen as an area of industrial development, and so fall under the purview of the Ministry of Economy, Trade, and Industry (METI), which has a Science and Technology budget of 5.41 billion U.S. dollars.[4] In contrast, JAXA has focused on large satellites and other platforms. JAXAs support of small satellites largely comes in the form of launch and deployment opportunities, including rideshares for universities, deployment via the robot arm on the ISS, Kibo, and the development of a small satellite launcher.[5] Other relevant investments include development of de-orbiting technology (e.g., Kounotori Integrated Tether Experiments (KITE)[6]), and a broader interest in space debris management.[7] However, generally, JAXA is not seen as a customer of small satellite technologies.

JAXA has participated in collaborative projects with other government funded small satellite projects, including developing the antennae for a small Synthetic Aperture Radar (SAR) satellite program under the Cabinet-level Impulsing Paradigm Change through Disruptive Technologies Program (ImpACT) program. The ImpACT program is one of two government-funded programs designed to compensate for the relative lack of venture capital in Japan by funding innovative technologies.[8] Another includes the Innovation Network Corporation of Japan (INCJ).[9] However, the only small satellite company supported by the Innovation Network Corporation is Astroscale, a space company discussed in the Singapore section. Together, ImpACT and INCJ have significant funding,

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3 Expert interview.

4 H. Ikukawa, "Science, Technology and Innovation Policy in Japan," presentation at the 22nd German-Japanese Joint Committee on Cooperation in Science and Technology, Bonn, Germany, 30 November 2016.

5 L. Grush, "Tiny Japanese Rocket Fails to Make it to Orbit after Communications Issue during Flight," *The Verge*, January 16, 2017, http://www.theverge.com/2017/1/16/14285080/jaxa-ss-520-4-small-rocket-satellite-launch-fails.

6 Q. Kiokno, "JAXA KITE Mission to De-orbit Dangerous Space Junk," *STGIST*, December 11, 2016, http://stgist.com/2016/12/11/jaxa-kite-mission-to-de-orbit-dangerous-space-junk/.

7 JAXA, "JAXA: Explore to Realize," promotional material.

8 For more information, visit ImPACT's website at http://www.jst.go.jp/impact/en/intro.html.

9 For more information, visit INCJ's website at http://www.incj.co.jp/english/.

relative to Japan's R&D budget. ImpACT's budget is $550 million USD over 5 years,[10] and INCJ has $2.5 billion USD from the government, with an additional $122 million from companies. While only a fraction of this money goes to small satellite projects, this does present a sense of scale for the value of public-private partnerships in science and technology (S&T) development in Japan, especially given that the total S&T budget is $34.7 billion USD.

Academic

Universities have also pursued small satellite technology across Japan, mostly in CubeSats. Two examples include the Kyushu University and University of Tokyo CubeSat programs. The Kyushu Space Systems Dynamics lab allows graduate students to work on small satellite projects,[11] including IDEA, In-situ Debris Environmental Awareness Project, a small satellite designed for monitoring space debris.[12] The University of Tokyo has developed a deep space small satellite in collaboration with JAXA, as a secondary payload with Hayabusa, the asteroid explorer.[13] University of Tokyo and Keio University have also collaborated on the SAR satellite project. Keio University is significantly involved in the ImpACT program that has funded the small SAR satellite, as one of their Professors, Professor Shirasata, is a manager for the fund. Tokyo University has collaborated with the Vietnam National Satellite Center in building and launching a Vietnamese CubeSatS, and Hokkaido University and Tohoku University partnered with the University of the Philippines to develop the Philippines' first satellite, aimed at disaster monitoring. The Kyushu Institute of Technology has similarly reached out beyond Japan to collaborate on a nanosatellite with Bangladesh's BRAC University and the Bangladesh Space Research Organization.[14] Indeed, Kyutech has its own program, BIRDS, designed to train students from non-space faring nations, both in nearby countries such as Bangladesh and elsewhere, to build and operate CubeSats.[15]

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[10] Ikukawa, "Science, Technology and Innovation Policy in Japan."

[11] For more information, visit the Kyushu Space Systems Dynamics lab website at http://www.eng.kyushu-u.ac.jp/e/research/aero/lab/lab08.html.

[12] M. Uetsuhara, T. Hanada, M Tagawa, and H. Hinagawa. "IDEA: In-situ Debris Environmental Awareness," presentation at the 3rd Nano-Satellite Symposium, November 12, 2012.

[13] JAXA, "Flight Status of Micro Deep-Space Explorer PROCYON," *JAXA*, December 4, 2014, http://global.jaxa.jp/press/2014/12/20141204_procyon.html.

[14] Harebottle, "The Big Power of the Smallsat Revolution."

[15] Ibid.

Industry

Outside of government and academia, Japan is noted for its strong technology industry. Some of the larger industries are now making moves to serve the small satellite community in addition to their more traditional markets by providing small satellite components and services. This is something that the government is trying to encourage through the Next Generation Space System Technology Research Association (NESTA),[16] with the goal of moving more of the technical production behind small satellites to Japan, rather than importing it. The advanced manufacturing industry has been encouraged to shift some development of components to make them space worthy, focusing on low cost, and moderate reliability,[17] rather than state of the art components.

There are several examples of large companies shifting to small satellite technologies already occurring, Canon develops cameras that can be placed on small satellites,[18] and is now developing their own 50 kg small satellite busses, with future plans for developing Near-IR capabilities. Additionally, IHI Aerospace Co, a large aerospace firm, is now expanding to small satellite launchers[19] and electric propulsion for small satellites.[20]

Technology development of small satellites is not limited to large firms working on small satellites, as there are some small satellite startups, including Axelspace which is selling 50 kg small satellites. Their first customer is WeatherNews, looking at Arctic shipping lanes, and the company has another project with the University of Tokyo. They are assembling their own Earth observation constellation, AxelGlobe. The constellation is planned to be made of 50 microsatellites of 100 kg, with resolution of 2.5m panchromatic and 5m multispectral, starting with the launch of two prototypes in 2017 and with the entire constellation being launched in 2022. Axelspace's plans distinguish themselves from other Earth observation companies by having all of their satellites in the same orbital plane, allowing for 14 revisits per day. They have no plans for upgrading imaging technology between 2017 and 2022, so images would be comparable over time, though there would be differences in the addition of de-orbiting technology and the reduction of weight and volume of components between generations. For now they are conducting most of their work in house, but they see a role for the Japanese government in developing de-orbiting

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16 For more about NESTRA, see their website http://www.nestra.jp/eng/index.html.

17 NESTRA, "Purpose: Next Generation Space System Technology Research Association," accessed February 19, 2017, http://www.nestra.jp/eng/mokuteki.html.

18 D. Mathies, "Canon Looks to the Final Frontier with New 5D Mark III Based Imaging Satellite," *Digital Trends*, October 14, 2016, http://www.digitaltrends.com/photography/canon-imaging-satellite/.

19 IHI Aerospace Co., Ltd., "Epsilon Launch Vehicle," accessed February 19, 2017, http://www.ihi.co.jp/ia/en/product/rocket_b_05.html.

20 Ibid.

technologies as well as improving lightweight, cost-competitive components that Axelspace can then use. Ultimately, though, Axelspace does not see the government as a customer for their satellites and services.

We identified a few illustrative small satellite startup companies in Japan to highlight. First, Interstellar Technologies Inc. is looking to make a small satellite launcher.[21] Another space startup is Infosteller, which seeks to connect antenna owners and satellite operators in order to make effective use of idle antenna time. While they are not producing small satellite specific technology, if successful, this technology has the potential to reduce costs for small satellites. This startup is small, with only 6 employees, but plans to have 100 sites by 2018. They have 31 million yen in capital from private sources, according to stakeholder interviews.

Japan does have a tech VC environment,[22] though not one with a strong and specific focus on space technologies. Generally, Japanese venture firms that specify beyond technology focus on Internet or digital media startups.[22] However, small satellite startups such as Axelspace and Infostellar were able to gather private funding,[23] with the government significantly augmenting the VC environment, as well as providing technology collaboration.

Singapore

Singapore is an up-and-coming player in the small satellite world, frequently referenced by small satellite stakeholders in interviews. Much of Singapore's internal work on small satellites is based in universities. However, Singapore is becoming a hub for the small satellite industry by attracting foreign companies, encouraging them to see Singapore as neutral access point for the Asian market.[24]

Government

Singapore has no national space agency, however, the Economic Development Board has an Office of Space Technology and Industry. The office was formed in 2013 to

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[21] For more on Interstellar, visit their website http://www.istellartech.com/company

[22] T. Tsuchiya, "Meet Japan's Seed Accelerators and VC Firms," *The Bridge*, April 18, 2013, http://thebridge.jp/en/2013/04/japan-seed-accelerators-vc-firms.

[23] Nikkei, "Japanese Companies to Invest in Microsatellite Venture," *Nikkei Asian Review*, September 16, 2015, http://asia.nikkei.com/Business/Deals/Japanese-companies-to-invest-in-microsatellite-venture.

[24] This is representative of Singapore's general economic attitude and motivation for staying as diplomatically neural as possible. This attitude is highlighted in Singapore Ministry of Foreign Affairs, "Straits Times: Singapore: The Hyphen Connecting the World and Asia," accessed February 19, 2017, https://www.mfa.gov.sg/content/mfa/media_centre/singapore_headlines/2012/201209/news_20120929.html.

coordinate investments in space.[25] Additionally, there is an Agency for Science, Technology, and Research, which helps drive R&D startups and projects, despite not having a specific Space branch. DSO National Laboratories, Singapore's defense R&D center, has also been involved in small satellites through their partnership in the Satellite Research Center (SaRC), which also includes ST Electronics, a Singapore defense manufacturer (with the majority of the stock owned by the government) and the Nanyang Technological University, discussed further below.[26]

Academic

Singapore's government plans to build up a pool of talent and training in space technology by supporting university small satellite programs. Several examples of this can be seen, including the National University of Singapore and the Nanyang Technological University.

The National University of Singapore recently started to build up a small satellite heritage, with their first satellites launched in 2015. These satellites went beyond repeating a simple student CubeSat model. One of the satellites was designed to test small quantum technologies in space in pursuit of developing quantum communications technologies similar to technologies that China has developed.[27]

The Nanyang Technological University has been an early driver of small satellites in Singapore, building a small satellite tradition since the first Singapore-built satellite, VELOX 1, a 3U CubeSat, was launched in 2014.[28] VELOX 1 focused on Earth observation, with an image sensor built in house, in addition to verifying other technologies and carrying a quantum physics experiment[29]. VELOX 1 also contained a picosatellite, VELOX P3, released from VELOX 1 after launch. For this first project, the University worked as part of SaRC, discussed above.

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[25] T. Lee, "As Space Industry Democratizes, Tiny Singapore Could Play a Leading Role," *Tech in Asia*, January 28, 2015, https://www.techinasia.com/space-industry-singapore-emtech.

[26] For more information, visit Nanyang Technological University's webpage at http://www.sarc.eee.ntu.edu.sg/aboutUs/Pages/DirectorsMessage.aspx.

[27] Asian Scientist, "Singapore Universities Launch Satellite," *Asian Scientist*, December 22, 2015, accessed February 19, 2017, http://www.asianscientist.com/2015/12/tech/singapore-universities-launch-satellites/;A. Navarro, "Scientists Test Quantum Satellite Device in Space: What This Means for the Future," *Tech Times*, June 3, 2016, http://www.techtimes.com/articles/162721/20160603/scientists-test-quantum-satellite-device-in-space-what-this-means-for-the-future.htm.

[28] Gunter's Space Page, "Velox-1 (Velox 1-NSAT)" accessed February 19, 2017, http://space.skyrocket.de/doc_sdat/velox-1.htm.

[29] Amsat-UK, "Student Nanosat VELOX-1," *Amsat-UK*, April 22, 2012, accessed February 29, 2017, https://amsat-uk.org/2012/04/22/student-nanosat-velox-i/.

The Nanyang Technological University has launched six new satellites in 2015 with ISRO's Polar Satellite Launch Vehicle (PSLV).[30] Singapore is too small of a country to support an indigenous launch provider.

Industry

Singapore's government has focused on attracting international space companies to open in Singapore. Its diplomatic neutrality makes it a popular location for companies to start or open up new Asia offices. This has provided several opportunities for collaboration.

For example, the Nanyang Technological University's small satellite program, as discussed previously, collaborates with Thales Alenia Space, a key European company, which has opened Thales Solutions Asia in Singapore. The creation of a joint research laboratory, S4TIN, in NTU has allowed the university to take advantage of the technology expertise in Thales Alenia.

In addition to Thales, Spire (U.S. based, with another office in the UK), Clyde Space (UK), and GomSpace (Denmark) all have or are placing offices in Singapore to reach Asian markets, in addition to potentially adding new manufacturing facilities. A number of interviewees noted that keeping R&D and manufacturing out of the United States allows companies to avoid ITAR restrictions when selling internationally. Singapore benefits from existing experience in semiconductors and other consumer electronics, and is regarded as having a strong technology workforce, which is another factor drawing companies from outside Singapore.

Companies originating in other countries have found advantages in developing their headquarters in Singapore. For example, Astroscale, though founded by a Japanese entrepreneur, is based in Singapore for neutrality in dealing with other nations. The company has since opened a Tokyo office, and also partners with Yuki, a Japanese company, for manufacturing,[31] as well as receiving funding from the Japanese government through the Innovation Network Corporation of Japan. Additionally, Microspace Rapid is officially a Singapore small satellite company, with another office in Italy, despite the fact that the founder is Italian.[32]

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[30] J. Chow and N. Ganapathy, "Straits Times: Milestone for Singapore as Six Satellites Launch into Orbit," Ministry of Foreign Affairs Singapore, accessed February 19, 2017, https://www.mfa.gov.sg/content/mfa/media_centre/singapore_headlines/2015/201512/headlines_20151217.html#.

[31] A. McKirdy, "Astroscale Opens Lab in Tokyo in a Bid to Clean Up Space Junk," *Japan Times*, May 15 2015, http://www.japantimes.co.jp/news/2015/05/15/business/tech/astroscale-opens-lab-tokyo-bid-clean-space-junk/#.WG04X_krKUk.

[32] For more information, visit Microspace's website at http://www.micro-space.org/rule.html#company.

Generally, the perception by observers of technology industries in Asia is that the high level of government involvement in Singapore's companies creates an environment that doesn't favor an extensive startup community.

India

Government

The India Space Research Organization (ISRO) is India's national space agency. India has a strong launch program with ISRO's PSLV, which provides rideshare to numerous small satellites both from within and from outside India. ISRO is also developing a scramjet in hopes of developing reusable launch systems in the future, which would further reduce launch costs.[33] India is also reaching out to provide their satellite technology to other countries, even beyond their local region, with a recent agreement to build an Earth observation satellite for Armenia and train Armenian scientists to handle the satellite and data.[34] ISRO outsources much of its manufacturing to private Indian companies, however up until mid-2016 these companies have only been supplying components, while ISRO assembles and integrates. As India hopes to launch >10 Indian satellites a year, it is now offering contracts for the manufacture of full satellites, rather than just components, to private companies.[35] This outsourcing is discussed further below.

Academia

The university system, supported by ISRO, has been developing small satellite expertise since their first university picosat launch around 2010.[36] ISRO not only provides launch services but also technical expertise to universities producing small satellites. Examples include Sri Ramaswamy Memorial (SRM) University, which launched a small

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[33] Department of Space: Indian Space Research Organization, "Reusable Launch Vehicle–Technology Demonstration Program (RLV-TD)," accessed February 19, 2017, http://www.isro.gov.in/technology-development-programmes/reusable-launch-vehicle-technology-demonstration-program-rlv-td; V. Sharma, "ISRO Scramjet Engine Test: Here's What It Signifies for the Space Agency," *Indian Express*, August 29, 2016, http://indianexpress.com/article/technology/science/isros-scramjet-technology-why-is-it-important-for-the-space-agency-3000387/.

[34] SpaceWatch Middle East, "India to build Earth observation satellite for Armenia, build human capacity, *SpaceWatch Middle East,* https://spacewatchme.com/2017/04/india-build-earth-observation-satellite-armenia-build-human-capacity/

[35] P. Bagla, "ISRO Throws Satellite Making Open to Private Sector," *NDTV*, June 24, 2016, http://www.ndtv.com/india-news/isro-throws-satellite-making-open-to-private-sector-1423043.

[36] Staff Reporter, "Students' Satellite Project All Set to Take Off," *The Hindu*, April 2, 2010, http://www.thehindu.com/news/cities/bangalore/Students-satellite-project-all-set-to-take-off/article16352464.ece.

satellite in 2011, designed for greenhouse gas monitoring;[37] Indian Institute of Technology (IIT) Bombay launched a small satellite named Pratham in 2016 as a technology demonstration mission. The satellite carried a Global Positioning System (GPS) receiver and sun sensor, as well as two communication antennas. The satellite was designed to test the bus system, built in house, in hopes that it could provide a platform to test new technologies from the university.[38] Pes University's Crucible of Research and Innovation also launched in 2016, an imagery satellite called Pisat.[39] Upcoming launches include one small satellite from IIT Madras, IITMSAT, which was previously scheduled to launch in 2016. This satellite is designed to monitor charged particles in order to aid in earthquake prediction.[40] Support from ISRO has thus far been successful in encouraging university efforts.

Industry

The PSLV has created a draw for outside companies to work with India. For example, one stakeholder interviewed is building a manufacturing facility in India in exchange for PSLV launches. In discussing the PSLV as an attraction for companies to build in India, it should be noted that U.S. companies have to file with the U.S. Government for exemptions to Federal Aviation Administration (FAA) and Commercial Space Transportation Advisory Committee (COMSTAC) policy to be allowed to buy launches on ISRO's launchers, as India has not signed a Commercial Space Launch Agreement.[41]

In terms of local industry, a major Indian satellite company, Bharti, is one of the founding shareholders of OneWeb. The Indian company would be the "preferred distributor" of OneWeb broadband services in India, Bangladesh, Sri Lanka and Africa.[42] Dhruva Space is a local company that looks to assemble, test, and operate satellites. (See

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[37] Staff Reporter, "SRM University's satellite to take to the skies," *The Hindu*, October 11 2011, accessed February 19, 2017, http://www.thehindu.com/news/cities/chennai/srm-universitys-satellite-to-take-to-the-skies/article2527789.ece.

[38] IIT Bombay Student Satellite Initiative, "Pratham," accessed February 19, 2017, http://www.aero.iitb.ac.in/pratham/.

[39] PES University "Evolution of PISAT," accessed February 19, 2017, http://pes.edu/pisat/.

[40] Indian Institute of Technology Madras (IITMSAT), "IITMSAT: A Student Satellite Initiative," presentation, http://iitmsat.weebly.com/.

[41] P. B. De Selding, "U.S. Launch Companies Lobby to Maintain Ban on Use of Indian Rockets," *SpaceNews*, March 29, 2016, http://spacenews.com/u-s-space-transport-companies-lobby-to-maintain-ban-on-use-of-indian-rockets/.

[42] Economic Times, "Bharti Enterprises Buys into OneWeb, Aims to Bring Internet to Rural Places via Satellites," *Economic Times*, June 26, 2015, http://economictimes.indiatimes.com/industry/telecom/bharti-enterprises-buys-into-oneweb-aims-to-bring-internet-to-rural-areas-via-satellites/articleshow/47815759.cms.

case study in Appendix G.) Founded in 2012, this company initially planned to launch in 2016 but has been delayed. They've partnered with Berlin Space Technologies in order to develop EO satellites in India.[43] This company may help ISRO take up the challenge of launching more Indian satellites and become the Indian industry's first provider of whole small satellites.

China

Government

The Chinese National Space Administration (CNSA) is China's primary government space agency. The Chinese military is heavily involved in China's space endeavors, controlling launch options for would-be satellite operators. Launch is a key bottleneck. China has been fairly conservative in allowing rideshares, though they have recently become more open to rideshares with domestic university technology demonstration small satellites. China lists space infrastructure as a key priority for the next five years, including satellite remote sensing, communication, and navigation, where small satellites have an opportunity to play a role.[44] Generally, where small satellites are used, larger small satellites are favored over CubeSats.[45] Additionally, deep space exploration is a priority, based on the 5 year plans, with the Chang'e missions continuing to pursue lunar exploration, and a university CubeSat is expected to be included with Chang'e-4. China has a stated interest in protecting against and avoiding generating space debris, protecting space by ensuring their own satellites and rockets deorbit after their end of life and contributing to space debris monitoring.[44] However, tests of anti-satellite missiles and a small satellites (Aolong-1 and Shiyan) that can grab onto and remove other satellites create concerns for the broader community.[46]

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43 Entrepreneur India, "It's a Space Age! Dhruva Set to Privatize India's Satellite Industry," *Entrepreneur India*, September 24, 2015, https://www.entrepreneur.com/article/250987.

44 Xinhuanet, "China's Space Activities in 2016," *Xinhuanet*, December 27, 2016, accessed February 20, 2017, http://news.xinhuanet.com/english/china/2016-12/27/c_135935416_2.htm

45 Expert Interview.

46 P. D. Spudis, "Continuing the Long March to the Moon," *Air & Space Magazine*, July 1, 2016, accessed February 20, 2017, http://www.airspacemag.com/daily-planet/continuing-long-march-moon-180959672/;J. Sciutto and J. Rizzo, "War in Space: Kamikazes, Kidnapper Satellites, and Lasers," CNN, November 29, 2016, http://www.cnn.com/2016/11/29/politics/space-war-lasers-satellites-russia-china/index.html?sr=twcnni113016space-war-lasers-satellites-russia-china0155AMStoryLink&linkId=31718930.

Academic

While there is not a long heritage of small satellites in universities in China, there has been rapid growth in small satellite programs and aerospace schools at universities, with nearly every university now having an aerospace school.[47] There does appear to be a clearly distinguished top-league of schools emerging, according to observers consulted in this research, including Harbin Institute of Technology, Beijing Institute of Technology, Beihang University, Northwestern Polytechnic University (NWPYU), Nanjing University of Aeronautics and Astronautics (NUAA), and Tsinghua University. There is a substantial focus on building new testing facilities and other facilities to support small satellites. Newer programs are more focused on education (e.g., Xidian), while more established programs (e.g., NWPYU, NUAA) are more closely linked to the military and other institutions, and other national programs that are more ambiguous. Programs highlighted by observers are listed below.

- NUAA launched Tian Xun- in 2011, with a CCD camera payload. They also have stealth laboratory work, as well as work on GPS payloads, one of which was expected to be launched in late 2016.
- NWPU operated and launched a 50 kg spacecraft, Star of Aoxiang in June 2016, plan to launch a "deployable" small spacecraft in addition to another small satellite built around a 1u CubeSat design.

Industry

An "Aerospace Maker Union" established in 2015 aims to promote the development and use of small satellites. This has driven space startups focused both on telecom but also remote sensing. It should be noted that many of these startups receive government funding and direction, however, there are some signs of private VC helping to build companies through recent investment in small satellite launcher startups One Space, Link Space, and Landspace Technologies.[48] Landspace, whose medium-scale launchers are planned to be capable of loads above small satellite size, has recently won a launch contract with the Danish company GomSpace. (See the GomSpace case study in Appendix G). This is the first private space launch contract between a Chinese and foreign company. The launch is

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[47] Expert Interview

[48] S. Chen, "Space the Final Frontier for Chinese Startups and Venture Capitalists," *South China Morning Post*, May 20, 2016, accessed February 20, 2017, http://www.scmp.com/news/china/article/1947369/space-final-frontier-chinese-start-ups-and-venture-capitalists.

J. Lin and P.W. Singer, "Watch out SpaceX: China's Space Start Up Industry Takes Flight," *Popular Science*, April 22, 2016, accessed February 20, 2017, http://www.popsci.com/watch-out-spacex-chinas-space-startup-industry-takes-flight.

planned for 2018. In a reverse case of international partnership, SSTL has provided a satellite to China that SSTL operates, while China receives the data.[49] International partnership on space technologies is also seen among several space companies that make up the Venture Leaders China 2017 team of Swiss startup leaders, including Astrocast.[50]

Another example is startup CommSat who plans to launch a 2U CubeSat in 2017 named "Juvenile Satellite" that aims to encourage interest in the technology. Following this, the company plans to launch two 100 kg spacecraft in 2018 as technology demonstrators for a planned global constellation of around 300 spacecraft offering a 10Mb/s internet service. CommSat plans to use lasercomm for the inter-satellite links in this constellation. CommSat, and its CEO and founder Xie Tao, have been referred to as China's answer to SpaceX and Elon Musk, emphasizing a common perception that, in this area, China is mostly following and imitating U.S. capabilities.

South Korea

Government

South Korea also has its own space agency, the Korea Aerospace Research Institute, or KARI.[51] They are currently developing indigenous launch capabilities, and were successful in a 2013 launch with a Russian partnership.

Academic

The major research institute is the Korean Advanced Institute for Science and Technology, or KAIST, of which the key R&D center is the Satellite Technology Research Center (SATREC). The center developed the KITSAT small satellite series, which eventually produced South Korea's first wholly domestic satellites.[52] The STSAT series

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[49] Expert interview.

[50] VentureLab, "Ten new high growth Swiss startups would compose the venture leaders China team 2017. They would showcase Swiss innovation at the World Economic Forum in Dalian," *VentureLab*, http://www.venturelab.ch/Ten-new-high-growth-Swiss-startups-will-compose-the-venture-leaders-China-team-2017-They-will-showcase-Swiss-innovation-at-the-World-Economic-Forum-in-Dalian.

[51] World Politics Review, "South Korea Makes Moves to Become a Global Space Power," World Politics Review, October 13, 2016, accessed February 20, 2017, http://www.worldpoliticsreview.com/trend-lines/20179/south-korea-makes-moves-to-become-a-global-space-power.

[52] SATREC, "KITSAT Series," SATREC, accessed February 20, 2017, http://satrec.kaist.ac.kr/e_02_01.php.

further verified technologies, including Hall thrusters, and performed space science.[53] They are currently developing NEXTSat-1, a 100 kg standardized platform.[54]

Other South Korean universities involved in or planning to become involved in small satellites include Chosun University, Chungnam University, Kyung Hee University, Yonsei University, Seoul National University, and the Korea Aviation University.[55]

Industry

The main company handling small satellites is the SATREC Initiative. The SATREC Initiative is an industry spinoff of KAIST. The SATREC Initiative sells small satellites and components internationally, and has collaborated with Malaysia, Turkey, and ESA among others.[51] South Korea's larger Aerospace firms have generally been focused on larger satellites.

Europe

Key Takeaways

Europe is not seen by U.S. stakeholders as pushing the state of the art (SOTA) broadly, though individual companies may push in specific technology areas. Generally, disparate interests are seen as keeping the broader European satellite community from making overarching breakthroughs. Large companies are moving towards small satellites, but VC for small satellite specific startups still lags behind the United States. UK leads European space VC, with other companies spread across the continent, but generally the community is seen as more risk averse than the United States.[56] At the same time, European stakeholders typically see the United States as an important market.

Overview of Actors

Europe has a wide variety of major companies involved in small satellites, including Surrey Satellite Technology Ltd. (SSTL) and GomSpace, in addition to smaller startups and other companies. Various international companies have European headquarters and have taken advantage of European manufacturing capabilities (e.g., in OneWeb's case,

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[53] SATREC, "STSAT Series," SATREC, accessed February 20, 2017, http://satrec.kaist.ac.kr/e_02_02_03.php.

[54] SATREC, "NEXTSat-1," SATREC, accessed February 20, 2017 http://satrec.kaist.ac.kr/e_02_03.php.

[55] Euroconsult, "Prospects for the Small Satellite Market," 2016.

[56] G. Degtyareva, "SpaceTech Is Going Global: European Funding Opportunities for Space Startups," February 18, 2017, accessed March 2, 2017, https://medium.com/@GalyaD/spacetech-is-going-global-57ccfe6f654d#.kfluktici.

Airbus). Large companies such as Kongsberg Satellite Services (KSAT), a major ground station provider, are based in Europe but are providing services internationally, increasingly catering to small satellites. A variety of European launch options for small satellites are available, such as Arianespace and Eurockot. Currently, the focus is on large, traditional launchers, but development of small satellite launch capabilities is ongoing among smaller startups.[57]

Additionally, the European Space Agency (ESA) has taken on several small satellite projects, in collaboration with European companies and supports university efforts, acknowledging the value of small satellites in scientific research and technology demonstrations. For CubeSats in particular, ESA has seen a wave of more practical applications, including constellations, proximity operations including swarming and docking, and science beyond LEO, starting in 2018 and continuing onward.[59]

Based on interviews with small satellite companies and community members, European companies are generally seen as competitive, even against U.S. providers, and the European market for the technology is strong, but the European small satellite community is not seen as pushing the state of the art. The United States is seen as an important market to European companies such that many are opening or already have offices or facilities in the United States. This fact is not suggestive of a major near-term shift away from the United States by European companies.

Governments

ESA is a space leader but relatively late to the game on small satellites, as space agencies within Europe such as Centre National d'études Spatiales (CNES) (see subsequent discussion) were developing small satellites in the 1990s, whereas ESA's early small satellite programs started in the 2000s. ESA has a variety of ongoing small satellite projects, including the 3U OPSSAT testing experimental computers, and the PROBA missions, which are EO small satellites launched from 2001–2013.[58] ESA's technology transfer program office has business incubation centers fostering startups, including the small satellite industry. ESA plans for a wave of more practical applications for small satellites, including constellations, proximity operations - including swarming and docking—and science beyond LEO, starting in 2018 and continuing onward.[59]

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57 Additional information on SSTL, Gomspace, and KSAT can be found in Appendix G.

58 ESA, "Proba-1 Overview," ESA, May 27, 2009, accessed February 20, 2017, http://www.esa.int/Our_Activities/Observing_the_Earth/Proba-1_overview.
ESA, "About Proba-V," ESA, accessed February 20, 2017, http://www.esa.int/Our_Activities/Observing_the_Earth/Proba-V/About_Proba-V

59 R. Walker, Cubesat Evolution: From Educational tools to Autonomous Drones and Beyond, ESA, (presentation at European Cubesat Symposium, September 2016).

The French space agency, CNES has had an early start in developing a variety of small satellite programs. This includes the microsatellite platform, Myriade (100 kg) developed at the end of the 1990s, which flew 12 Earth observation missions, and is now commercialized by Thales Alenia and Airbus. This was followed by Myriad Evolution (150–200 kg). CNES is also supporting the JANUS program for university nanosats, but don't have their own platform for that program.

The German space agency, Deutsches Zentrum für Luft- und Raumfahrt (DLR), has collaborated with CNES on a now-stalled project for a SAR small satellite.[60] They have also developed the CLAVIS nanosat platform. The UK space agency has partnered with Clyde Space on UKube-1, a tech demo project.[61]

Industry

Several large space companies play important roles in the European small satellite community. For example, Airbus has partnered with One Web in the construction of One Web's constellation. SSTL is Airbus's subsidiary, which is working on developing NovaSAR, a small satellite SAR demo, among other projects.[62] (See case study in Appendix G). Similarly, OHB systems formed their own spinoff, Luxspace, to focus on microsatellites. Thales Alenia, another large space company, has developed NIMBUS, a microsatellite solution.

With regards to launch options, Arianespace and the German-Russian company Eurockot both provide launch options. These are both large launchers, but pursuit of small satellite specific launch is ongoing.[63]

In regards to other large companies relevant to the small satellite field, Kongsberg is not a space specific company, but they are a large Norwegian company whose subsidiary, KSAT, is now serving small satellite customers specifically with their KSAT Lite network. (See case study in Appendix G.)

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[60] eoPortal, "MERLIN (Methane Remote Sensing Lidar Mission) Minisatellite, accessed February 20, 2017, https://directory.eoportal.org/web/eoportal/satellite-missions/m/merlin

[61] European Union-Brazil Sector Dialogues, "Study on the Brazillian and European Initiatives for the development of the micro- and nano-satellite industry" European Union—Brazil Sector Dialogues, December 18, 2014, http://sectordialogues.org/sites/default/files/acoes/documentos/micro_nano.pdf

[62] D. Werner, "Star Wars: A New Hope for Commercial Space-based Radar," Space News Magazine, Marc 28, 2016..

[63] T.-A. Grönland, "Small Satellite Express: A European Launch Capacity for Cubesats," SSC Nanospace, (Presentation at the European Cubesat Symposium, September 2016).

E. Gonzalez, "PLDSpace," PLDSpace, (Presentation at the European Cubesat Symposium, September 2016).

When it comes to small space startups specific to small satellites, most have spun off of university projects or larger companies. One example of this is Berlin Space Technologies, which formulated out of projects the founders were working on at the Technical University of (TU) Berlin. This company started mostly off of founders' money because in the early 2000s there was very limited VC supporting the space sector. Now they are pursuing additional sources of funding in order to build up more mass manufacturing for their small satellites, which are larger than CubeSats. (See case study in Appendix G.)

This mold of small satellite specific companies includes Innovative Solutions in Space (ISIS), a company headquartered in the Netherlands, providing end-to-end solutions for small satellites and CubeSats, covering R&D, payload and platform design, components, integration, launch brokering, and ground stations. They have been involved in a variety of science projects, from lower thermospheric science to looking for exoplanets to developing CubeSats for the asteroid orbit, as well as AIS tracking, deorbiting technologies, and working on a small satellite launch vehicle as part of a consortium. They also work on In Orbit Verification of European Space Technologies (INVEST), a platform for in-orbit verification of European space technologies, in order to push their maturation.[64]

GomSpace is based in Denmark, and manufactures small satellite subsystems and components. (See case study in Appendix G.) They are now shifting to becoming a prime contractor for full missions and doing more mission design and management. They recently acquired a Swedish propulsion company in order to expand their capabilities. They're planning on expanding to offices in both the U.S. and Singapore in order to have access to the American and Asian markets. They have been able to take advantage of past expertise in cellphone technology from Denmark.

Academic

There are a variety of European universities involved with small satellites. University of Aalborg and Deft University of Technology were the first two European CubeSat projects. European universities have also been the source of some small satellite technology spinoffs, such as Berlin Space Technologies, discussed above, which spun off of work at TU Berlin. Similarly, SSTL spun off from work at the University of Surrey. While some universities have pursued basic small satellites as tech demos in the early 2000s and 2010s, Universities ranging from the KTH Royal Institute of Technology in Stockholm, Sweden[65]

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64 For more information, visit INVEST's webpage at http://invest-space.eu/.

65 J. Zhou and G. Tibert, "Attitude Determination and Control of the CubeSat MIST," (Presentation at the 8th European CubeSat Symposium).

to Poletecnico di Milano in Milano, Italy[66] do not only build CubeSats as demonstrations but are working on developing new GNC technologies for CubeSats.

Russia

Key Takeaways

Similar to the discussion of Asia, Russia does not have a strong distinction between government and industry or government and academia due to the strong degree of government involvement in both sectors. Where notable, these connections are highlighted.

Russia has a history in satellites since Sputnik. Early research in the former Soviet Union on Hall thrusters provided Russia with a head start on electric propulsion technology[67]; although this is not specific to small satellites, as Russian electric propulsion systems tend to be larger, expertise developed from these endeavors have been applied to the small satellite technology sector.

While most Russian actors are mainly government and state owned companies, there are some nominally private enterprises, and some space VC organizations,[68] and collaboration with European companies as well as other countries. It has been suggested that there is increasing interest in small satellites.

Overview of Actors

Government

The state corporation Roscosmos serves as Russia's space agency. Roscosmos is responsible for Russian launch vehicles, Strela, Rokot, and Dnepr, generally offering prices in the $7,000–$12,000 USD/kg payload range. One of Roscosmos' subsidiaries, Glavkosmos, coordinates launch of small satellites as secondary payloads, including satellites from customers outside of Russia.[69] Roscosmos has also developed small satellites (Kosmos 2499 and Luch) capable of maneuvering close to larger satellites, allowing for monitoring or directed collisions.[70]

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[66] G. Parissenti, "GNC Design and Testing for an IOD/IOV 1/3U Platform," (Presentation at the 8th European CubeSat Symposium).

[67] IPPT, "Hall Thrusters," IPPT, accessed February 20, 2017, https://web.archive.org/web/20110816154150/http://fluid.ippt.gov.pl/sbarral/hall.html

[68] Degtyareva, "SpaceTech Is Going Global."

[69] J. Foust, "Glavkosmos Seeks to Become a Major Smallsat Launch Provider," *SpaceNews*, Accessed June 21, 2017, http://spacenews.com/glavkosmos-seeks-to-become-a-major-smallsat-launch-provider/

[70] J. Sciutto and J. Rizzo, "War in Space, Kamikazes, Kidnapper Satellites and Lasers."

Academic

Russian universities have been developing small satellites for decades. With a heritage that stretches back well before CubeSats, these satellites tend not to conform to a form factor and are larger than more typical university small satellites. Russian university satellites launch for free with Roscosmos, incentivizing university space programs. Several examples of such programs are listed below:

- Moscow Aviation Institute, Radio Sputniks 2 in the 70s,[71] Iskra1-3 in the 80s,[72] and MAK1&2 and Skipper[73] in the 1990s[74]
- Space Research Institute of the Russian Academy of Sciences, Kolibri 2001,[75] Chibis 2011[76]
- Bauman Moscow State Technical University with NPO Mashinostroyeniya, Baumenets, first lost in launch failure in 2006,[77] two more are planned for 2017[78]
- Siberian State Aerospace University and Samara University with AIST, two satellites in 2013[79] and follow ups in 2016[80]

Industry

Most Russian industry is state owned or has significant government involvement, though some exceptions are identified in the following sections.

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71 Gunter's Space Page, "Radio Sputnik 2 (RS 2, Iskra)," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/rs-2.htm.

72 Gunter's Space Page, "Iskra-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/iskra-1.htm.

73 Gunter's Space Page, "Skipper," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/skipper.htm.

74 Gunter's Space Page, "Mak-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/mak-1.htm.

75 Gunter's Space Page, "Kolibri-2000," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/kolibri-2000.htm.

76 Gunter's Space Page, "Chibis-M," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/chibis-m.htm.

77 Gunter's Space Page, "Baumanets," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/baumanets.htm.

78 Gunter's Space Page, "Baumanets-2," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/baumanets-2.htm.

79 Gunter's Space Page, "Aist," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/aist.htm.

80 Gunter's Space Page, "Aist-2," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/aist-2.htm.

There are several large space and aerospace companies in Russia with a long history. ISS Reshetnev is a satellite manufacturer, building satellites from large telecom satellites to small scientific research and experimental missions, operating since the 1960s. The vast majority of their satellites are large satellites, but they do have smaller more recent satellites for science missions, such as MiR, a magnetic-gravitational research satellite with a mass of 65 kg. Gazprom Space Systems is a subsidiary of the publically owned Russian gas giant, Gazprom, and is mostly focused on communications constellations and their own ground stations[81], though they are considering an Earth observation and aerospace monitoring constellation[82]. It is unclear whether this would be made up of small or large satellites. Some of their satellites are built by Thales Alenia, indicating that not all of their capabilities are internal[83]. Lavochkin is an aerospace company better known for its planes but with a long history in satellites and rockets. They developed a 100 kg Karat platform, but only one mission flew in 2012 as they were deemed too expensive for science missions.[84]

Some exceptions to the rule of Russian government control—at least nominally—include Dauria Aerospace, a private company which produced the first private wholly Russian satellite for launch in 2014.[85] The satellite used AIS (Automatic Identification System) to track shipping vessels. It has since produced two remote sensing satellites, MKA-N 1&2, for Roscosmos, scheduled for launch in 2017. Interestingly, these two are 6U CubeSats; most of the other Russian satellites discussed have not been built to a form factor. They have their own ground station and continue to develop satellites for Russian companies. Sputnix, also a private company, is producing its own TabletSat platform for small satellites.[86]

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81 Gazprom, “Services and Solutions,” *Gazprom*, accessed February 20, 2017, http://www.gazprom-spacesystems.ru/en/services_and_solutions/.

82 Gazprom, “Smotr System,” *Gazprom*, accessed February 20, 2017, http://www.gazprom-spacesystems.ru/en/new_projects/smotr/.

83 Thales Alenia Space, “Thales Alenia Space, to build Yamal-601 satellite for Gazprom Space Systems,” *Thales Alenia Space*, accessed February 20, 2017, https://www.thalesgroup.com/sites/default/files/asset/document/pr_yamal601_jan2014_en.pdf

84 Russian Space Web, “MKA-FKI (PN1) Zond-PP,” Russian Space Web, accessed February 20, 2017, http://www.russianspaceweb.com/karat1_zond_pp.html.

85 Gunter’s Space Page, “DX-1,” accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/dx-1.htm.

86 For more information, visit Sputnix’s webpage at http://www.sputnix.ru/en/projects.

Australia

Government

As of this writing, no Australian Space Agency exists; however, there have been several calls for the government to institute one, notably from the Space Industry Association of Australia.[87] The current arrangement has an inter-departmental committee designed to coordinate satellite services, including 11 different departments and agencies, and their own space policy. Space programs have included the time-limited Australian Space Research Program, in collaboration with industry, with relevant projects including research on tracking space debris.[88] Additionally, the Cooperative Research Centre for Satellite Systems, funded and coordinated by the government, allowed for the creation of FedSat, a scientific microsatellite launched in 2002.[89]

Academic

Australian Universities were responsible for three Australian made CubeSats launched in early 2017, the first Australian made satellites in 15 years, part of the international QB50 mission studying the lower thermosphere. These satellites were produced by teams and collaborations from the University of New South Wales (USW) in Sydney, the University of Sydney, the Australian National University, the University of Adelaide, and the University of South Australia.[90]

Industry

The smallsat industry in Australia is aided by Delta-V, "Australia's Space Startup Accelerator." Important members include Fleet Space, with headquarters in Australia and additional offices in the United States and the Netherlands, which plans to launch nanosatellites to provide connectivity for the internet of things.[91] Launches are planned for this year. Together, several Delta-V member space startups have raised over 10 million

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87 Space Industry Association of Australia, "SIAA White Paper: Advancing Australia in Space," *Space Industry Association of Australia*, March 2017, http://www.spaceindustry.com.au/Documents/SIAA%20White%20Paper%20-%20Advancing%20Australia%20in%20Space.pdf.

88 Ibid.

89 Gunter's Space Page, "FedSat1," http://space.skyrocket.de/doc_sdat/fedsat-1.htm

90 A. Dempster, "Australia's Back in the Satellite Business with a New Launch," *Space Daily*, April 2017, http://www.spacedaily.com/reports/Australias_back_in_the_satellite_business_with_a_new_launch_999.html.

91 For more information, visit Fleet Space's website at http://www.fleet.space/.

dollars (Australian) in private series A funding,[92] and thirteen Australian companies, including Fleet Space, as well as Delta V presented at an Australian CubeSat conference.[93]

Latin America

Key Takeaways

- International collaboration is necessary for most countries, as they take advantage of the option to learn from kits and technology transfer, testing and launch provisions
  - More significant players—Argentina and Brazil—have wide ranging partnerships with the United States, Russia, China, and Europe, while newcomers more often stick to partnerships in their own region
- Environmental monitoring (climate, weather, deforestation, etc.) is a key focus of small satellites
- VC and startups are limited, government funding and collaboration continues to be key, academic institutions important drivers of development
- CubeSats are a popular form factor due to low cost and the availability of kits.
- Satellogic remains the largest small satellite specific company centered in South America, but is broadly international
- Argentina and Brazil are in a class of their own in space, small satellites included, as they have space programs that do work across the board, and significantly greater funding than most of the smaller countries. Mexico is also unique; their space work has a long heritage of industry and academic activity rather than government, as well as having the advantage of larger budgets. The other Latin American countries are examples of new space countries, with space endeavors that don't distinguish between civil and military space, smaller budgets, and academia as important players.
- New players are interested in being responsible space actors and following international best practices. Many have been involved in international space conversations before ever developing space capabilities.

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[92] Delta V, "$10M of Investment in 8 Companies since 2016," *Delta V*, http://www.deltavspacehub.com/#space20.

[93] Australian Centre for Space Engineering, "Cubesat Innovation Workshop," *Australian Centre for Space Engineering*, http://www.acser.unsw.edu.au/cubesat2017/proceedings

Brazil

Government

Agência Espacial Brasileira (AEB)[94] is the Brazilian space agency, working closely in cooperation with the Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research) (INPE),[95] a research institute under the Brazilian Ministry of Science, Technology and Innovation. The agency fosters international collaboration, has a longstanding large satellite collaboration (Chinese-Brazil Earth Resources Satellite [CBERS]) with China, and maintains an agreement with Thales Alenia to help facilitate technology transfer to Brazil.[96] Brazil's space agency is developing a small satellite launcher, Microsatellite Launch Vehicle (VLM), in collaboration with the German Space Agency, DLR.[97] Natal CRN, another government agency, developed Conasat, a 6 satellite nanosatellite constellation, for environmental data collection.[98]

INPE has facilities for thermal vacuum, acoustics, and vibration testing, and facilities for component and satellite integration. The CIENTEC foundation is further developing testing capabilities with a small satellite focus.[99] INPE, with support from AEB, started the small sat program in 2003, generally working in collaboration with universities.

Some example projects are as follows:

- NanoSatC-BR1, launched in 2014,[100] was a product of INPE in partnership with the Federal University of Santa Maria.[101]

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[94] For more information, visit AEB's website at http://www.aeb.gov.br/.

[95] For more information, visit INPE's website at http://www.inpe.br/ingles/institutional/about_inpe/history.php.

[96] C. Henry, "Brazil's Visona Tecnologia Espacial about Halfway to Self-Sufficient Satellite Capability," *Via Satellite*, April 21, 2015. http://www.satellitetoday.com/technology/2015/04/21/brazils-visiona-tecnologia-espacial-about-halfway-to-self-sufficient-satellite-capability/.

[97] D. Messier, "Agreement Signed for Brazillian/German Microsat Launcher," *Parabolic Arc*, January 11, 2015, http://www.parabolicarc.com/2015/01/11/agreement-signed-braziliangerman-microsat-launcher/.

[98] D. Ereno, "Small Satellites Make Their Mark," *Pesquisa*, May 2014, http://revistapesquisa.fapesp.br/en/2014/05/20/small-satellites-make-mark/.

[99] European Union-Brazil Sector Dialogues, "Study on Brazillian and European Initiatives," http://sectordialogues.org/sites/default/files/acoes/documentos/micro_nano.pdf.

[100] Gunter's Space Page, "Nanosatc-br-1," Gunter's Space Page, accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/nanosatc-br-1.htm.

[101] Ereno, "Small Satellites Make Their Mark," http://revistapesquisa.fapesp.br/en/2014/05/20/small-satellites-make-mark/.

- Serpens was deployed in 2015.[102] This small satellite came from a broad collaboration both inside and outside Brazil. Inside Brazil, participants included:
  - AEB
  - The Federal University of Santa Catarina (UFSC)
  - The Federal University of ABC (UFABC)
  - Federal University of Minas Gerais UFMG
  - University of Brasilia
  - Federal Fluminense Institute in Campos de Goitacazes
  - Rio de Janeiro State (responsible for ground stations)
- Internationally, participants included
  - The University of Vigo in Spain
  - The Sapienza Universita di Roma in Italy
  - Morehead State University
  - California State Polytechnic.
- AESP-14, an Instituto Tecnológico de Aeronáutica (ITA) and INPE collaboration, was built in house by students from 2012–2014, with the exception of the radio, which was purchased. The satellite was deployed in 2015, but no signals were received.[103]
- Tancredo-1, a satellite assembled in Brazil from components made by Interorbital Systems (a U.S. company), by primary and middle school students, with help from an INPE engineer, was launched in 2016.[104]
- Itasat is another ITA and INPE collaboration, carrying the same sensors as NanoSatC, and designed to follow on to that product with radiation sensors as well as imaging with 80m resolution. Itasat is planned for launch in 2017.[105]

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[102] Gunter's Space Page, "SERPENS," accessed February 20, 2017http://space.skyrocket.de/doc_sdat/serpens.htm.

[103] Gunter's Space Page, "Aesp-14," accessed February 20, 2017 http://space.skyrocket.de/doc_sdat/aesp-14.htm.

[104] Gunter's Space Page, "Tancredo-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/tancredo-1.htm.

[105] Gunter's Space Page, "Itasat-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/itasat-1.htm.

Academic

Of the universities mentioned above, ITA has participated in the most ongoing collaborations and is the primary academic institution for aerospace in the country. It is located in Sao Jose Dos Campos, Brazil's central aerospace city, with several space companies clustering there.

Industry

Government remains the main source of funding for small satellites. Based in Sao Jose Dos Campos, Visiona is a joint venture between Telebras and Embraer Defense and Security, a government-created company seeking to build domestic satellite manufacturing capability. Though they have stated that their technology is close to being ready to compete internationally with small satellites by improving internal production capabilities, their most recent focus has been on SGDC, a large satellite program with Thales Alenia for GEO satellites providing internet. Government funding is likely to remain their main source of funding for the near future, and current focus is on serving Brazillian customers before competing internationally.

The Brazilian VC community, specifically the firm Pitanga Invest, is investing in space startups; however they have not invested in any homegrown companies, rather they have invested in Satellogic, an international company with manufacturing and R&D in South America.[106] There aren't strong indicators of a space startup community in Brazil, as the companies noted as being involved in small satellite are large and government funded.

Argentina

Government

Comisión Nacional de Actividades Espaciales (CONAE), the Argentine Space Commission, serves as the country's space agency. They are developing local launch capabilities; Tronador I and II, Tronador III has been proposed as a smaller launcher that could serve as a small sat dedicated launch vehicle.[107]

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[106] A. Heim, "March in Latin America: All the Tech News You Shouldn't Miss from the Past Month," The Next Web (TNB), April 1, 2015.

[107] CONAE, "Tronador II," *CONAE*, accessed February 20, 2017, http://www.conae.gob.ar/index.php/espanol/acceso-al-espacio/tronador-ii.

Academic

Universidad Nacional del Comahue built a nanosatellite launched in 2007[108] with *La Asociación Argentina de Tecnología Espacial* (AATE)[109] and AMSAT Argentina. AMSAT Argentina is the Argentinian branch of the international amateur satellite radio nonprofit radio organization AMSAT,[110] responsible for an Argentinian small satellite launch in 1990 of their own amateur radio satellite.[111]

Industry

Argentina has some industrial space experience but is only just starting to break in to small satellites. INVAP is an Argentine company with wide international operations, ranging from energy, including nuclear, to aerospace. The company started off from the Argentine Commission of Atomic Energy, and works closely with CONAE. They have built up expertise in larger satellites but have not worked on small satellites independently.[112]

The main small satellite player in Argentina is Satellogic, a multinational company founded by Argentinean Emiliano Kargieman with plans to build their own constellation of small satellites;[113] the main R&D facility is based in Argentina.[114]

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[108] Gunter's Space Page, "PehuenSat 1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/pehuensat.htm.

[109] AATE (the Argentine Association for Space Technology) is a nonprofit organization that promotes space activities. For details, visit AATE's website at http://www.aate.org/.

[110] For more information on AMSAT, see http://www.amsat.org.ar/.

[111] Gunter's Space Page, "Lusat," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/lusat.htm.

[112] INVAP, "Satellites: Prime Contractor and Provider of Custom-Made Solutions," accessed February 20, 2017, http://www.invap.com.ar/en/aerospace-and-government/products-and-services-aerospacial/satellites.html.

[113] For more on Satellogic, see their website: https://www.satellogic.com/.

[114] Caleb Henry, "Satellogic on Its Way to Launching 300 Satellite Constellation for Earth Observation," *Via Satellite*, March 17, 2016, accessed February 20, 2017, http://www.satellitetoday.com/technology/2016/03/17/satellogic-on-its-way-to-launching-300-satellite-constellation-for-earth-observation/.

Argentina has also seen increased investment in small satellite subcomponents.[115] They would host the first Latin American Symposium on Small Satellites at the Universidad Nacional De San Martin.[116]

Mexico

Mexico's space agency, Agencia Especial Mexicana (AEM), was started in 2010, relatively late, and is currently still in the process of establishing its role. The Aerospace Development Center, Autonomous University of Nuevo Leon, and National Autonomous University of Mexico have been key small satellite players, and were part of the push for the creation of a national space agency. Mexican Commission for Outer Space, the agency's predecessor, was established in the 1960s, but closed in 1977 due to lack of interest and other challenges in the country.[117] However, this is indicative of this country's long space heritage, not just in government but through industry and academia, as well as in collaboration with the United States. The academic sector has been involved in small satellites since the 1990s, with the SATEX-1[118] and UNAMSAT[119] microsatellites from the University of Mexico, and expanded small satellite capabilities in the 2000s with SATEDU.[120] Other recent university projects included Sensat and Condor.[121] The first Mexican propulsion system was a collaboration with MIT,[122] demonstrating the value of international collaboration. There is a clear focus on small satellites as a way to increase

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[115] Marboe, I. 2016. Small Satellites: Regulatory Challenges and Chances. Leiden, The Netherlands: Brill - Nijhoff.

[116] Universidad Nacional de San Martin, "1st IAA Latin American Symposium on Small Satellites: Advanced Technologies and Distributed Systems," Universidad Nacional de San Martin, accessed February 20, 2017, http://www.unsam.edu.ar/institutos/colomb/IAA.asp.

[117] Southern Hemisphere Space Studies Program, "Small Sats Big Shift: Recommendations for the Global South," Southern Hemisphere Space Studies Program, 2017, accessed March 2, 2017, https://swfound.org/media/205747/isu-unisa_shssp_whitepaper_smallsats_8feb2017.pdf?utm_content=buffer0e143&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer.

[118] R. Peralta et al.,"Structural Design, Development, and Testing of a Small Experimental Satellite System," Paper presented at the Utah Small Satellite Conference.

[119] Gunter's Space Page, "UNAMSAT-A," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/unamsat-a.htm.

[120] Satelite Educativo Mexicano, "SATEDU" accessed February 20, 2017, http://proyectos2.iingen.unam.mx/SATEDU/start.htm .

[121] F. J. Mendieta et al. "Optical Communications in the Mexican Small Satellite Project," *AEM*, accessed February, 20, 2017, https://perso.telecom-paristech.fr/~gallion/documents/free_downloads_pdf/PG_revues/PG_R129.pdf.

[122] Southern Hemisphere Space Studies Program, "Small Sats Big Shift"

the availability and affordability of space access,[123] and to forward important national goals such as climate monitoring and air pollution measurement.[124]

Uruguay

Uruguay's involvement in small satellites is limited. CIDA-E is the Uruguayan aerospace agency, covering aviation and space issues, but does not have noted small satellite investments.[125] Uruguay's first and only small satellite so far is ANTELSAT, a collaboration with Facultad de Ingenieria de La Universidad De la Republica and the national telecom service provider ANTEL, launched in 2014.[126] Additionally, Satellogic has a manufacturing facility in Uruguay.[127]

Costa Rica

Costa Rica does not have its own space agency but is represented by the Central American Aeronautics and Space Administration.[128] The country's first step into small satellites took an unusual approach by using crowdfunding as one source of funds for its first project. The last stages of Costa Rica's first satellite, a joint project between the Central American Aeronautics and Space Administration and the Costa Rica Institute of Technology, are being crowdfunded. A ground station would also be built for this satellite.

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[123] United Nations, Office for Outer Space Affairs, "United Nations/Mexico Symposium on Basic Space Technology "Making Space Technology Accessible and Affordable"" United Nations, Office for Outer Space Affairs, October 2014, accessed February 20, 2017, http://www.unoosa.org/oosa/en/ourwork/psa/schedule/2014/symposium_mexico_basic_space_technology.html

[124] Southern Hemisphere Space Studies Program, "Small Sats Big Shift"

[125] For more on CIDA-E, see their website: http://www.dinacia.gub.uy/comunidad-aeronautica/2013-11-01-16-45-49/centro-de-investigacion-y-difusion-aeronautico-espacial-cida-e.html

[126] El Pais, "Se pone hoy en órbita el primer satélite uruguayo" *El Pais*, June 19, 2014, accessed February 20, 2017, http://www.elpais.com.uy/vida-actual/se-pone-orbita-satelite-uruguayo.html

Republica, "Se apagó el satélite uruguayo AntelSat," *Republica*, July 16, 2015, accessed February 20, 2017, http://www.republica.com.uy/se-apago-antelsat/526384/

[127] C. Henry, "Satellite on Its Way to Launching 300 Satellite Constellation for Earth Observation," *Via Satellite*, March 17, 2016, accessed February 20, 2017, http://www.satellitetoday.com/technology/2016/03/17/satellogic-on-its-way-to-launching-300-satellite-constellation-for-earth-observation/.

[128] L. Arias, "Costa Rica joins Space Cooperation Network," *The Tico Times*, October 15, 2015, accessed February 20, 2017, http://www.ticotimes.net/2015/10/15/costa-rica-joins-space-cooperation-network.

The launch coordination is a collaboration with Kyushu Institute of Technology,[129] and the satellite platform is provided by GomSpace[130].

Ecuador

The Ecuadorian Civilian Space Agency (EXA), is supported by the Ecuadorean Air Force but not a formal government agency[131]. EXA is the only source of small satellites from Ecuador so far. These satellites are NEE-01 Pegasus[132] and Nee-02 Krysaor,[133] both launched in 2013, first a Chinese and second a Russian launch. The first satellite failed after collision with debris.

Peru

Comisión Nacional de Investigación y Desarrollo Aeroespacial (CONIDA) is Peru's space agency. They have early development of rockets for small launch systems,[134] but no other noted involvement in small satellites. Peru's small satellite involvement has come largely from universities, and is listed below:

- Pontificia Universidad Catolica del Peru's Institute for Radio Astronomy—designed the first two Peruvian small satellites, PUCP-SAT 1, CubeSat, and Pocket-PUCP, a femtosat deployed from PUCP-SAT 1, which had a Russian launch in 2013[135], three years after the project began in 2010[136]

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[129] ARCAE "Irazú Project: The First Satellite Made in Costa Rica," *Kickstarter*, accessed February 20, 2017, https://www.kickstarter.com/projects/irazu/irazu-project-the-first-satellite-made-in-costa-ri

[130] GomSpace, "GomSpace and ACAE have just signed a MoU," *Twitter*, September 29, 2016, accessed February 20, 2017, https://twitter.com/gomspace_aps/status/781747053953245184.

[131] For more on EXA, see their website: http://exa.ec/index-en.html.

[132] D. Turing, "Ecuador y su primer satélite artificial," El Diario, January 8, 2013, accessed February 20, 2017, http://www.eldiario.es/turing/Satelite-Pegaso-Ecuador_0_158884782.html.

[133] Andes, "Ecuador already has its second satellite in space, NEE-02 Krysaor," Andes, November 21, 2013, accessed February 20, 2017, http://www.andes.info.ec/en/news/ecuador-already-has-its-second-satellite-space-nee-02-krysaor.html.

[134] Space Travel, "Peru launches first homemade rocket," Space Travel, June 19, 2013, accessed February 20, 2017, http://www.space-travel.com/reports/Peru_launches_first_homemade_rocket_999.html.

[135] R. Chase, "First Peruvian Satellites launched into space," Peru this Week, November 21, 2013, accessed February 20, 2017, http://www.peruthisweek.com/news-first-peruvian-satellites-launched-intospace-101517.

[136] Gestion, "La PUCP lanza al espacio primeros satélites hechos íntegramente en el Perú," November 21, 2013, accessed February 20, 2017, http://gestion.pe/tecnologia/lanzan-satelites-hechos-integramente-peru-construidos-pucp-2081686.

- Alas Peruanas University—UAPSAT-1—third Peruvian sat, NASA launch with robotic deployment from ISS, the project also started in 2010 and launched in 2014[137]
- Universidad Nacional de Ingenieria del Peru, in collaboration with the Russian Southwest State University—Chasqui 1—fourth Peruviansat, launched by a Russian craft and deployed from the ISS in 2014, no signals were received[138]

Chile

Chile does not have a civilian space agency, only a council of Ministers for Space Development. The Chilean Ministry of Defense is responsible for FASat Charlie, an Earth observation satellite (117 kg) launched in 2011[139] and reaching the end of its lifetime with plans to replace it.[140] The Universidad de Chile, specifically Electrical Engineering, Physics and Mechanical Engineering Departments of the Faculty of Physical and Mathematical Sciences (FCFM),are preparing SUCHAI, a 1U CubeSat designed to study the atmosphere– due for launch in 2017 on a Falcon 9. Chile also hosted the ITU symposium and workshop on small satellite regulation and communication systems in 2016.[141] Chile is just starting in startups and has limited VC but this has not yet moved into space.

Colombia

Colombia's space efforts have been mostly lead by the Colombian Air Force, with the Colombian Space Commission not formed until 2006. Colombia's first small satellite was Libertad 1, launched by students at Universidad Sergio Arboleda.[142] According to

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[137] La prensa, "NASA envió al espacio satélite peruano UAP-SAT 1" *La prensa*, January 9, 2014, accessed February 20, 2017, http://laprensa.peru.com/tecnologia-ciencia/noticia-nasa-envio-al-espacio-satelite-peruano-uap-sat-%201-18596.

[138] Gunter's Space Page, "Chasqui-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/chasqui-1.htm.

[139] Gunter's Space Page, "SSOT," accessed February 20, 2017. http://space.skyrocket.de/doc_sdat/ssot.htm.

[140] Chile's Defense and Military, "Chile Looking to China for Satellite Acquisition," *Chile's Defense and Military*, June 20, 2015, accessed February 20, 2017, http://chiledefense.blogspot.com/2015/06/chile-looking-to-china-for-satellite.html.

[141] ITU, "ITU Symposium and Workshop on Small Satellite Regulation and Communication Systems, Santiago de Chile, Chile, 7-9 November 2016," *ITU*, November 2016, accessed February 20, 2017, http://www.itu.int/en/ITU-R/space/workshops/2016-small-sat/Pages/default.aspx.

[142] Gunter's Space Page, "Libertad-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/libertad-1.htm.

interviewees, universities play an important role, with space policy largely considered at an academic level.

Middle East

Overarching Points

Small satellite development is occurring across the Middle East; we identified small satellite activity in Israel, Saudi Arabia, Oman, Turkey, Pakistan, Iran, and the United Arab Emirates. These are at varying degrees of involvement, as Oman has yet to launch a small satellite, and Pakistan only has one CubeSat on orbit, whereas more established programs such as Iran and Israel have a variety of small satellites, and industry and academia surrounding them. Others, such as UAE, have largely remained focused on somewhat larger satellites, though this may change as UAE's Thuraya is now partnering with a Swiss smallsat company focused on IoT.[143]

Israel

Israel has its own space agency, in addition to some space activities being coordinated through the Ministry of Defense. This includes the Ofeq series of Earth observation satellites, the first (launched starting in 1988) and second generation (launched starting in 2002) of these small satellites, launched starting in 2002, are <200 kg.[144] Israel Aerospace Industries is also a key space player, producing rockets for Israel's internal space launch capabilities, and manufacturing the Ofeq series. They are currently collaborating on an environmental monitoring satellite with France.[145] IAI also supports university efforts, such as the Samson project out of Technion (Israel Institute of Technology). This project is focused on formation flying for a future three satellite constellations.[146] Other work comes out of the Herzliya science center, which has already launched a small satellite, Duchifat 1,[147] and supports additional CubeSat programs for Israeli high school students.

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[143] P. B. de Selding, "Interview: ELSE/Astrocast CEO Fabien Jordan & CFO Kjell Karlsen," Space Intel Report, April 2017, https://www.spaceintelreport.com/interview-elseastrocast-ceo-fabien-jordan-cfo-kjell-karlsen/

[144] Gunter's Space Page, "Ofeq-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/ofeq-1.htm; "Ofeq-3," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/ofeq-3.htm; and "Ofeq-5," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/ofeq-5.htm.

[145] Spacewatch Middle East, "Israel's IAI Successfully Completes Environmental Testing of Israeli-French Venus Satellite," February 2017.

[146] I. Agamy et al., "SAMSON—SAtellite Mission for Swarming and GeOlocatioN," *Israel Institute of Technology*.

[147] Herzliya Science Center, "About Us," accessed February 20, 2017, http://www.h-space-lab.org/php/index-en.php.

Other small satellite players include smaller startups such as NSLComm provide new deployable products for small satellites,[148] as well as other small satellite firms such as SkyFi, which looks to deploy its own constellation.

Iran

Iran has worked on developing a rocket capable of launching small satellites to LEO, though their tests have raised fears that such technologies could bring them closer to ICBMs.[149] Iran has had domestic small satellites since Omid's launch in 2009,[150] and has followed that with Earth observation satellites in 2011[151] and 2012,[152] with follow on goals for 2017,[153] coming from students at the Iran University of Science and technology. However, much of Iran's space efforts have been focused on live animals in space with a stated end goal of putting humans in space.

Turkey

The Scientific and Technological Research Council of Turkey (TUBITAK) has largely coordinated small satellite activity alongside Turkish Aerospace Industries (TAI). In addition, the Istanbul Technical University (ITU) has launched three small satellites, and has plans to launch a fourth in 2017[154] and a fifth in 2018.[155] ITU's first satellite was in coordination with TUBITAK,[156] while later satellites have collaborated with Turkish

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[148] For more information, visit NSLComm's website at https://www.nslcomm.com/.

[149] L. Grego, "Iran's Upcoming Simorgh Launch," Union of Concerned Scientists, February 14, 2016, accessed February 20, 2017, http://allthingsnuclear.org/lgrego/irans-upcoming-simorgh-rocket-launch

[150] Gunter's Space Page, "Omid," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/omid.htm; R. Tait, "Iran Launches First Domestically Produced Satellite," *The Guardian*, February 3, 2009, https://www.theguardian.com/world/2009/feb/03/iran-satellite-launch-omid.

[151] Gunter's Space Page, "Rasad-1," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/rasad-1.htm

[152] T. Malik, "Iran Launches Small Earth-Watching Satellite Into Orbit: Report," *Space.com*, February 3, 2013, accessed February 20, 2017, http://www.space.com/14464-iran-launches-small-satellite-orbit.html

[153] Gunter's Space Page, "Tadbir," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/tadbir.htm.

[154] Gunter's Space Page, "Havelsat," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/havelsat.htm.

[155] ITU, "Small Satellites Commuication Laboratory," *ITU*, accessed February 20, 2017, http://www.faa.itu.edu.tr/Icerik.aspx?sid=13637.

[156] Gunter's Space Page, "Rasat," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/rasat.htm.

technical industry,[154] suggesting an increasing industrial interest in small satellite capabilities.

Africa

Small satellite activity in Africa has been limited, and has started largely with government institutions. The Algerian and Nigerian space agencies are currently operating small satellites, in addition to the Egyptian Armed Forces and National Authority for Remote Sensing and Space Science (NARSS). The manufacture of these satellites has been contracted out, though these contracts allowed for training of local engineers,[157] with the Nigerian satellite specifically being built by Nigerian engineers with SSTL supervision.[158] Earth Observation is an issue of strong interest, especially in the case of improving precision farming and weather prediction in order to improve crop yields, as well as improving other commercial applications such as communications.[159] Similar partnerships have come through is the Kyushu Institute of Technology's BIRDS program, training scientists from non-space faring nations in CubeSat technologies, which Ghana and Nigeria have both participated in.[160]

South Africa leads the way in small satellites on the African continent, with government investment in small satellites via the South African National Space Agency (SANSA). The agency was established in 2010. The universities that lead the way include Cape Peninsula University of Technology and University of Stellenbosch. Cape Peninsula University of Technology launched the country's first small satellite.[161] The University of Stellenbosch has launched three satellites,[162] and has also collaborated on two other projects with several European and U.S. companies and universities. The collaborators include SSTL, the prime on both projects, the University of Surrey, and Caltech. These are

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[157] S. Shay, "Egypt Wishes to Join the 'Space Club'," *Israel Defense*, December 23, 2015, accessed February 20, 2017, http://www.israeldefense.co.il/en/content/egypt-wishes-join-space-club;eoPortal, "AlSAT-2," accessed February 20, 2017, https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/alsat-2.

[158] Sci Dev Net, "Nigeria Launches First Satellite Built by Africans," *Sci Dev Net*, accessed February 20, 2017, http://www.scidev.net/global/earth-science/news/nigeria-launches-first-satellite-built-by-africans.html.

[159] SpacewatchME, "Satellite Sovereignty, Africa," accessed February 20, 2017, http://spacewatchme.com/2017/01/satellite-sovereignty-part-2/.

[160] Harebottle, "The Big Powr of the Smallsat Revolution."

[161] Gunter's Space Page, "Zacube-1," Gunter's Space Page, accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/zacube-1.htm.

[162] Gunter's Space Page, "Za-aerosat," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/za-aerosat.htm;"Sumbandila," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/sumbandila.htm; and "Sunsat," accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/sunsat.htm.

a test de-orbiting sail for small satellites, which was launched in 2015 and failed to deploy, and an active debris removal satellite, planned for launch in 2017.

These are not merely recreations of existing capabilities, but true tech advancement, illustrative of how international partnerships, such as those offered by SSTL, can allow countries to become both players in international technology development as well as further improving and establishing their own capabilities. SSTL, as well as other foreign organizations, have generally been open to partnerships that include training for local engineers, having pursued similar opportunities with other nations before. South Africa also has several industrial players in the small satellite community, including Denel Spaceteq, providing a range of mission services.[163] This also includes NewSpace systems, (a subsidiary of SCS Aerospace Group) which manufactures small satellite and CubeSat specific components, and also has offices in the UK.[164]

[163] For more information, visit Denel Spaceteq's website at http://www.spaceteq.co.za/home/products-services/.

[164] For more information, visit NewSpace's website at http://www.newspacesystems.com/.

Appendix F.
Small Satellite Applications

Remote Sensing (Earth Observation and Situational Awareness)

Overview of Sector

Companies such as Orbit Logic, Descartes, Cape Analytics, and Orbital Insight buy data from satellite operators. Their decisions on who to buy from and whether or not their data is acquired from small satellites would be shaped by the increasing capabilities of small satellites, which include variables like resolution, spectrum, and revisit rate, as well as the cost of imagery. Because the rate at which data gets to the customer is key, if small satellites can provide images faster and more frequently, they would gain an advantage. Because small satellites are typically launched as constellations, they would also gain an advantage in revisit rates over larger, single satellites.

Companies such as Astro Digital, UrtheCast, and OmniEarth all intend to launch their own satellites, but are currently buying data from other satellites in order to prove a demand for their data analytics products and build a customer base to help fund their satellites. These purchases tend to be relatively indiscriminate in choosing between small satellites, large satellites, or hosted payloads, with contracts established based on availability.

Current small satellite constellations offer a range of capabilities, from visible and infrared multispectral, multispectral and panchromatic, multispectral with a greater range of bands, GPS-radio occultation, and automatic identification system (AIS). Future constellations would both duplicate these capabilities and expand to SAR, RF, and ADS-B. (While LIDAR may be making the move to space if the planned Franco-German Merlin satellite, designed for methane monitoring, goes forward, it has not yet reached small satellite size, as Merlin is still hovering at 400 kg[1]). Daily revisit rates already exist in the case of Planet, which has achieved "Mission 1," global daily revisit.[2] Spire's Sense

[1] eoPortal, "MERLIN (Methane Remote Sensing Lidar Mission) Minisatellite," eoPortal, https://directory.eoportal.org/web/eoportal/satellite-missions/m/merlin.

[2] A. Foerch, "Rapid Growth for Planet," *Trajectory Magazine*, February 15, 2017, http://trajectorymagazine.com/got-geoint/item/2327-rapid-growth-for-planet.html.

constellation, which conducts tracking AIS, promising 34 min revisit rates.[3] The goals of future constellations generally focus on getting down to daily/hourly revisit rates.

Many small satellite operators express some interest in using their sensors to look around and up, however smallsat based SSA is not yet an area of notable commercial focus. The STARE mission, led by Lawrence Livermore National Laboratory, with a first launch in 2012, uses CubeSats to observe and track orbital debris in order to encourage space assets to move and avoid collisions[4]. This expands the capabilities of JSPOC by adding flexibility and imaging capacity, with the intention of reducing false collision warnings. Better SSA is broadly a public good, which may explain the relatively low levels of private sector activity.

The capabilities of select planned and existing remote sensing constellations are discussed in Table F-1 and Figure F-1.

Table F-1. Select Smallsat Remote Sensing Companies

Company (HQ Country)	Constellation Name	Constellation Size Planned (as of 12/2016)	Payload; Re-visit Rate
Astro Digital (United States)	Landmapper HD	20	2.5 m (RBG, NIR); every 3–4 days*
	Landmapper BC	10	22 m (RBG, NIR)
Source: Astro Digital, "Our Satellites," accessed February 20, 2017, https://astrodigital.com/satellites/ *Notes*: The planned EO constellations would be launched into LEO. The HD constellation would collect images that would be used to provide data products for a range of industries, including agriculture and natural resource monitoring. The BC constellation would support the HD constellation. * This is not global revisit, but sufficient coverage to capture all agricultural lands.			
Planet (United States)	Rapideye	5 (currently operating)	5 m, Ground Sampling distance 6.5 m (RBG, Red edge, NIR); daily off Nadir, 5.5 days at Nadir
	PlanetScope (ISS orbit)	55, 1-year lifetime	2.7–3.2 m ground sample distance (RBG, NIR); daily
	PlanetScope (SSO)	100–150, 2–3 year lifetime	3.7–4.9 m ground sampling distance (RBG, NIR); daily
Sources: Planet, "Planet Imagery Product Specification: Planetscope and Rapideye," February 2017, accessed February 20, 2017, https://www.planet.com/products/satellite-imagery/files/Planet_Imagery_Product_Specs.pdf; Planet, "Planet Labs Specifications: Satellite Imagery Products," July 2015, accessed February 20, 2017, http://www.rsgis.ait.ac.th/main/wp-content/uploads/Planet-Labs-Spacecraft-Ops.pdf; Planet, "Planet Labs Specifications: Spacecraft Operations & Ground Systems," June 2015, accessed February 20, 2017, http://www.rsgis.ait.ac.th/main/wp-content/uploads/Planet-Labs-Spacecraft-Ops.pdf; and A. Foerch, "Rapid Growth for Planet," *Trajectory Magazine*, February 15, 2017, http://trajectorymagazine.com/got-geoint/item/2327-rapid-growth-for-planet.html. *Notes*: The first two EO constellations are currently operational in LEO, the third is being deployed. The imagery is processed and delivered through a cloud-based platform for use by end users.			

3 SecureOceans, "Spire Sense," Secure Oceans, accessed February 20, 2017, http://www.secureoceans.org/tech/spire_sense.

4 eoPortal, "Stare," accessed February 20, 2017, https://directory.eoportal.org/web/eoportal/satellite-missions/s/stare.

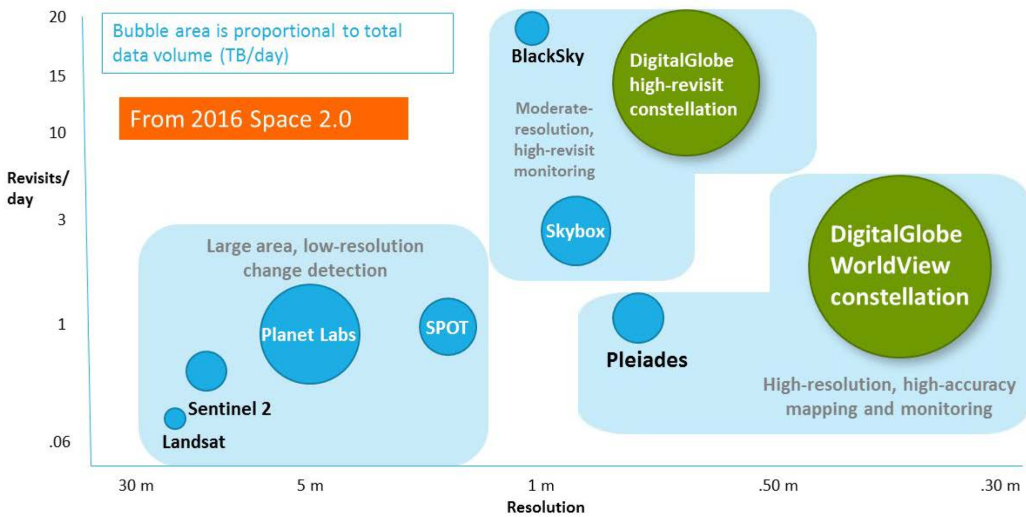
Company (HQ Country)	Constellation Name	Constellation Size Planned (as of 12/2016)	Payload; Re-visit Rate
Planetary Resources‡ (United States)	Ceres (abandoned)	10, 3-year lifetime	10 m (hyperspectral), 15 m (midwave-IR); twice daily
Source: Planetary Resources, “Earth Intelligence from Ceres,” accessed February 20, 2017, http://www.planetaryresources.com/earth-observation/#eo-ceres-constellation.			
Notes: The EO constellation is expected to launch into LEO in 2018–2019. The sensor capabilities would allow for imaging at night, as well as temperature measurement, measurement of water content, and identification of crops			
PlanetiQ (United States)		12 by 2018; 18 by 2020	Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS), funded by NSF
Source: PlanetiQ, “PlanetiQ,” accessed February 20, 2017, www.planetiq.com/.			
Notes: The planned EO constellation would be launched into LEO. The constellation would focus on weather, climate and space weather.			
Satellogic (Argentina)		300 (1st constellation of 16)	1 m (multi-spectral); 2 hours with full constellation
Source: C. Henry, “Satellogic on Its Way to Launching 300 Satellite Constellation for Earth Observation,” *Via Satellite*, March 17, 2016, http://www.satellitetoday.com/technology/2016/03/17/satellogic-on-its-way-to-launching-300-satellite-constellation-for-earth-observation/.			
Notes: The EO constellation is in development, three test satellites were launched over the course of 2013–2014, followed by two more launched in 2016. The complete 16 satellite constellation is expected to be done by 2017. It would provide near-real time imagery of the earth; pilots are in place in the energy and agriculture sector.			
Spaceflight (BlackSky, United States)	Pathfinder	60	1 m (RBG); 40–70 per day*
Source: Expert interview.			
Notes: The EO constellation is in development (6 planned for launch to LEO in 2017). The analysis of the data from the *constellation* would provide insights to customers, and taskable based on user demands. They are currently integrating satellite images, social media, news and other data feeds for insights.			
* Over most inhabited parts of the globe, but not truly global *coverage*.			
Terra Bella (United States)	SkySat	21 by end of 2017	<0.9 m (imagery; RBG, NIR), 1.1 m (video, Pan); 3 per day
Source: Terra Bella, “Our Satellites,” accessed February 20, 2017, https://terrabella.google.com/?s=about-us&c=about-satellites.			
Notes: The EO constellation is partially operational in LEO, with the remaining satellite expected to be launched in 2017. The data from this constellation would be used to provide insights for customers on a range of topics.			
Twenty-First Century Aerospace (China)		3	1 m (Pan), 4m (Multi)
Source: Twenty-First Century Aerospace, “Imagery Products,” accessed February 20, 2017, http://www.21at.sg/imageryproducts.html.			
Note: The EO constellation is currently operational in LEO.			
UrtheCast (Canada)	Deimos 1	1	22 m (Pan, multi-spectral, NIR); by request
Source: UrtheCast, “Diverse Data Offering,” accessed February 20, 2017, https://www.urthecast.com/data			
Note: The Deimos satellites currently operate in LEO. The constellation would integrate multiple sources of geo-spatial data, alongside the imagery, with APIs to deliver insights. The Deimos satellite can be tasked and cued.			
HawkEye 360 (United States)	Signals mapping	21	Software-defined radio
Source: Expert interview.			
Note: The constellation would be launched into LEO and would provide a network for RF signals monitoring. Launch is expected in 2017.			

Company (HQ Country)	Constellation Name	Constellation Size Planned (as of 12/2016)	Payload; Re-visit Rate
Spire (United States)	Weather monitoring, Signals tracking	40 operational, 60 planned for 2017	STRATOS (GPS RO); SENSE AIS (AIS signal sensor); ADS-B

Sources: Spire, "Strato," accessed February 20, 2017, https://spire.com/products/stratos/; Secure Oceans, "Spire Sense," accessed February 20, 2017, http://www.secureoceans.org/tech/spire_sense; and J. Foust, "Spire to Enter Aviation Tracking Market," *Space News*, December 6, 2016, http://spacenews.com/spire-to-enter-aviation-tracking-market/.

Notes: The partially operational (8 satellites) STRATOS constellation uses radio-Occultation (RO) to provide precise and accurate meteorological measurements such as temperature, wind and moisture from space. Spire is also tracking maritime traffic using AIS signals on its SENSE constellation. Spire intends to add 25 satellites with ADS-B sensors to track aircraft in 2017.

Note: Information provided is sourced from company websites and are not based on STPI's evaluation.



Source: Digital Globe

Figure F-1. Companies Focusing on Earth Observation

These constellations of small satellites are not only competing against large satellites but also drones, planes, hosted payloads, payloads on the ISS, and other sources of data. Companies providing intelligence don't necessarily care where data is coming from, so long as it is providing the information the company wants. The high revisit rates, in tracking daily changes, are where small satellite data provides greater value. However, the largest demand is for intelligence, rather than simply pixels. Data analytics is the key development area, and is not specific to small satellites. Many companies feed in data from a range of satellites, as well as aerial imagery and social media, in order to provide their intelligence.

It should also be noted in discussing these application areas that most companies cover more than one area. Once a data stream is established, whether it's from your satellites or someone else's, it is comparatively easy to tailor analytics to multiple models, or those specific to the customer. This allows companies to look for demand in a range of areas, and tailor their model in that way.

Economic Forecasting

Economic forecasting is a broad area, both in terms of application and satellite inputs. The scale can vary anywhere from predicting national GDP or determining poverty levels to tracking individual assets or predicting company stock prices. Inputs can vary from tracking ships based on AIS to using imagery to monitor retail traffic.

Companies have a range of options to monitor their supply lines. Companies such as Twenty First Century Aerospace Technologies advertise their ability for their satellite imagery to monitor mining and oil spills, while OmniEarth would monitor a company's pipelines.[5] Oil reserves can also be monitored by using satellite imagery to detect the height of oil tank lids. Shipping activity can be tracked statically by using visual imagery to identify trucks, boats and other systems of transportation, and dynamically through the tracking of AIS signals from maritime operators, and ADS-B signals from aviation. AIS signals tracking is currently offered by Spire, who plans to offer ADS-B signals from future satellites.[6] Combining this data with weather data or ice monitoring can allow for a better understanding of new routes available as well as hazards faced and possible delays. More frequent coverage allows for more effective tracking so that planes and ships are more regularly observed, allowing for greater confidence in tracking.

In moving beyond the supply lines, companies can understand the retail traffic of their own stores and their competitors by monitoring the number of cars in their parking lots. Automatic object identification can allow for machine counting of cars based on satellite imaging, and can feed that data into calculations of stock prices. Allowing for monitoring of day to day changes allows for more rapid decision making and a better understanding of key events, such as Black Friday sales.

Another step in understanding commercial activity is understanding development. This is not only a tool for understanding commercial competition, but also for understanding national and regional development. Construction projects, whether they are a competitor's new store or a key government infrastructure or development project, be monitored as they progress. Urban development can also be tracked through satellite imagery, and heights of buildings can be determined from satellite imagery. Building out

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5 OmniEarth, "Products&Services," OmniEarth.

6 J. Foust, "Spire to Enter Aviation Tracking Market," *SpaceNews*, December 6, 2016, http://spacenews.com/spire-to-enter-aviation-tracking-market/.

3d models from imagery is a key area of development in the analytics of satellite images[7]. This would only be improved by the addition of SAR data from small satellites, which can determine heights. Other construction projects, such as key infrastructure including roads and train tracks, can also be monitored. The construction and activation of phone towers can not only be monitored visually, but may also be monitored through RF detection from future constellations such as that planned by HawkEye360[8]. Feature tracking similar to this can be used from something as mundane as feature evaluation of houses in a neighborhood for property valuation or for tracking development of countries whose economic metrics may not otherwise be trusted. Additionally, IR monitoring of heat sources and visual monitoring of lights can be used to detect generators, running cars, and nighttime use of electric lighting, all useful inputs for a broader economic model. For example, Orbital Insight has worked with the World Bank to test predictions of poverty in Sri Lanka.[9]

Agriculture

Another input to an economic understanding is agricultural supplies. The ability to predict crop yields can help to better predict the stock prices of agricultural companies and the exports of key agricultural countries. Additionally, satellite imagery can help contribute to precision agriculture, helping farmers assess crop irrigation needs, water use, and sustainability, and using that data to direct irrigation or other attention where it's most needed. This can take inputs from visual data, which can be assessed using the Normalized Difference Vegetation Index, as well as Short Wave Infrared Imagery, which can often be used to distinguish between different types of vegetation, such as finding the boundary between corn and soybean fields.[10]

Weather data and predictions can also help to develop predictions of crop success and output, as well as precision agriculture irrigation needs. Descartes Labs is a key player in this sector, offering weekly predictions of soy and corn production in the United States, with future expansions to other major crop countries, as well as offering an improved understanding of water and land use and overall sustainability. While Descartes does not operate satellites of its own, it purchases data from NASA, ESA, and commercial

7 For one example of research into 3D modeling from satellite imagery, see the webpage for IARPA's 3D challenge at https://www.iarpa.gov/challenges/3dchallenge.html.

8 For more information, visit HawkEye 360's website at http://www.he360.com/.

9 Orbital Insight, Leveraging commercial applications to help the World Bank map poverty," *Medium*, January 4, 2016, accessed January 20, 2017, https://medium.com/from-the-macroscope/leveraging-commercial-applications-to-help-the-world-bank-map-poverty-79bca51814ee#.oxf2g16mh

10 M. Alderton, "More Than Meets the Eye," *Trajectory Magazine*, 2016 Issue 4, http://trajectorymagazine.com/trajectory-mag/item/2274-more-than-meets-the-eye.html.

constellations[11], leaving open the opportunity for small satellite constellations to make further inroads in this sector as daily revisits and increasing numbers of satellites with near infrared sensors provide increasing data for more timely predictions and assessments.

Resource Management

Water management extends beyond agriculture; it is a crucial aspect of resource management. Tracking water reserves, from observing water reservoirs, to tracking individual water use, can be a key area of understanding especially when dealing with drought or other extreme weather conditions.

In addition to monitoring mineral, coal, and oil resources by monitoring mining, pipelines, and reserves as discussed in relation to economic monitoring, another key resource to manage and monitor is lumber. Tracking illegal logging and burning is key to forest management, and, more broadly, tracking deforestation from an environmental standpoint, and can be aided by the improved timeliness of small satellite constellation revisit rates. By assessing changes on a daily basis or less, key cases of illegal logging can be better addressed and monitored. Broadly, satellites have the capability to track land and resource use on a broad scale.

Identification of Hazards and Bad Actors

Not only can satellite data be used to identify illegal logging, but other "bad actors" as well. For example, visual and AIS tracking of ships can be used to identify illegal port activity, illegal fishing, attribute the source of oil spills, or identify ships that have turned their AIS off. By adding RF monitoring of AIS signals to imagery data, operators have the opportunity to identify ships that are broadcasting an inaccurate location, an application highlighted by Hawkeye 360.

RF signals monitoring can also be used to identify unexpected sources of signals, which may be used to identify camps or key headquarters. Additionally, IR can point to anything generating heat, whether that's running cars or other vehicles, planes, generators, or large weapons such as active missiles. Such capabilities allow for identification of key hotspots of mobilization. Merging IR satellite data with local data, such as geotagged twitter feeds or other social media, can predict likely areas of conflict.

Security and Warfighting

Building on the concepts discussed above (Identification of Hazards and Bad Actors), satellite imagery has additional applications for security and warfighting. For example, in

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[11] Descartes Labs "About the Descartes Labs Forecast," Descartes, October 2016, accessed January 20, 2017, http://www.descarteslabs.com/forecast.html

addition to tracking ports, regular imagery can also be used to track and identify border activity. As imagery is acquired more frequently and at higher resolution, such tracking would be more effective, however, even now it could make major border movements visible to anyone willing to pay for the data.

Increased satellite coverage, mobility, and numbers can also allow for dedicated tasking to support the needs of warfighters, whether that is monitoring of weather data around them, key deployment movements around them, or supplying reliable communications (discussed further under communications) in otherwise inaccessible places. The number and rapid life cycle of small satellites also provides potential redundancy for major space assets. Rapid launch systems could allow for quick replacement of assets lost to attack, providing system resiliency. However, commercial satellites in a theater of war is a double-edged sword; on one hand, satellites can augment the United States' warfighting assets, but on the other, enemies have similar access to the commercial data and could use it against U.S. troops.

Weather Prediction and Monitoring

Weather prediction is crucial across many areas previously discussed, whether it's tracking shipping, monitoring agriculture, or predicting future conditions for warfighting. Satellites have long played an essential role in predicting the weather and monitoring atmospheric and climate shifts. Smallsats are beginning to play a role, particularly in the case of Spire, which is using its Stratos constellation, equipped with GPS-RO to build out weather prediction from atmospheric sounding data.[12] More dispersed and frequent measurements allow small satellite constellations to significantly improve on existing weather data, which is why this is an active sector, as companies such as Geooptics and PlanetiQ are investing in putting their own GPS-RO constellations up. Several of these companies are also interested in using their measurements to monitor space weather.

Other atmospheric monitoring measures include GHGSat, a commercial small satellite which measures carbon dioxide and methane emissions.[13]

Disaster Monitoring

All of these sectors may play a role in monitoring disasters, whether they are extreme weather events or earthquakes. Improved weather monitoring can help to predict hurricanes and extreme weather events that can lead to flooding or mudslides. Monitoring buildings and infrastructure can allow for determinations of what damage has been done to buildings and infrastructure, determining key areas for assistance and routes that may be blocked to

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[12] For more on Stratos, see Spire's website on this product: https://spire.com/products/stratos/.

[13] For more on the GHGSat, see the GHGSat website: http://www.ghgsat.com/.

relief workers. Better weather predictions can help determine the smallest and most accurate areas that need to be evacuated and help disaster response coordinators pre-position their emergency response resources before the event. Tracking RF signaling may help to better determine when cell towers are down, allowing for better rerouting of communications, and may even provide backup systems. Infrared monitoring can help to monitor volcanos and forest fires. Signals, monitoring human movements, and data fusion with on the ground social media can help to highlight potential areas of follow-on conflicts or crucial need for relief.

Communications

A number of operators are currently developing constellations of smallsats to meet consumer demands related to communications. Applications include broadband internet and machine to machine communications ("Internet of Things"). Recent filings to the FCC in the United States provide a snapshot of the diversity of projects currently being planned in the communications application sector (Table F-2).

Table F-2. Select FCC Filings for Smallsat Communication Satellites

Company	Location	No. of Satellites	Bands	Services
SpaceX	Hawthorne, CA	4,425	Ka, Ku	Global broadband
Boeing	Seattle, WA	2,956	Ka,V	Advanced communications, Internet-based services
OneWeb	Arlington, VA	720	Ku	Global broadband
Kepler Communications	Toronto, ONT	140	Ku	Machine-to-machine communications (Internet of Things)
Telesat Canada[a]	Ottawa, ONT	117	Ka	Wide-band and narrow-band communications services

Source: Adapted from D. Messier, "Companies Propose Launching 8, 70 Satellites into Non-Geosynchronous Orbit," *Parabolic Arc,* November 29, 2016, http://www.parabolicarc.com/2016/11/29/companies-propose-launching-8700-satellites-nongeosynchronous-orbit/.

[a] P. B. de Selding, "Telesat to Order Two Small Ka-Band Satellites to Test Constellation, February 26, 2016, http://spacenews.com/telesat-to-order-two-small-ka-band-satellites-to-test-constellation/.

This section provides an overview of the applications and companies currently planning constellations to deliver broadband internet and machine to machine communication.

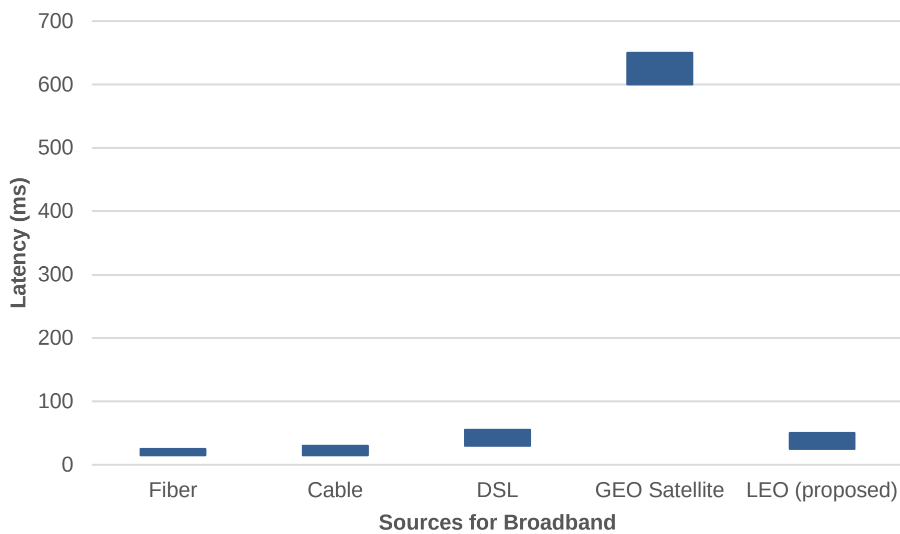
Broadband Internet—LEO-Based Constellations

A number of smallsat operators are currently developing constellations of smallsats to deliver global broadband internet to terrestrial users. This section examines the proposed constellation and current market drivers.

Proposed Capabilities Delivered by LEO Constellations

Numerous constellations have been proposed that would be developed based on current technology and technology currently under development.

Constellations would become technically competitive against current broadband options deployed if proposed constellations are capable of achieving projected latency and speed rates. Shown in Figure F-2, proposed LEO constellations, which seek to reach a latency as low as 25 ms, would become competitive in latency relative to ground based options (fiber, cable and DSL). The degree of magnitude difference relative to GEO-based systems exists for the very simple reason that LEO satellites are closer to Earth than GEO satellites.[14]



Source: W. A. Hanson, "Satellite Internet in the Mobile Age."

Figure F-2. Proposed Latency Rates for LEO Broadband Would Be Competitive with Terrestrial Options

However, LEO-based systems face challenges; as the satellites are not geostationary, they require larger constellations for continuous coverage, and satellites and ground antennas must integrate multiple signals being handed off. Paired with the decreasing per

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[14] W. A. Hanson, "Satellite Internet in the Mobile Age," *New Space* 4 (3, September 2016): 138–152. doi:10.1089/space.2016.0019.

unit costs of smallsats, one advantage of large constellations of smallsats is that they would allow for a greater distribution of high transmission loads, which eases congestion.

Two business models are currently publicized for LEO-based broadband. The first is direct to home; this model involves users receiving signals directly via small receivers. The second model is community aggregator; this model involves ground stations that receive signals and then users are subsequently connected by fiber systems. Different providers are taking different approaches (Table F-3). For example, OneWeb's system is designed to integrate existing smartphone handsets and cellular networks—complementing current technology rather than substituting.[15]

Table F-3. Major Planned Smallsat Broadband Constellations

Company/Operator	OneWeb	SpaceX	Boeing
Country of Headquarters	United Kingdom	United States	United States
Approximate constellation size	720	4,425	2,956
Expected satellite lifetime		5–7 years	
Orbit (LEO, MEO, GEO)	LEO	LEO	LEO
Operational Status	In-development, project deployment in 2017	In-development, project deployment in 2019	Planned
End-User Peak bandwidth	50 Mbps	1 Gbps	
Latency	50 ms	25–35ms	
Spectrum Used	Ka Ku band	Ka Ku band	V and or C band
Launch Provider	Arianespace, Virgin Galactic	In-house	In-house
Target Satellite Cost	$600,000	$100,000–200,000	
Key Funders	Virgin Galactic, Intelsat, Airbus Group, Softbank Group, Bharti Enterprises, Qualcomm, Coca-Cola, and others	Elon Musk, Google & Fidelity	
Key Partners	Airbus	None disclosed	None disclosed

Note: Information is sourced from 2016 FCC filings, interviews, and company websites.

[15] Ibid.

Market Drivers for LEO-based Broadband

During the dot-com era of the 1990s, companies like Teledesic attempted, unsuccessfully, to deploy constellations of larger satellites to deliver broadband from LEO. Since this first attempt, computer power has increased in accordance to Moore's Law,[16] the smallsat platform has emerged as COTS parts and miniaturized instrumentation have proliferated and decreased the cost of missions by orders of magnitude, and the demand for internet has grown globally with a projected 4.4 billion people lacking internet access.[17] The projected costs of satellites today have decreased by two orders of magnitude relative to plans proposed in the 1990s; for example, projects in the 1990s projected costs of $60–70 million per launch per satellite.[18]

Four demand drivers for a LEO-based smallsat broadband constellation include the following:[19]

- **Cheap and short-lived platform allows for rapid upgrading:** Unlike current GEO large satellite assets, the short lifetimes of small satellites allow for the state of the art in technology (particularly payloads) to rapidly develop, effectively replacing the entire infrastructure every 5 years. If launch becomes an inhibitor, GEO operators could become competitive
- **Performance upgrades would make satellite-based broadband competitive:** As described prior, smallsat LEO constellations project to decrease latency by an order of magnitude relative to operating GEO large satellites. High upload speeds paired with bandwidth, provided by smallsat constellations, would enable faster intercontinental communications, streaming of video, and reasonably fast download speeds, becoming competitive against ground-based options (e.g., fiber).
- **Universal access would connect under-developed markets:** Cheaper access to internet, through satellites, would connect regions that are too costly to reach effectively by fiber cables (due to low population density or geographical

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[16] Marboe, I. 2016. Small Satellites: Regulatory Challenges and Chances. Leiden, The Netherlands: Brill - Nijhoff.

[17] Hanson, "Satellite Internet in the Mobile Age"; United Nations Educational, Scientific, and Cultural Organization (UNESCO), "Broadband Commission Report 2016: More than Half of the World's Population Remains Offline and the Gender Gap Is Widening," September 16, 2016, http://www.unesco.org/new/en/media-services/single-view/news/broadband_commission_report_2016_more_than_half_of_the_worl/.

[18] D. Majumdar, "Why the Time Seems Right for a Space-Based Internet Service," *MIT Technology Review*, January 27, 2015, https://www.technologyreview.com/s/534361/why-the-time-seems-right-for-a-space-based-internet-service/

[19] W. A. Hanson, 2016. "Satellite Internet in the Mobile Age."

limitations). "Governments are increasingly relying on the Internet to deliver public services, such as healthcare and education. There is a strong policy belief in the benefits of connecting workers and firms to the wider economy. However, reaching the last 5% or 10% of potential users can be exceedingly expensive."[20]

- **LEO constellations could appease current infrastructure demand overload:** With the growing use of mobile telephony capabilities, a LEO-based constellation could combine internet and mobile capabilities to improve coverage of both globally.

Drivers in Developed World Markets

LEO constellations would only serve as a speed upgrade in advanced countries, since GEO-based services already cover most areas.[21] As currently implemented, GEO satellites have reduced the number of Americans without access to broadband providers from 20M to <1.5M.[22] However, in 2016, 39% of rural Americans lived without access to broadband internet.[23] Constellations can provide cheap coverage to these Americans, as well as provide global coverage to high-latitude regions (Alaska, Norway, Russia) where GEO satellites do not cover and terrestrial solutions are expensive or do not reach many users. LEO satellites also have the advantage of being able to provide cellular coverage as well as internet access, as planned by OneWeb.[24]

To summarize, the most likely initial successes for LEO constellations in developed economies are:[25]

- Broadband internet coverage in rural areas
- Low-latency upgrades (order of magnitude) to directly compete with current GEO-based broadband providers
- Self-contained cellular service boosting
- Internet of Things coverage for asset tracking, production monitoring, scientific monitoring, autonomous vehicle connectivity (discussed further below)

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[20] Ibid.

[21] Ibid.

[22] Ibid.

[23] Space and Innovation (OECD 2016)

[24] W. A. Hanson, "Satellite Internet in the Mobile Age." 2016

[25] Ibid.

However, it is ultimately uncertain if satellite internet service would remain viable for use in the developed world if bandwidth and cost of fiber optics outpaces the satellite model.[26] Satellites also face competition in delivering remote internet access from balloons (Google) and high-altitude drones (Facebook).

Developing World Markets

Prices for basic broadband in developing countries are higher relative to developed countries; poorer countries have the most expensive internet (Figure F-3).[27] The proclaimed social mission of many proposed LEO constellations is to provide Internet access to the half of the world's population that currently lacks it, an example being OneWeb. Internet has broad implications for health, education, worker training, job seeking, entrepreneurship, entertainment, communication, low-cost shopping. For example, increased access can provide health training to remote areas and report outbreaks. Internet technology is a primary driver of economic development, and so there is a strong drive to gain access to internet technologies. Satellite communications is already affecting the way some NGO's approach addressing poverty.[28] If small satellites can provide such technologies at low enough cost, they are likely to find an expansive market.

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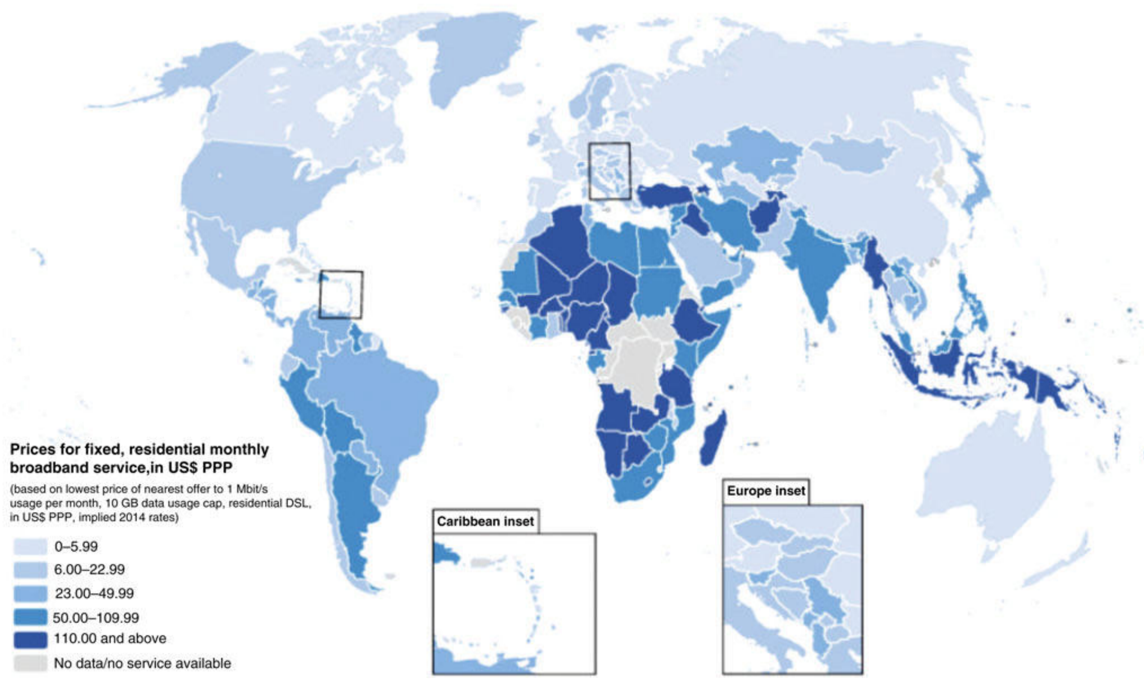
[26] Majumdar, "Why the Time Seems Right for Space-Based Internet Service"

[27] W. A. Hanson, 2016. "Satellite Internet in the Mobile Age."

[28] K. Russell, "SES & Friendship: How Satellites Fit into Humanitarianism," *ViaSatellite*, June 16, 2017, http://www.satellitetoday.com/telecom/2017/06/16/ses-friendship-satellites-fit-humanitarianism/



Source: Satellite Internet in the Mobile Age, 2016. Data based on World Bank. Digital Dividends Report, 2014.

Figure F-3. High Cost of Basic Broadband, Potential Markets for Satellites in Absence of Cheap Ground-Based Options

Machine-to-Machine Communication: Internet of Things

The Internet of Things (IoT) is a conceptual world (Figure F-4) that is hyper-connected, allowing billions of machines and devices to connect with one another to track activity or other machines or humans with world-wide breadth.[29] In practice, satellites receive and direct data from millions of small, uncoordinated sensors from remote areas with low data rates. Flat antennas would allow for IoT backhauling on any platform, including high throughput satellites or other fixed satellite services, which would allow for IoT to have a more significant presence.[30] Small satellites are already being considered as a possibility for this role; for example SpaceWorks' Blink Astro seeks to deploy thousands of monitors (e.g., in agriculture fields) that would communicate with a planned constellation of smallsats.[31]

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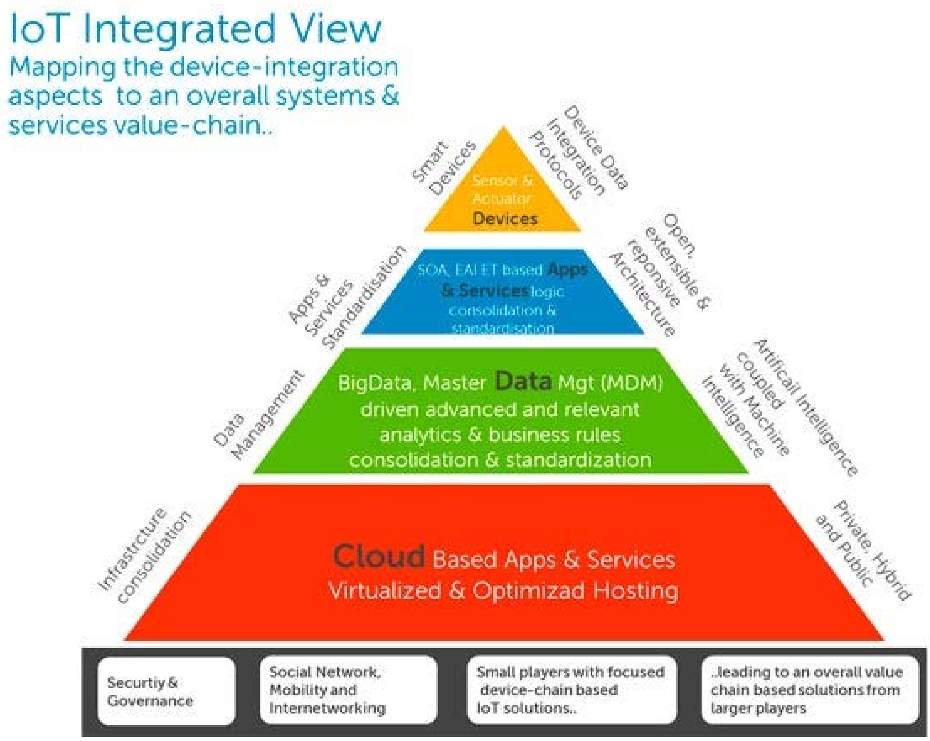
[29] M. Holmes, "An Internet of Things World: Where Does the Satellite Fit In?" *Via Satellite,* October/November 2016.

[30] Holmes, "An Internet of Things World."

[31] D. Messier, "SpaceWorks Launches Blink Astro LLC, New Satellite Subsidiary," *Parabolic Arc*, November 20, 2015.



Source: A. Banafa. "10 Predictions for the Future of IoT," *Open Mind*, May 23, 2016, accessed February 20, 2017, https://www.bbvaopenmind.com/en/10-predictions-for-the-future-of-iot/?utm_source=facebook&utm_medium=techreview&utm_campaign=MITcompany&utm_content=predictionIoT.

Figure F-4. Internet of Things (IoT) Ecosystem

Alternative platforms currently exist to provide limited coverage for IoT-connect devices from terrestrial infrastructure, balloons, UAVs and GEO-based HTS satellites. However various operators are developing low cost, low latency small satellite constellations to address part of the growing market. M2M via satellite provides unique capabilities relative to terrestrial infrastructure due to the worldwide coverage, higher reliability, better terminal battery life, and a single platform to provide services. Data aggregation services for M2M/IoT would be well suited for LEO constellations, mainly applications such as critical military or transportation missions, oil and gas industry, mining or civil government applications in remote areas where large data rates and low latency are important. Others include:

- Ship, cargo and vehicle tracking
- Weather stations
- Exploration for resources
- Expansion of trade through globalization
- Personal trips to remote locations (leisure/sports)

- Wearables, e.g., Thuraya, an IoT company that partners with a company, WiCis, which provides wearables for mountain climbers, WiCis, in order to allow data on climbers' health to be transmitted to base camp even in remote locations.[32]

On Orbit Activities

On Orbit Repair

On-orbit servicing is an emerging application that may utilize small satellites in repair, refueling, damage inspection, and payload substitution of satellites and spacecraft. Enabling these tasks would help to extend the operational lifespans of satellites and could allow assets to be upgraded or even repurposed for different missions. Although on-orbit servicing capabilities have yet to reach maturity, they offer tremendous upside to civil, commercial, and military operators alike. For example, we estimated that performing an on-orbit technology refresh midway through the lifespan of a telecommunications satellite could generate an additional $300 million of revenue.[33] A variety of technologies for on-orbit servicing are currently under development that would enable basic inspection and refueling services performed by small satellites within the next few years.

Some monitoring activities are currently in development that may lead to satellite repair. Chandah is building small satellites designed to visually inspect large satellites in GEO (Table F-4); however, the satellites are not yet close to launch. The fact that there are few active players in this field, as this is a sector complicated enough that large satellites have not fully occupied the market. Orbital ATK is pursuing one option for on orbit refueling and orbit management via Vivisat's Mission Extension Vehicle, looking at a 2018 launch and having just received licensing to observe customer satellites,[34] while NASA is funding Space Systems Loral to build Restore-L, which hopes to launch in 2020, with the ability to refuel and repair satellites.[35]

Table F-4. Key In-Space Activities of Smallsat Companies

[32] Holmes, "An Internet of Things World: Where Does the Satellite Fit In?"

[33] I. Boyd et al., *On-Orbit Manufacturing and Assembly of Spacecraft*, Alexandria, VA: IDA, Paper P-8335, forthcoming, 2017.

[34] For more information, visit Vivisat's website at http://www.vivisat.com/.

[35] S. Fecht, "NASA's New Satellite would Circle the Globe Repairing Broken Space Robots," *Popular Science*, December 6, 2016, http://www.popsci.com/nasa-hires-satellite-repair-robot.

Company	Service Offered	Country of HQ	Constellation Size (as of 12/2016)	Key Payloads
Astroscale	IDEA OSG (Debris identification)	United States	Not-specified	Optical
	BOY (Debris removal)	United States	Not-specified	Adhesive surface
Astroscale seeks to launch its IDEA OSG in 2017 and ADROS “Boy” in 2018 (for demo) in an effort to track and remove space debris respectively. The “Boy” would be a smallsat that would be deployed from a mothership to remove debris.				
Chandah Space	SSA	United States	20	Optics at 2–2.5cm
The planned constellation (InsureSat) would be launched to inspect client GEO satellites. They would be launched 200km above GEO (and then fly down to 5Km for stand-off inspections).				
Planetary Resources	Asteroid mining	United States	Not-specified	Thermographic IR, hyperspectral
Through its CERES EO mission, Planetary Resources is was testing and demonstrating key payload sensors on its ARKYD bus; a modified version of the bus and payloads would be used for identifying asteroids for water (potential fuel for deep space missions) and metals (for on-orbit manufacturing).				

Note: All information is from either public sources (company website and press releases) or conducted interviews.

This market has been difficult to enter a variety of reasons, not the least of which is the technical challenge of maneuvering near another satellite without damaging it, and having the capability to attach, refuel, and move or repair autonomously. In particular, this is a challenge for small satellites, whose propulsion is limited by size relative to larger satellites. However, perhaps the greater challenge is finding customers willing to work with the issues of safety, threat, and legality surrounding such capabilities with the funding to do so. Even a well-intentioned actor may damage or disable a client satellite through improper maneuvering, or worse, damage another satellite in the process of maneuvering to the client satellite. Malevolent actors could deliberately damage a satellite, interfere with its activity, or move it out of its orbit. This concern has been raised by Russia’s Kosmos 2499, a small satellite, and Luch, both capable of maneuvering close to larger satellites. This not only allows for observation of or spying on the larger satellite, but also such targeted maneuvering could allow the smaller satellite to collide with and destroy the larger satellite.[36] Fears of such a capability being used malevolently could engender concerns

36 J. Sciutto and J. Rizzo, “War in Space, Kamikazes, Kidnapper Satellites and Lasers,” CNN, November 29, 2016, accessed February 20, 2017, http://www.cnn.com/2016/11/29/politics/space-war-lasers-satellites-russia-china/index.html?sr=twcnni113016space-war-lasers-satellites-russia-china0155AMStoryLink&linkId=31718930

even about Chandah's future satellites, designed for proximity operations, or satellites developed by NASA or Orbital ATK. DARPA opened a commission to try and better understand the legal issues and jurisdictions surrounding this field in August of 2016,[37] and is now pursuing their own program.[38]

Debris Management

Similar concerns surround the field of debris management. Any capability that would allow a small satellite (or any satellite) to maneuver and pull a dead satellite or piece of orbital debris out of orbit such that it would no longer be a hazard would also be a capability that would allow a satellite to pull other "live" satellites out of their orbit or otherwise deliberately damage them. This is the concern raised by China's Shiyan and Aolong-1, small satellites whose robotic arms are capable of grabbing other satellites. While reportedly designed for orbital debris management, these satellites' capabilities leads to the fear that it may be used to drag other satellites out of their orbit and off mission.[39] Astroscale is a Singapore-based company pursuing this capability by building small satellites that can stick to orbital debris and then pull them down into the atmosphere where satellite and debris would burn up. Astroscale also hopes to provide capabilities to track space debris that may not be able to be tracked from the ground, similar to STARE's space debris tracking goals (Table F-4). However, this sector also faces the problem of the service provided being, essentially, a public good, as a cleaner space benefits all operators indiscriminately, it is hard to find individual demand to fund cleanup. Whereas on orbit repair, if benevolent, targets specific client satellites, cleaner space benefits all actors in space.

Beyond Earth

In the commercial sector, asteroids are a key target of interest. Planetary Resources and Deep Space Industries both propose to use small satellites to mine asteroids for key resources, both for Earth and as fuel for future space exploration. Both companies are still

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[37] D. Werner, "DARPA to Establish Satellite-Servicing consortium to Discuss On-Orbit Repair Standards," *SpaceNews*, August 22, 2016.

[38] D. Messier, "Orbital ATK Sues to Stop DARPA Satellite Servicing Program," *Parabolic Arc*, February 8, 2017. http://www.parabolicarc.com/2017/02/08/orbital-atk-sues-stop-darpa-satellite-servicing-program/.

[39] J. Sciuttio and J. Rizzo, "War in Space Kamikazes, Kidnapper Satellites and Lasers," CNN, November 29, 2016, http://www.cnn.com/2016/11/29/politics/space-war-lasers-satellites-russia-china/index.html?sr=twcnni113016space-war-lasers-satellites-russia-china0155AMStoryLink&linkId=31718930; P. D. Spudis, "Continuing the Long March to the Moon," *Air & Space Magazine*, July 1, 2016, accessed February 20, 2017, http://www.airspacemag.com/daily-planet/continuing-long-march-moon-180959672/.

working on building technology and capital to fund such a mission. While not strictly scientifically motivated, the resources and insight provided by such commercial endeavors could further future scientific exploration. Planetary Resources ARKYD bus is included in Table F-4.

A different approach is demonstrated by B612, a nonprofit, which intends to put small satellites into deep space to track Near Earth Objects that may pose a collision risk for Earth.[40] These missions have not yet launched.

When venturing into deep space, small satellites face different challenges than they do in Earth orbit. For example, while LEO CubeSats rarely have to contend with surviving radiation over the long term, as radiation exposure is more limited in LEO and relatively regular satellite replenishing is typically built in to company plans as a way to avoid obsolete technology, the deep space environment requires significantly more capability to handle radiation. Communication is also more difficult at greater distances from Earth stations, as small satellites are comparatively limited in antenna and dish size. One advantage small satellites may have in interplanetary missions, however, is inherent to their small size, safely landing a smaller satellite requires smaller sized deorbiting and decelerating tools than a larger, more expensive mission.

Science

Some of the applications based on satellite communications have relevance for science. For example, internet of things technology can enable the collection of data from widely dispersed sensors in areas where it may otherwise be difficult to access for data collection. Similarly, many of the applications for small satellite Earth Observation can also be used for science purposes, including Earth weather and atmospheric and climate monitoring, as well as space weather. Monitoring atmospheric radiation is a popular topic for student satellites, including the planned satellite from IIT Madras, an Indian University, which intends to measure atmospheric radiation to study space weather and earthquakes,[41] encompassing weather monitoring and disaster monitoring. This kind of student innovation highlights the value of small satellites for relatively low cost technology development and demonstration, providing scientific value through new technologies. Another illustration

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[40] J. Foust, "B612 Studying Smallsat Missions to Search for Near Earth Objects," *SpaceNews*, June 20, 2017, http://spacenews.com/b612-studying-smallsat-missions-to-search-for-near-earth-objects/

[41] IITMSAT, "IITMSAT: A Student Satellite Initiative."

of this is the National University of Singapore's use of a small satellites to test quantum communications technologies.[42]

While small satellites are typically thought of as tools for Earth Observation, moving small satellites beyond Earth is moving forward in several areas. Much of the sector is driven by NASA, for example the Lunar Cube Quest challenge,[43] Lunar flashlight Mission,[44] and the MarCO CubeSats, flying to Mars with the InSight mission.[45] Companies looking to design small satellite systems for interplanetary travel see NASA as a key customer and driver of the design of their work. Small satellites have the opportunity to provide additional data and relays when serving with larger missions, and may well be able to scope out future exploration targets for other missions.

Other

Small satellites may see a variety of other applications, such as in entertainment. Imagery from space may prove an interesting source for new VR program development. Additionally, one Japanese company sees the value of small satellites for entertainment, by creating on-demand shooting stars or fireworks through the deorbiting of such satellites.[46]

Remote Sensing and Communications Constellations

As a consequence of the growing perception that space-based activities can be profitable there are many new communication and remote sensing smallsats constellations that are scheduled to be launched in the next 10 years (Table F-5).

Table F-5. Information on Constellation Projected to be Launched between 2017 and 2025

42 Asian Scientist, "Singapore Universities Launch Satellite," *Asian Scientist*, December 22, 2015, accessed February 19, 2017, http://www.asianscientist.com/2015/12/tech/singapore-universities-launch-satellites/ http://www.asianscientist.com/2015/12/tech/singapore-universities-launch-satellites/

43 STMD: Centennial Challenges, "Cubequest," *STMD Centennial Challenges*," accessed February 20, 2017, https://www.nasa.gov/directorates/spacetech/centennial_challenges/cubequest/index.html

44 NASA JPL, "Lunar Flashlight", *NASA JPL*, accessed February 20, 2017, http://www.jpl.nasa.gov/cubesat/missions/lunar_flashlight.php

45 NASA JPL, "Marco," *NASA JPL*, accessed February 20, 2017, http://www.jpl.nasa.gov/cubesat/missions/marco.php

46 Kate Springer, "Fireworks of the future? Japan to create fake shooting stars," CNN, October 24, 2016, accessed February 20, 2017, http://edition.cnn.com/2016/10/23/asia/on-japan-artificial-meteors/index.html?sr=fbcnni102416on-japan-artificial-meteors0300AMStoryLink&linkId=30261945.

Company	Constellation Size (approximate number of satellites)	Country	Orbit altitude (kilometers)	Use	Mass (kg)
OneWeb	720	United Kingdom	1,200	Broadband	150–200
Boeing	2,956	United States	1,000–1,200	Broadband	*Unknown*
SpaceX	4,425	United States	1,110–1,325	Broadband	450
XinWei (Unclear Status)	32	China	800	Broadband	*Unknown*
BitSat (Dunvegan Space Systems and Deep Space Industries Inc.)	24	United States	*Unknown*	*Unknown*	CubeSat
Telesat*	117	Canada	*Unknown*	Wide- and narrow-band comms.	*Unknown*
Blink Astro	*unknown*	United States	700	IoT/M2M	CubeSat
Magnitude Space	*unknown*	Netherlands	700	IoT/M2M	Nanosatellites
Sky and Space Global	200	UK, Israel, Australia	500-800	IoT/M2M/ Voice Narrowband	3C CubeSat
Kepler Communications	140	Canada	500-600	Relay/M2M, IoT	Nanosatellites
Analytical Space	*unknown*	United States	*unknown*	RF data Relay/IoT	6U CubeSat
Audacy	3	United States	14,000	Relay	*unknown*
ELE SA	64	Switzerland	500-650	IoT/M2M	3U CubeSat
Fleet Space	100	Australia	600	IoT/M2M	12U CubeSat
Helios Wire	30	Canada	*Unknown*	IoT/M2M	16U CubeSat
EightyLEO	80	Germany	*Unknown*	IoT/M2M	200
DigitalGlobe/TAQNIA	6	United States	*Unknown*	Optical imagery	*Unknown*

Company	Constellation Size (approximate number of satellites)	Country	Orbit altitude (kilometers)	Use	Mass (kg)
GHGSat	20	Canada	500	Emission monitoring	15
Promethean Labs, LLC	*Unknown*	Canada	*Unknown*	Earth observation/ monitoring GHGs	*Unknown*
Karten Space	14	Spain	*Unknown*	Earth observation/ AIS	6U CubeSat
Planet	150+	United States	475	Earth observation	3U CubeSat
Satellogic	300	Argentina	500	Earth observation	37
BlackSky	60	United States	690	Earth observation	Microsat
Astro Digital (Aquila)	30	United States	600	Earth observation	6U CubeSat
Planetary Resources (abandoned)	10	United States	*Unknown*	Earth observation	12U CubeSat
Hera Systems	48	United States	*Unknown*	Earth observation	22
Terra Bella	21	United States	600	Earth observation	120
Axelspace	50	Japan	*Unknown*	Earth observation	Less than 95 kg
Conasat	6	Brazil	*Unknown*	Environmental data collection	8U CubeSat
Magna Parva/Kleos Geolocation Intelligence	20	United Kingdom	*Unknown*	AIS/RF mapping	Microsat
Hawkeye 360	21	United States	550-650	RF mapping	15
CICERO (GeoOptics)	*Unknown*	United States	*Unknown*	GPS-RO	*Unknown*

Company	Constellation Size (approximate number of satellites)	Country	Orbit altitude (kilometers)	Use	Mass (kg)
PlanetiQ	18	United States	800	Weather (GPS-RO)	6U CubeSat
Spire Global	120	United States	500	AIS/ADS-B/ GPS-RO	3U CubeSat
AISTech	25	Spain	*Unknown*	IoT/M2M/ ADS-B/AIS/ IR imaging	6U Cubesat
NovaSAR (SSTL)	Initially planned for 4 satellites; now working with 1	United Kingdom	*Unknown*	SAR	440
Iceye	18	Finland	400	SAR	Microsat
XpressSAR	4	United States	*Unknown*	SAR	*Unknown*
Capella Space	30	United States	*Unknown*	SAR	16U CubeSat
Chandah Space	20	United States	GEO	SSA	Less than 100

Appendix G. Case Studies

STPI researchers conducted formal and informal interviews with companies engaged in the smallsat ecosystem. Provided in this appendix is a series of 22 case studies developed from formal interviews conducted and publicly available information. The companies were chosen to provide a snapshot of the types of companies that are engaged in the smallsat industry. The case studies seek to capture the diversity of activity that occurs across the industry, given the varying sizes, customer bases, products and geographical operations of the companies identified.

For each case study, the following categories are explored:

- Company Overview: a short snapshot of the company
- Company Information: founding year, size of organization (by revenue or size of staff, when available) and location of operations
- Leadership Heritage: the heritage and background of the company's leadership
- Organizational Goals and Mission: general vision and business case of each company, role they seek to play in the smallsat ecosystem
- Ongoing and Future Plans: an overview of the type of missions and products served by the company
- Customers and Partners: key partners and customers are identified
- Competitors and Major Actors: other companies working on similar projects are identified (many had none to note)
- Financial: an overview of major revenue streams for the company

A complete list of the 22 case studies is provided in Table G-1.

Table G-1. List of Companies in Case Studies

Name of Organization (Country)	Location in Ecosystem	Principle Product	Operation Status	Main Funding Sources
Accion Systems (U.S.)	Upstream	Propulsion	Demonstration	Venture Capital, Department of Defense contracts
Berlin Space Technologies (Germany)	Upstream	Components and subsystems	Operational	Public and private contracts
Blue Canyon Technology (U.S.)	Upstream	Components and subsystems	Operational	SBIR (AF), Public and private contracts
Busek Co. (U.S.)	Upstream	Propulsion and power systems	Operational	SBIRs, Public and private contracts
Clyde Space (U.K.)	Upstream	Platforms and components	Operational	Private equity, private and public contracts
Ecliptic Enterprises (U.S.)	Upstream	Components	Operational	Public and private contracts, STTR
GomSpace (Denmark)	Upstream	Components and subsystems	Operational	Publicly traded, seed money from founders
NovaWurks (U.S.)	Upstream	Commoditized bus units (“satlets”)	Demonstration	SBIR, public and private contracts
Phase Four	Upstream	Propulsion	Demonstration	Public contracts (DARPA), venture capital
Pumpkin (U.S.)	Upstream	Components and platforms, software	Operational	Private and public contracts
SSTL (U.K.)	Upstream	Components, subsystems and platforms	Operational	Private and public contracts (owned by Airbus, 99% and University of Surrey, 1%)
Planetary Resources (U.S.)	Up- & Midstream	Components and platforms, operator (EO and asteroid mining)	Demonstration	Venture capital, Government of Luxembourg
SpaceX (U.S.)	Up- & Midstream	Launch, operator (broadband internet)	Demonstration (broadband constellation)	Venture capital, private and public contracts

Name of Organization (Country)	Location in Ecosystem	Principle Product	Operation Status	Main Funding Sources
Tyvak International (U.S.)	Up- & Midstream	Subsystems and platforms, launch integrator	Operational	SBIRs, mostly public contracts
Chandah Space Technologies (U.S.)	Midstream	On-orbit Observation operator (SSA)	Demonstration	Venture capital and private equity
Hawkeye 360 (U.S.)	Midstream	RF data analytics, operator	Demonstration	Venture capital
KSAT (Norway)	Midstream	Ground systems	Operational	Public and private contracts (dominated by NASA)
OneWeb (U.K.)	Midstream	Operator (broadband internet)	Demonstration	Private equity and venture capital
USRA/VALT (U.S.)	Midstream	Launch system	Demonstration	Internal, finalizing public contracts (DARPA, AFRL and DIUX)
Blacksky/Spaceflight (U.S.)	Mid- & Downstream	Operator (EO), data analytics and aggregation	Operational (constellation in development)	Venture capital
Spire (U.S.)	Mid- & Downstream	Operator, Data analytics and aggregation	Operational	Venture capital, contracts (NOAA)
Terra Bella (U.S.)	Mid- & Downstream	Operator (EO), data analytics	Operational	Venture capital

Note: Terra Bella was acquired by Planet in early 2017. The interviewee was interviewed prior to 2017, thus all content provided in this case study is based on the company prior to acquisition.

Accion Systems

Type: Manufacturer

Sells: Propulsion

Operational: Future; test demonstrations occurring

Company Overview

- This MIT-graduate led start-up is developing an electrospray method for propulsion. The chip-based technology is currently in development, and could be operational as early at 2017.

Company Information

- Headquartered in Somerville, MA
- Founded in 2014; 15 staff
  - The first technology demonstrations occurred when the founders were in graduate studies at MIT.

Leadership Heritage

- Natalya Brikner, Founder and CEO
  - Graduate work in the Space Propulsion Lab at MIT
  - 10 years' experience in propulsion; systems engineer at Aurora Flight Sciences
- Louis Perna
  - Graduate work in the Space Propulsion Lab at MIT
- Advisory Board
  - Paulo Lozano (Dir. of MIT Space Propulsion Lab)
  - Bill Swanson (former CEO of Raytheon)
  - Akshay Patel (VP at Planetary Resources)
  - Jason Spinell (Venture Dir. at Undercurrent)

Organizational Mission and Goals

- "Working to make space more affordable and accessible by leveraging breakthroughs across industries" [1]
- Accion's business model is to make ion engines scalable, the goal is to increase thrust density by 10,000x above current capabilities while retaining chip size.

Ongoing and Future Plans

- Accion is currently working to commercialize a miniature electrospray ion engine after years of development and testing at MIT
  - Ion engine is the size of a penny (called a "chip")
  - Each chip has a thrust of approximately 15 micro-Newton; thrust is generated by accelerating charged particles at high speeds
  - Non-flammable, non-toxic and non-volatile propellant allows the product to be relatively safe for rideshares
- Accion is currently developing and testing an electrospray propulsion unit that would compose of 36 chips, which would cover the face of a 1U CubeSat.
  - System would be scalable, by integrating units, for 3U to 200 kg smallsats
- Chips have been space tested, in random coupon demonstrations, but the unit (36 chips) is in development and has only undergone ground tests
- Current manufacturing rate is 200 chips per week with 2 technicians.
  - Outsourcing production could increase rate to 1,000 chips per week; the equivalent of 30 single face units per week

Customers and Partners

- Chip technology was tested on-flight by Aerospace; currently working with SPL to launch another on-flight test
- Secured three ground testing contracts with the U.S. Air Force, Lockheed Martin and an unnamed small consulting firm.
- Has three customers: one government and two commercial
  - First orders to be delivered in 2017

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[1] Accion Systems, "Team,"http://www.accion-systems.com/team/.

Financial

- Funding has been sourced from contracts and angel/venture investors, total of $17 million raised.
  - Angel and venture investors including, Dylan Taylor, RRE Ventures, Founder Collective, Founders Fund, Shasta Ventures
  - U.S. DOD Rapid Innovation Fund Contract ($6.5 million)

Berlin Space Technologies (BST)

Type: Manufacturer
Sells: Small satellite components and subsystems
Operational Status: Operational

Company Overview

- Vertically integrated provider of smallsat systems. Develop all major subsystems in-house; seek to develop low-cost, COTS-based systems[2]

Company Information

- Headquartered in Berlin, Germany
- Founded in 2010, 24 staff
  - BST resulted from the merger of two small companies which separately focused on payloads and buses.
  - Started with 3 people, expanded to 5 in 2013, and then to 24 by end of 2014

Leadership Heritage

- Tom Segert, Director of Business Development and a founder[3]
  - First worked as a project manager at *Technische Universität* (TU) Berlin, then spent 5 years in business development as an Innovations Manager at the Space Industry Association Berlin-Brandenburg.
  - Was one of three who founded Berlin Space Technologies; all three have a technology background at TU Berlin.
- "Berlin Space Technologies was founded by senior staff of the Department of Aeronautics and Astronautics [at TU Berlin] to answer the global demand for cost effective and responsive missions."[4]

Organizational Mission and Goals

- "Offering about 80–90% of capability of today's state-of-the-art microsatellites in the 100–150-kg class at a price that is around about 10% to maybe 20% the price of traditional systems. We can basically offer a system that is very similar

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[2] Tom Segert, Matthias Buhl, and Bjorn Danziger, "Berlin Space Technologies: Small Satellites Made in Berlin," (Presented at the Satellite Masters Conference,) http://www.satellite-masters-conference.eu/pdf/presentations/2015/151021_snapshot_2_small_satellites/tom-segert_bst.pdf.

[3] Spaceoneers, "Tom Segert BST," http://www.spaceoneers.io/blog-rss/2016/5/11/tom-segert-bst.

[4] Berlin Space Technologies, "About BST,"https://www.berlin-space-tech.com/about-bst/.

in cost to a traditional CubeSat or nanosatellite with the capabilities of a grown-up microsatellite." Tom Segert, BST

- One business concept includes being a "venture technologist," to expand to downstream markets; not currently their main business
  - "Rather than say 'I sell you a satellite system', we say, 'ok I give you the satellite system for free or at a very efficient price point in exchange for some equity…. All our products can be bundled with comprehensive training and technology transfer programs.'"[5]

Ongoing and Future Plans

- Berlin Space builds 85% of products in-house, based on industrial components[6]
- Components
  - Platforms
  - EO missions, mission needs include disaster mitigation and security
  - Payloads
  - Broad swath multispectral line imagers (WSI)
  - High-resolution imaging systems (HRVI and HRI)
  - ADIstar [7]
  - Projects an artificial star to towards the night sky
  - "Developed for the Indonesian satellite LAPAN-ORARI. Once launched its main purpose would be to highlight the space capabilities of Indonesia to the man in the street."
  - Bus components
  - Batteries, data systems, power, reaction wheels, star trackers
- Training Program
  - "Key elements are technology transfer and hands-on training."[8]

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5 Spaceoneers, "Tom Segert BST."

6 Spaceoneers, "Tom Segert BST."

7 Berlin Space Technologies, "Adistar-700,"https://www.berlin-space-tech.com/portfolio/adistar-700/.

8 Berlin Space Technologies, "BST Training Program," https://www.berlin-space-tech.com/products/bst-training-program/.

- “Depending on which level of independence you want to achieve: operation (level 0), system design (level 1), system assembly (level 2) or subsystem design and manufacturing (level 3) we can tailor the training accordingly.”

- Manufacturing
    - Build roughly 85% of products in house. Currently capable of assembling a satellite in 4 weeks with 2 people (1 week assembly, 3 weeks testing). To do 4 satellites a day (to compete with OneWeb production rates), would only need roughly 50–60 staff.

Customers and Partners

- Kent Ridge 1—Dec. 2015 (built)
    - BST developed a LEO microsatellite with the National University of Singapore. The smallsat has two hyper-spectral imagers and video camera for Earth observation applications[9]
- NExSat—launch to SSO in 2017–2018
    - Project for the National Authority for Remote Sensing and Space Sciences (NARSS) of Egypt
    - BST is delivering subsystems for the micro satellite mission (i.e., ACD systems, power, on-board computing); the experimental spacecraft would carry multiple optical payloads (multispectral)
- LAPAN-A1, LAPAN-A2 and LAPAN-ORARI[10]—2003 (developed by key staff prior to the founding of BST)
    - LAPAN and TU Berlin developed the first Indonesian micro-satellite (LAPAN-Tubsat, later renamed LAPAN A1)[11]

Financial

- BST started with seed money from the 3 founders. Since then, they operate off revenues made directly from contracts with customers. In the early 2000s they

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9 SpaceRef, “World’s Blackest Coating Material Makes its Debut in Space,” http://spaceref.com/nanotechnology/worlds-blackest-coating-material-makes-its-debut-in-space.html.

10 LAPAN is the Indonesian National Institute of Aeronautics and Space.

11 Gunter’s Space Page, “Lapan-Tubsat,” accessed February 20, 2017, http://space.skyrocket.de/doc_sdat/lapan-tubsat.htm.

sought out capital from banks and venture investors, but were denied under the assumption that there was no viable commercial space sector.

- Currently in the process of considering outside investment mediums. Outside capital would be used to expand offices and automatic manufacturing to compete for larger contracts to manufacture constellations.
- “BST is one of three German companies that today builds complete satellite systems and the only one who has achieved that without requiring aid of the German DLR or European Space Agency (ESA)”[12]

[12] SpaceRef, “World’s Blackest Coating Material Makes its Debut in Space.”

Blue Canyon Technologies

Type: Manufacturer
Sells: Components, subsystems
Operational: Yes

Company Overview

- BCT began with a SBIR with the Air Force to develop a state-of-the-art attitude determination and control subsystem for small spacecraft. The company has now moved into components, subsystems and turn-key systems for smallsats, including power systems, solar panels, deployment mechanisms, and thermal systems.

Company Information

- Headquartered in Boulder, CO
- Founded in 2008, 40 staff

Leadership Heritage

- George Stafford, CEO and President, co-founder
  - Over 10 years at Ball Aerospace, engineer
- Stephen Steg, CTO, co-founder
  - Over 15 years at LASP (University of Colorado), mechanical engineering
- Matthew Beckner, COO, co-founder
  - Over 20 years at Ball Aerospace, engineer
- Stafford (CEO) and Steg (CTO) met at CU Boulder; Stafford and Beckner (COO) met at Ball Aerospace. Business began with a SBIR from the Air Force.
  - "Our first customer, the Air Force, said they wanted smaller satellites…we bid on the SBIR and won it—that provided the impetus for U.S. to push into the industry."[13]

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[13] University of Colorado Boulder, "Blue Canyon Technologies," http://www.colorado.edu/aerospace/industry-connections/private-industry/blue-canyon-technologies.

Organizational Mission and Goals

- "BCT employees have experience spanning design, manufacturing, test and operations of more than 20 high-performance space systems currently in operation and providing years of reliable service on orbit."[14]

Ongoing and Future Plans

- Spacecraft Buses
  - "The BCT XB1 Spacecraft provides a complete CubeSat solution with a highly integrated, precision spacecraft bus platform. This includes: Ultra-high-performance pointing accuracy, robust power system, command and data handling, RF communications, optional propulsion, and multiple flexible payload interfaces."[15]
  - BCT Nano Star Tracker
  - Detects stars down to 7.0 magnitude
  - Life range from 3-16 years
  - BCT Reaction Wheels
  - BCT XACT Attitude Determination and Control System Technology
  - BCT CubeSat Electrical Power System (EPS)
- Integration and Launch
  - Provide launch brokering (for integration onto launch vehicles and secondary dispensers) with partner launch service providers
- Mission Operations
  - Provide operational support for smallsat constellations. This includes scheduling, automated execution, monitoring and visualization and customer delivery (of payload and telemetry data to customers)[16]
  - BCT partners with ground system operators (e.g., KSAT, Atlas, NASA Wallops and others) to receive data, they then provide this data to

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[14] Blue Canyon Technologies, "Blue Canyon Technologies,"http://bluecanyontech.com/.

[15] Blue Canyon Technologies, "Spacecraft Buses," http://bluecanyontech.com/portfolio-posts/spacecraft-buses-2/.

[16] Blue Canyon Technologies, "Mission Operations," http://bluecanyontech.com/mission-operations/.

consumers through their "Mission Center." Currently operate their own ground antenna (on top of offices in Boulder) for the RAVEN mission.[17]

Customers and Partners

- Work with national labs, Air Force, NASA centers and commercial companies. Example partnerships include:
  - PlanetIQ: selected BCT in 2015 to build its weather, climate and space weather satellite constellation (to be launched by 2017).[18] Each 10 kg sat would carry a PlanetIQ sensor called Pyxis-RO to collect atmospheric data (using GPS radio occultation).[19]
  - NASA: in 2015, NASA and BCT created a partnership to advance BCT's Hyper-XACT—a longer lifespan, high performance attitude determination and control system[20]
  - Further partnerships with JPL, John Hopkins Applied Physics Lab, and University of Colorado Boulder

Financial

- Company is employee owned (no private investors), dependent on contracts and SBIRs. This gives the company relative freedom for investment decisions.
- BCT was initially "funded through the Air Force Research Lab to develop a standard microsatellite bus for the EELV secondary payload adapter (ESPA) ring." (SBIR)
  - The eXact Attitude Control Technology (XACT), an attitude determination and control system (ADCS), resulted from the SBIR funding[21]

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17 The RAVEN mission is investigating real-time spacecraft navigation systems to support SSA operations for satellites. https://www.nasa.gov/mission_pages/station/research/experiments/1995.html.

18 PR Newswire, "PlanetiQ and Blue Canyon Technologies Partner to Transform Weather Satellite Industry and Dramatically Improve Weather Forecasting," http://www.prnewswire.com/news-releases/planetiq-and-blue-canyon-technologies-partner-to-transform-weather-satellite-industry-and-dramatically-improve-weather-forecasting-300103827.html.

19 J. Foust, "PlanetiQ Selects India's PSLV To Launch its First Satellites," *SpaceNews*, http://spacenews.com/planetiq-selects-indias-pslv-to-launch-its-first-satellites/.

20 NASA, "NASA Announces New Public-Private Partnerships to Advance 'Tipping Point,' Emerging Space Capabilities," http://www.nasa.gov/press-release/nasa-announces-new-public-private-partnerships-to-advance-tipping-point-emerging-space.

21 Wright-Patterson Air Force Base, "Air Force, Small Business Partnership Improves Control of Mini Space Satellites." July 15, 2014, http://www.wpafb.af.mil/News/Article-Display/Article/819164/air-force-small-business-partnership-improves-control-of-mini-space-satellites.

Busek Co.

Type: Manufacturer, R&D
Sells: In-Space Propulsion and Electronics/Power Systems
Operational: Yes

Company Overview

- Busek is both a vendor (to government and industry) and R&D organization focused on propulsion systems for satellites (including smallsats). The organization has been awarded a number of SBIRs from NASA and the DOD, and has secured contracts from a number of Industry actors.

Company Information

- Headquartered in Natick, MA
- In continuous operation for >25 years; staff of ~55 and growing
- Three major vacuum test facilities, and ~20 medium and small vacuum facilities
  - Vacuum chambers simulate conditions of outer space, and are customized for testing of propulsion devices.
  - In-house capability allows for rapid testing and characterization of new designs, duration/life testing, and acceptance-testing of flight hardware.
  - Fully owned facilities rival those of large institutions, representing millions of dollars of investment and technical expertise.

Leadership Heritage

- Dr. Vlad Hruby, President and Founder
- Highly educated technical staff; ~40% Masters or PhDs
- Series of technical firsts within the Industry including:
  - Designed and built first U.S. Hall effect thruster in space (BHT-200 on TacSat-2), all U.S. Hall thrusters in space based upon Busek technology.
  - BPT-4000 on AEHF satellites are licensed Busek technology; thrusters credited with saving billion dollar DOD mission for orbit raising (necessary when chemical apogee failed).
  - Designed and built World's first carbon nanotube propellant-less cathodes in space (NASA ST-7), first operational electrospray thrusters in space (NASA ST-7, AKA ESA LISA Pathfinder), and first micro pulsed-plasma thrusters in space (FalconSat-3)

    - Busek holds numerous patents in the field of electric propulsion and power processing for solar electric thrusters.

Organizational Mission and Goals

- Busek designs and builds high quality propulsion solutions for spaceflight, enabling new missions and capabilities for their customers.
- Five Propulsion technologies under one roof allow U.S. to provide a range of solutions to best fit customer needs.
    - Systems range from 5W power up to 25kW, suitable for spacecraft of 7 kg mass up to 7,000 kg
- "Whether it's studying plasma physics or building propulsion systems, we always push the envelope to deliver real results."[22]
- "The technology behind many of Busek's flight programs has been the result of early SBIR funding; we've demonstrated success transitioning from SBIRs to flight demonstration of new technology."

Ongoing and Future Plans

- Technology
    - Busek has completed development and flight demonstration of several new products for small and large spacecraft including
    - Electrospray, Hall thrusters, RF ion thrusters, micro-resistojet, pulsed plasma (based on tech developed by AFRL), and green monopropellant thrusters
    - Iodine fuel in Hall and RF ion thrusters; replaces high pressure Xenon and enables high delta-V missions.
    - Miniaturization of electric propulsion systems by mass, volume, and power efficiency, enabling precision attitude control (10uN-s impulse bits) and large delta-V maneuvers (up to 410m/s in less than 1U volume)
    - Busek also develops power electronics and power management systems, and digital interface electronics and instrument electronics
    - Further, they demonstrate new propellants with existing thruster technology and develop and spin-out or license non-core technologies
- Research and development is focused on

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[22] Busek, "Message from the President," http://www.busek.com/home__message.htm.

- Spacecraft propulsion, electronics, power systems and high-power payloads
- Materials R&D (e.g., carbon nanotube manufacturing etc.) and plasma research; environmental testing (in-house)

- Systems Engineering
  - Support with detailed analysis the implementation of manufacturing and test processes for large scale constellations.[23]
- Current programs focused on smallsat/CubeSat propulsion include:
  - iSAT: world's first iodine fueled Hall thruster on a small (12U) spacecraft. Iodine fueled BHT-200 thruster, cathode, and power-processing unit being supplied by Busek to NASA.
  - BET: 100uN miniature electrospray thruster system, a NASA Commercialization Readiness Program (NASA STMD Pathfinder flight candidate)
  - Lunar IceCube (Morehead State Univ.): Busek BIT-3 radio frequency ion thruster system fueled by iodine. Manifest on SLS EM-1.
  - LunaH-Map (Arizona State Univ.): Busek BIT-3 radio frequency ion thruster system fueled by iodine. Manifest on SLS EM-1.
  - Green monopropellant propulsion systems in 0.1N, 0.5N, 5N, and 22N thrust-classes. Replaces toxic Hydrazine propellant.

Customers and Partners

- Work closely with Civil (NASA, ESA) DOD (Army, Navy, Air Force, Marines, DARPA), and Industry customers. Sample projects include:
  - FALCONSAT-3-6: supplied micro pulsed-plasma thrusters, Hall thrusters and payloads
  - SOUL: Spacecraft on Umbilical Line enables debris removal, proximity operations, inspection, and servicing with inexpensive deployable small spacecraft. Initially funded by the Navy and Air Force, selected for further funding.[24]
  - Heavy Fuel Atomization: Enables use of heavy fuels in small engines. Offshoot of electrospray technology developed by Busek.

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[23] Busek, "Systems Engineering," http://www.busek.com/capabilities__syseng.htm.

[24] D. Werner, "NASA's Interest in Removal of Orbital Debris Limited to Tech Demos," *SpaceNews*, June 22, 2105.

- Busek works with most major U.S. and European Primes; commercial relationships governed by non-disclosure agreements.
- Frequent collaboration with U.S. Universities via STTR program as well as flight programs with Morehead State University and Arizona State University.

Financial

- Busek revenue is derived manufacturing of flight hardware with SBIRs providing irreplaceable R&D funding.
- Large number of Busek products are high TRL and poised for market entry
  - Crossing the "valley of death," between TRL-6 to TRL-8 (flight), represents a significant hurdle for every new thruster design across the industry. Cost is dominated by long-duration life tests ($M) for most hardware.

Clyde Space

Type: Manufacturer
Sells: Small satellites
Operational: Yes

Company Overview

- Clyde Space is a UK-based smallsat company. The company has supported the development of over 70 satellites in 2016, shipping over 1000 units to customers globally, and now have the production capacity to manufacture 10 spacecraft per month. The organization claims to be involved in 40% of CubeSat missions.
- The growth in the CubeSat sector, is a key sector of the market that drives revenue for Clyde Space. To meet the demand, internal investment has been focused on recruitment, expansion of facilities, increased product development and a new U.S. office.

Company Information

- Headquartered in Glasgow, UK
  - Cleanroom recently built for in-house manufacturing and environmental testing
  - Onsite environmental test capability includes a large area solar simulator, multiple thermal cycle chambers, a thermal vacuum chamber large enough to accommodate up to 12U CubeSats and a vibration testing rig capable of achieving NASA GEVS levels.
- U.S. Subsidiary, Clyde Space Inc., incorporated in 2016
  - Seeking to scale up to eventually have a manufacturing facility in the United States,[25] likely on the east coast.
- Founded in 2005, 80 staff (growing 50% per year)
  - First space company in Glasgow, Scotland
  - Turnover in prior financial year (through April 2016) reached £5m, an increase of £2m over prior year

Leadership Heritage

- Craig Clark, CEO and CTO, founder

[25] Clyde Space, "Clyde Space 'Catapults' to More Success," https://www.clyde.space/latest/56-clyde-space-catapults-to-more-success.

- Veteran of the industry, worked for Surrey for 11 years.

- The appointment of Will Whitehorn, the former president of Virgin Galactic, to the post of non-executive chairman was announced in 2016.

Organizational Mission and Goals

- "The space market [is] showing sustained growth at almost 10% over the past few years, and our specific market segment of smallsats [is] growing at close to 40% per year"
- "These applications and subsequent data generation could benefit a number of industries from agriculture and energy to the government for town planning"[26]

Ongoing and Future Plans

- Clyde Space provides end to end satellite handling—they would partner with ground station networks or use their individual ground station in Glasgow, launch companies, and data analytics companies to provide for customer needs
- Platforms
  - Have platforms that range from 1U to 27U, with 3U being most popular
- Components
  - Reaction wheels with speed control to +/-1RPMm, maximum torque of 40mNm, radiation tolerant to 10krads
  - Solar panels (deployable and non-deployable) for CubeSats and smallsats
  - Third-generation CubeSat Electrical Power Systems, batteries and packages, on-board and on-ground computer hardware and software
  - Attitude determination and control systems including control algorithms, sensors, and actuators/actuator drivers
  - S-band antennas and transmitters; UHF/VHF transceivers and antennas
  - Pulsed plasma thruster (Total Impulse: 42 Ns and 63 Ns, two versions available)
- In the future Clyde Space seeks not to push fantastical technology, but to make the more basic technology better, more capable and more reliable

[26] Clyde Space, "Clyde Space 'Catapults' to More Success."

Customers and Partners[27]

- Customers relatively evenly split between industry, government (civil and defense) and academia; a few partnerships are discussed below.
  - Over 90% of sales are exported out of the United Kingdom.
  - 40% of business currently from the United States; supply subsystems to customers like SPIRE Global, MIT, NASA and the U.S. Air Force.[28]
  - New U.S.-based Clyde Space branch would develop sales, with goal of opening a manufacturing base in the U.S. to build spacecraft domestically.
- Satellite Applications Catapult In-Orbit Demonstration program—for Catapult Sat Applications and Innovate UK
  - Will launch 4 CubeSat "from the International Space Station (ISS) in an 'in-orbit demonstration of technical and business propositions that have a high projected return on investment."[29]
- Seahawk—for the Gordon and Betty Moore Foundation
  - Developing two 3U CubeSat platforms to observe the changing biology of the ocean surface and its implications for the marine food chain, climate scientists, fisheries, coastal resource managers, and oil spill responders
  - Clyde Space is providing a platform along with power systems, deployable solar panels and a X-band coms system
- Outernet—for UK Space Agency and Outernet Inc.
  - Funded through the UK Space Agency's International Partnerships in Space Program (IPSP), project is developing 3 communications CubeSats
  - Project is a demonstration for a potential constellation of 100s of CubeSats for global broadband; ground station networks would transmit data
  - Incorporates Clyde Space's platform, deployable solar panels, electric power systems, and on-board computing systems
- Picasso—for ESA

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27 Clyde Space, "Our Missions," accessed December 23, 2016, https://www.clyde.space/our-missions.

28 Clyde Space, "Clyde Space Forms US Company and Reveals UK Expansion on Visit by First Minister Nicola Sturgeon," https://www.clyde.space/latest/20-clyde-space-forms-us-company-and-reveals-uk-expansion-on-visit-by-first-minister-nicola-sturgeon.

29 Clyde Space, "Clyde Space 'Catapults' to More Success."

    - A 3U CubeSat science mission, initiated by the Belgian Institute for Space Aeronomy (BISA), with the aim of studying the unexplored layers of the Earth's atmosphere
    - Incorporates Clyde Space's platform, ADCS subsystem (1 degree pointing accuracy), deployable solar panels, and data processor
- UKube–1—for UK Space Agency (launched in 2014)
    - Jointly funded by Clyde Space and the UK Space Agency, used for technology demonstration; using the Clyde Space S-band transmitter
- Spire partnership
    - Spire partnered with Clyde Space to use testing facilities prior to opening their own offices in Glasgow. The Scottish government awarded California-based Spire $3 million to manufacture smallsats in Glasgow.[30]
    - In support of Spire, Clyde Space expanded their "testing capabilities, including establishing a dedicated thermal vacuum test chamber, vibration table, thermal cycling systems, attitude determination and control system calibration and radio frequency testing"[31]

Financial

- Privately owned; backed by UK equity investors Nevis Capital and Coralinn (vehicles of Scottish entrepreneurs Hugh Stewart and John and James Pirrie)[32]
- 80% of sales are outside the EU, less than 5% in the UK[33]

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[30] BBC News, "US Satellite Firm to Create 50 Jobs in Glasgow," http://www.bbc.com/news/uk-scotland-scotland-business-33066479.

[31] Ibid.

[32] Ibid.

[33] Clyde Space, "About Us," https://www.clyde.space/about-us.

Ecliptic Enterprises

Type: Manufacturer
Sells: Components
Operational: Yes

Company Overview

- Ecliptic is a space avionics and sensor systems company with a customer base in commercial, civil and defense markets. Its flagship RocketCam™ product family is an onboard video system for rockets and spacecraft, with over 135 mission successes. Ecliptic avionics and sensor systems are also used to control and manage data for ISS experiments, science payloads, secondary payloads and hosted payloads. More advanced systems support various rendezvous, proximity operations and in-orbit servicing objectives.
- Ecliptic also serves as contractor for CubeSat projects and has ongoing technology-development activities involving advanced sensors, CubeSats, smallsats and lunar landers.

Company Information

- Headquartered in Pasadena, with offices also in Silicon Valley[34]
- Founded in 2001[35]

Leadership Heritage

- Rex Ridenoure, CEO, President and Board member, co-founder
  - Has worked on for several commercial space companies including BlastOff! Corporation, Space Dev, and Microcosm Inc., and prior to that worked at JPL for 11 years, Hughes Space and Communications for 5 years and Lockheed Missiles and Space Co. for 2 years. [36]
- John Scully, Ph.D., CFO and Board member, co-founder
  - Also worked at BlastOff! as well as Aon Consulting, Weston, and DuPont; also teaches Executive MBA classes at Pepperdine[37]

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[34] Ecliptic Enterprises, “Contact Us,” http://www.eclipticenterprises.com/contact-us.

[35] Ecliptic Enterprises, “Corporate Profile,” http://www.eclipticenterprises.com/profile.

[36] Ecliptic Enterprises, “Rex Ridenoure,” http://www.eclipticenterprises.com/bio/ridenoure.

[37] Ecliptic Enterprises, “John Scully,”http://www.eclipticenterprises.com/bio/scully.

- Mike Alvarez, VP of Business Development and Board member
  - Worked in software development engineering and managing for geostationary communication satellites, at L3 Communications, Storm Control Systems Division.[38]
- Steve Labrecque, CTO
  - Also worked at BlastOff!, as well as JPL and Caltech.[39]

Organizational Mission and Goals

- "Ecliptic is a product-oriented space-technology firm operating in commercial, civil and defense markets. We primarily provide rugged aerospace-grade data-acquisition and control systems for use onboard rockets and spacecraft."[40]

Ongoing and Future Plans

- Providing situational awareness via SD and HD video from onboard rockets and spacecraft (RocketCam™ systems)[41]
- Providing deployment sequencing and monitoring for secondary payloads on rockets and spacecraft[42]
- For CubeSat projects:
  - Integrating contractor, subsystem supplier, production supplier, provider of carrier/deployer systems[43]
- Ground support workstations for systems monitoring[44]
- Cameras—color video, HD and high-speed video, and infrared and ultraviolet video (and imagers)[45]
  - Data handling to cut down the amount of data that needs to be transmitted to the ground; e.g., recording at 30fps and transmitting at 10 fps

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38 Ecliptic Enterprises, "Mike Alvarez," http://www.eclipticenterprises.com/bio/alvarez.

39 Ecliptic Enterprises, "Steve Labrecque," http://www.eclipticenterprises.com/bio/labrecque.

40 Ecliptic Enterprises, "About Ecliptic," http://www.eclipticenterprises.com/about.

41 Ecliptic Enterprises, "RocketCam," http://www.eclipticenterprises.com/rocketcam.

42 Ecliptic Enterprises, "Featured Avionics Examples," http://www.eclipticenterprises.com/avionics.

43 Ecliptic Enterprises, "Featured Small Payload Systems," http://www.eclipticenterprises.com/small_payloads.

44 Ecliptic Enterprises, "Featured Ground Support Systems," http://www.eclipticenterprises.com/egse.

45 Ecliptic Enterprises, "Featured Sensors," http://www.eclipticenterprises.com/sensors.

- Store-and-forward capability via use of Solid-State Drives (SSDs)

- Future Capabilities and Technology
  - Small HD video and sensor systems (CubeSat-sized)
  - Remote Acoustic Sensor (RAS); converts light to sound
    - Small spinning lander (patented spacecraft architecture)

Customers/ Partners

- "Customers range from aerospace-related firms in the United States and abroad to academic and media outlets, as well as nonprofit organizations."[7]
- Approximately 95% of contracts are with private companies (e.g. Northrop Grumman, Orbital ATK, Lockheed Martin, Boeing, SpaceX, Blue Origin, Moon Express), with the remaining contracts signed with NASA centers, the Canadian Space agency, DARPA, NRO, univerisities and non-profits.[46]
- Lead systems contractor for The Planetary Society's LightSail-1 and -2 3U CubeSats

[46] Ecliptic Enterprises, "Customers,"http://eclipticenterprises.com/customers.

GomSpace

Type: Operator, Manufacturer
Sells: Small satellite subsystems and components
Operational Status: Yes, shifting to mission focus

Company Overview

- GomSpace envisions the main driver of their growth would be missions, adding to the existing platform and product sales line. Therefore, the company has shifted to a mission-focus business strategy rather than just technology development and product-focus.
- Company is currently growing, based in Denmark, and has opened offices in the United States and Singapore (2017) to access defense contracts as well as unique technologies/workforce.

Company Information

- Headquartered in Aalborg, Denmark
- Founded in 2007; 85 employees at end of 2016.
  - Growth in workforce; 35 in early 2016, plan to reach 130 in 2017
- Opening offices in United States (D.C. area) and Singapore, early 2017
  - United States—to focus on defense contracts and commercial opportunities
  - Singapore—to access the ASEAN market and tap into the technologies and workforce unique to the region
- ASTER Labs (R&D firm based in Shoreview, MN) in 2016 became the official "reseller" of GomSpace products in the U.S. and Canada for Academic and Government (e.g., NASA) segments[47]

Leadership Heritage

- Niels Buus, Managing Director
  - Experience in management roles in various companies prior to working at GomSpace.

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[47] Nick Waddell, "GomSpace ApS: GomSpace Selects ASTER Labs as Its CubeSat Reseller in American and Canadian Markets," http://www.cantechletter.com/newswire/gomspace-aps-gomspace-selects-aster-labs-as-its-cubesat-reseller-in-american-and-canadian-markets/.

  - Has degrees in business, applied optics and mechanical engineering.[48]
- Jacob Nissen, CTO
  - Was CEO and COO of BAE Systems; responsible for corporate governance
  - Has degrees in business and electrical engineering from Aalborg University
- Børge Witthøft, CSO
  - Extensive Board member experience and a long track record of top management roles in several companies.
  - Has a Master of Science degree from the Technical University of Denmark.
- Three founders
  - Founders were some of the first in Europe to work with CubeSats. They began during their master/PhD programs at Aalborg University.
  - In the company's growth phase, the founders hired their "bosses" so that they (the founders) could remain in technical roles and new leadership with business and management backgrounds would lead the company.
  - Lars Alminde, CMO (one of the cofounders) leads the Marketing and New Business area within the company positioning correctly the offerings in the market and building the future of the sector.

Organizational Mission and Goals

- GomSpace is in the process of shifting focus from a component supplier to a prime of full missions. Also, expanding their customer base from mostly academic institutions to the defense and commercial sectors delivering not only spacecraft but also mission design, management and operations.
  - "We provide high quality third generation CubeSat compatible subsystems allowing you to focus your resources on your specific mission objectives, while not spending resources getting basic platform subsystems working."[49]
- Company targets organizations who never thought of using space because it was too expensive—from companies to nations. Want to open up space, through cost efficient options, for other on-ground industries. GomSpace wants to "spacify" sectors and businesses that never thought of using space-based solutions.

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48 GomSpace, "Niels Buus," https://gomspace.com/corporate-governance.aspx.

49 GomSpace, "Subsystems,' https://gomspace.com/Shop/subsystems/Default.aspx

- GomSpace envisions large-sat companies as their main competitors. Want to challenge their approach and solutions, complementing their activities as well when they can't directly compete.
- GomSpace is based in the Aalborg region of Northern Denmark, what used to be the cell phone R&D hub a couple of decades ago. When cell phone R&D shifted to other locations, expert people remained in the region as consultants and professors (e.g., Bluetooth came from University of Aalborg). That expertise surrounds GomSpace, who has been working to bring developed COTS communications technologies to space.

Ongoing and Future Plans

- Acquired (October 2016) Swedish propulsion company, Nanospace, from SSC.
  - Cold gas propulsion technology and products are based on applying MEMS (Micro Electro Mechanical Systems) technology towards space propulsion—leading to miniaturization and precision in thrust control.[50]
  - Done to expand portfolio (propulsion) and geographic reach (Sweden)
- Signed (January 2017) a contract for the launch of a rocket from Landspace Technology Corporation of Beijing. GomSpace would launch many satellites into a unique Near-Equatorial orbit.
- Manufacture platforms and components ranging from payloads (SDR, ADS-B and AIS receivers), software, communications, computer hardware, ADCS and ground station equipment.
- Select (recently) signed agreements and projects
  - FAC contract (December 2016): Colombian Air Force entered a contract for the launch service of an Earth Observation satellite.
  - A&M contract (December 2016): African based Aerial and Maritime company entered a contract with GomSpace for the design, manufacturing, integration, testing, launch and commissioning of a constellation of up to 6 satellites for persistent tracking services in the Tropical region.
  - AISTECH contract (October 2016): GomSpace signed a deal to develop the platform and payload for this new Spanish satellite company that would focus for thermal imaging, aviation tracking, and bidirectional

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[50] Business Wire, "GomSpace ApS: GomSpace (Provider of Nanosatellites) Has Entered into a Non-Binding Letter of Intent to Acquire All Shares in Nanospace AB," http://www.businesswire.com/news/home/20160819005186/en/GomSpace-ApS-GomSpace-Provider-Nanosatellites-Entered-Non-Binding.

communication services. The first satellite is planned for launch in 2017, with the remaining 24 satellites in the constellation to be launched by 2020.

   – GOMX 4a&b (October 2016). The European Space Agency and the Danish Ministry of Defense signed contracts with GomSpace for the delivery of a joint tandem mission for 2 advanced nanosatellites to do formation flying as well as demonstrate a series.
   – ACAE MoU (September 2016): GomSpace signed a MoU with ACAE (Central American Assoc. of Aeronautics and Space) to develop space based solutions for Central America and signed a contract to supply the satellite platform for IRAZU—the first space project of Costa Rica.
   – Hawkeye 360 (August 2016): Contract for the delivery of advanced Software Defined Radio (SDR) payload to the Pathfinder mission of Hawkeye 360 from the United States.
   – Sky and Space Global (February 2017): Contract with the UK-based company to develop 200 satellites for a constellation to provide voice, data and instant messaging.

Customers and Partners

- Main customers 2 years ago were universities and civil government programs (e.g., ESA). Now, defense sector and operational missions for commercial constellations, are becoming main strategic focus, whilst still serving the academic sector.
- GomSpace has projects in the United States, Latin America, Japan, South Korea, China, Singapore, and Australia; has worked with customers in over 50 nations.
   – Potential seen in Asia and others, especially from those who originally didn't have access to space due to low budgets

Financial

- Publicly traded on the Nasdaq First North Premier exchange under "GOMX."
   – One of the first smallsat companies to be publicly traded; roughly 40% of the company is free floating on the market since June 2016.
   – The decision to go "public" was made to gain capital to push further expansion plans, including investing in technology development, building new facilities, doing M&A operations, starting subsidiaries, etc. as discussed above.

GomSpace initially received seed money from 3 founders and through initial customers. Then raised money to grow the company from private and public investors. Initial seed money was not sourced from VCs, given how difficult it is to receive VC money in Europe (relative to the United States).

NovaWurks

Type: Manufacturer, Operator
Sells: Satlets
Operational: Flight-Test Stage

Company Overview

- NovaWurks' main product, a Hyper-Integrated Satlet (HISat™) technology, is a satlet (funded through the DARPA Phoenix program), seeks to replace a commoditized bus through a uniform building block that houses power, thermal, and attitude determination and control subsystems. The company also operates ground systems, have assets in flight (working on the DARPA SeeMe Program) and are considering investing in data analytics.

Company Information

- Headquartered in Los Alamitos, CA
- Founded in 2011; currently staff of 30 (20 in 2013)
  - Revenues roughly $5 million a year; ¾ of customers are government

Leadership Heritage

- Talbot Jaeger, Founder and Chief Technologist
  - 30+ years of experience in aerospace at Northrop Grumman. Led the development of NG's Mayflower CubeSat program; was a chief architect in DARPA's System F6 program.
- James Greer, COO
  - 30+ years' experience in the information technology and government sectors, working in business operations, sales, marketing, and projection management.
- Bill Crandall, Chief of Advanced Projects
  - 25+ years of experience in hardware design, 15 years working on space-qualified hardware. Worked at Boeing on spacecraft programs, working on design, launch and on-orbit operations at ground stations.

Organizational Mission and Goals

- Establish flight heritage, move to greater reusability, more automated analysis, have timely, cost effective launches to make it easier to launch test satellites.[51]
- "HISats are designed and created as viable foundations for building unique scalable space platforms and innovative solutions for the space industry."[52]

Ongoing and Future Plans

- Hyper-Integrated Satlet (HISat™)—part of the DARPA Phoenix program
  - The satlet is a biologically inspired uniform building block that houses power, thermal, and attitude determination and control subsystems. Each module is identical; multiple modules can be paired together, allowing *activation* of functionalities when needed (for flexibility and redundancy).[53]
  - Two module designs exist, based on operator needs
    - LEO modules: lifetime of 2 years, 4 kg
    - GEO modules: *bullet proof*, lifetime of 10–15 years, 8 kg
  - Manufacturing timeline is rapid—can deliver a satlet in a max of 90 days from order to delivery
    - At peak, can manufacture one satlet in two days in-house or 10 satlets in one day off-site (at Raytheon).
    - Most of the components are developed in-house, except for solar panels, which are from Pumpkin.
  - Modules are roughly the cost of cars ($20,000–200,000). The cost is dependent on level of mass production, integration and assembly
- DARPA SeeMe Program

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[51] NovaWurks, "Applications," http://www.novawurks.com/applications/.

[52] NovaWurks, "NovaWurks and Arkisys Sign License Agreement for Development of Space Platforms and Solutions for Next Generation Exploration and Research," http://www.novawurks.com/novawurks-arkisys-sign-license-agreement-development-space-platforms-solutions-next-generation-exploration-research/.

[53] NovaWurks, "NovaWurks and Arkisys Sign License Agreement."

- The planned satlet constellation seeks to provide on-demand imagery for military teams with ~24 satlets in very low Earth orbit for 60–90 days before burning up on re entry[54]

Customers and Partners

- Academic organizations, such as Stanford, and NASA seen as potential customers; already collaborating with DARPA. Eventually envision a commercial market.
- DARPA, on the Phoenix and SeeMe projects[55]
- In May 2016, signed an agreement with Arkisys
  - Project would leverage satlets for in situ assembled space elements and platforms.[56] Arkisys would sell their products commercially.[57]

Financial

- Self-funded, contract-based company. [58] Have not pursued venture or equity capital.
  - Awarded a DARPA Phoenix Phase 1 $2.9 million grant in 2012 (phase 2 and 3 in 2013, $42.6 million); DARPA SeeMe Program

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54 NovaWurks, "Project: DARPA SEEME," http://www.novawurks.com/applications/darpa-seeme-program/.

55 NovaWurks, "Applications."

56 NovaWurks, "NovaWurks and Arkisys Sign License Agreement."

57 Ibid.

58 NovaWurks, "Fact Sheet,"www.novawurks.com/wp-content/uploads/2014/07/NovaWurks_Fact_Sheet.doc.

Phase Four

Type: Manufacturer
Sells: Propulsion
Operational: In demonstration

Company Overview

- This California-based start-up, supported by DARPA and VC funds, is currently developing a new plasma-based method for propulsion. The technology, exclusively licensed from the University of Michigan's Plasmadynamics & Electric Propulsion Lab, is being developed for use on satellites ranging from CubeSats to large satellites (the former using multiple thruster units). A proof of concept of an early design was completed by Phase Four and tested externally by the Aerospace Corporation and a space demonstration is planned for early 2018.

Company Information

- Headquartered in El Segundo, CA
- Founded in 2015; 10 staff

Leadership Heritage

- Simon Halpern, CEO and Founder
  - Experience in business development, as Co-Founder and VP at Aether Industries, also 8 years at Northrop Grumman as Systems Engineer on NASA, NOAA and DoD contracts
- M. Umair Siddiqui, CTO
  - Plasma physicist and engineer
- Daniel Nash, Senior Flight Systems Engineer
  - 4 years of experience with avionics systems integration, at SpaceX
  - Jason Wallace—VP Operations
    - 6 years as quality engineer and integration and mission manager in U.S. Air Force Space Launch Systems
- Jason Wallace—VP Operations
  - 6 years as quality engineer and integration and mission manager in U.S. Air Force Space Launch Systems

Organizational Mission and Goals

- Phase Four seeks to deliver a new, relatively low-cost, high performance plasma-based propulsion system that requires less propellant mass (relative to chemical propulsion units) and achieves an order of magnitude increase in performance, when on the CubeSat scale, relative to current SOTA technology (e.g., relative to other plasma-based technologies such as Hall thrusters and ion engines).
  - The company seeks to meet a current gap in the CubeSat market: between systems with high efficiency and low-thrust, and those with low efficiency and high-thrust.
- If the technology is successfully developed, magnetic fields would shape and direct plasma, eliminating exposure of metal parts to the plasma (which is an important failure point in current plasma-based propulsion technologies). The technology is being developed to be agnostic to propellant—the technology could support next generation propellants such as iodine and water, depending on research.
- Technology is scalable to larger applications, including large GEO satellites and interplanetary missions

Ongoing and Future Plans

- Phase Four provides the following services to customers[59]
  - Mission planning—the company has developed customized planning software to help coordinate constellations of satellites
  - Modular propulsion units—the Radio Frequency Thruster (RFT), discussed further below
- The Radio Frequency Thruster "uses RF waves to efficiently ionize and then heat xenon plasma, causing it to expand thermally. As the heated propellant expands outward, the thruster uses magnetic fields to direct the xenon plasma out of the thruster orifice, producing thrust."[60]

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[59] Phase Four, "About," http://www.phasefour.io/about.

[60] Phase Four, "Radio Frequency Thruster," http://phasefour.io/wp-content/uploads/2017/02/SPECv2.1.pdf.

- The thruster technology was developed at University of Michigan (at the Plasmadynamics & Electric Propulsion Lab),[61] and then licensed to Phase Four.
- The power amplifier builds upon miniaturized high-power density electronics (developed by the cell phone industry), P4 has independently developed these.
- Current technology is at a TRL level of 6 (for smallsats), and at a lower TRL (~4) for GEO (due to higher radiation conditions that the technology has yet to qualify for).
- Proof of concept was tested by Aerospace Corporation (as a third party)
- The technology is slated for on-orbit testing in early 2018 on a Landmapper satellite built by Earth observation company Astro Digital. Launch was brokered through Spaceflight Industries.
- The design is meant to be a "plug-and-play" modular system; the system is inclusive of the thruster, electronics and fuel tank. System could be capable of providing 1km/s delta-V (for a 3U CubeSat).

Customers and Partners

- The first on-orbit demonstration of the technology is planned for launch in late 2017 on an Astro Digital Landmapper satellite
- Potential future customers include CubeSat and smallsat operators, and in the longer term, larger satellite operators (e.g., in GEO); customers are expected to come from both the private and public (e.g., civil and defense) sectors.

Financial

- In 2015 the company secured a $1 million DARPA contract to further develop and commercialize the RFT technology.[62] The company has also received private venture capital (although the exact amount is not public).
  - Public funding, from DARPA, is cited as a sign of "good faith" that helped to attract private investors for additional investment

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[61] University of Michigan, "Welcome to PEPL," http://pepl.engin.umich.edu.

[62] Doug Messier, "Phase Four Receives $1 Million DARPA Contract for CubeSat Thruster," *Parabolic Arc*, http://www.parabolicarc.com/2015/11/25/phase.

Pumpkin

Type: Manufacturer
Sells: Components, Busses, Kits, Software
Operational: Yes

Company Overview

- Pumpkin is a CubeSat bus manufacturer focused on offering well tested, mass manufactured busses comparatively cheaply.

Company Information

- Pumpkin Space systems is a business unit of Pumpkin, Inc.
  - Pumpkin, Inc. was founded in 1995, in CubeSats since around 2000
- Headquartered in San Francisco, have a staff of approximately 20

Leadership Heritage

- Andrew Kalman, founder
  - Formerly co-director and founder of audio company Euphonix, Inc.
- A significant majority of staff have engineering expertise

Organizational Mission and Goals

- "Pumpkin Space Systems has enabled dozens of successful space missions by providing nanosatellite components and complete CubeSats to government, commercial and educational organizations. Experts in smallsats, product design, embedded systems, manufacturing and rapid turnaround, Pumpkin has delivered unique and cost-effective solutions to customers world-wide."[63]
- Values their capability to mass produce designs, as well as offering open information such that their clients can adapt their designs, take advantage of open platforms

Ongoing and Future Plans

- Pumpkin produces CubeSat busses and components, from <1U, 3U, 6U, and 12U, as well as a general nanosatellite bus.
- They also provide an operating system, Salvo, for a wide range of embedded applications

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[63] Pumpkin, "About Us," http://www.pumpkinspace.com/about.html.

- Offers 1U, 1.5U, 2U, and 3U CubeSat “kits”
- Future: Increasing the power available to CubeSats, increasing reliable testing at lower cost, and creating platforms that can fill the needs of a wide range missions

Customers and Partners

- Have worked with NRO, JPL, various academic institutions—no one customer makes up a huge slice of their work
  - Worked with NRO on Colony 1, built a CubeSat bus designed to allow various groups to integrate payloads

Competitors and Major Actors

- Clyde Space, GomSpace, ISIS, all are developing components and buses, taking different approaches

Surrey Satellite Technology Ltd. (SSTL)

Type: Manufacturer
Sells: Satellites
Operational: Yes, current

Company Overview

- SSTL is a smallsat manufacturer, which builds smallsats and additional satellites up to 1000 kg.

Company Information

- Headquartered in Guildford, UK
  - Facilities include cleanrooms and manufacturing facilities for composites and mechanisms
- U.S. office opened 8 years ago
  - SSTL began as a shopfront, but has developed into a fully owned subsidiary; however in 2017, SSTL closed its U.S. manufacturing facility
- Founded in 1985
  - One of the first to do "commercial off the shelf" satellite technology

Leadership Heritage

- Professor Sir Martin Sweeting FRS FREng, Executive Chairman
  - SSTL was spun out from his work on satellites at the University of Surrey, constructing the UO-11, a microsatellite, in 1984[64]

Organizational Mission and Goals

- "We can develop satellites throughout their life cycle—from design and build through to launch and in-orbit monitoring and maintenance—or any stage of that cycle. For customers who want to monitor and maintain their own satellites, we can set up their ground station and train their in-house team."[65]
- "We are able to offer our customers such flexibility because we design, build, assemble and test our satellites and almost all their components in-house."

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[64] Amateur Radio—PEOSAT, "UO-11," http://www.pe0sat.vgnet.nl/satellite/amateur-radio-satellites/uo-11/.

[65] SSTL, "About SSTL," accessed February 20, 2017, https://www.sstl.co.uk/About-SSTL.

Ongoing and Future Plans

- In-house design, manufacture, integration, launch and operation of smallsats from 3 kg to 600 kg, typically around 100 kg
  - Design and build sensing and communication payloads
  - Build and install ground station infrastructure
  - Provide consulting and training services
  - Test COTS parts as redundant systems and hosted payloads
- Subsystems
- Actuators and sensors, navigation, and communications
  - Onboard data handing (hardware and software), propulsion (Xenon, butane, electric), power management (solar arrays, power control and distribution)
  - Composite structures
- Platforms and composite structures
- Future: Improving their capabilities for the smaller end of their smallsat capabilities, reducing costs of key parts

Customers and Partners

- ESA, DOD, NASA, NOAA, international governments and commercial customers including both traditional and New Space commercial companies
- Subsidiaries
  - DMCII is a commercial data supply service from their Disaster Monitoring Constellation satellites.
    - The company focuses on precision agriculture and forestry, urban planning and development, general and land cover mapping, and Earth sciences
  - SSTL U.S. LLC is based in Denver, CO and was established in 2008.
  - Provides technology for U.S. customers, with production capacity.
- Constellation Partnerships
  - SSTL has been engaged in over 50 missions,[66] below are a few examples.

[66] SSTL, "SSTL Missions," accessed February 20, 2017, https://www.sstl.co.uk/Missions.

- SSTL is working with main contractor, OHB Systems, to develop and build the navigational payloads for the ESA Galileo GNSS Constellation. Developed payloads for this larger satellite constellation (500–600 kg) could be applicable to future smallsat missions.
- DMC3 Constellation (3 satellites, 440 kg, 2015 launched) for change detection, disaster monitoring and response planning
  - 21At, a Beijing-based company, has leased 100% of the imaging capability of the constellation
- FORMOSAT-7 Constellation (6 satellites, 200 kg)
  - For NOAA and Taiwan for weather forecasting
- RapidEye Constellation (5 satellites, 156 kg, 2008 launched)
  - EO constellation for crop monitoring, yield predictions and disaster assessment. Currently owned by BlackBridge
  - Will provide daily revisit rates, multispectral imagery and 6.5m GSD resolution

Competitors and Major Actors

- Major competitors include Ball, Sierra Nevada, Millennium Space Systems, BCT, and Clyde Space

Financial

- Privately owned—99% Airbus DS Holdings DV and 1% University of Surrey

Planetary Resources

Type: Manufacturer, operator
Sells: EO and SSA (potentially abandoned), asteroid mining
Operational: development stage

Company Overview

- Planetary Resources is currently developing technology that would fly on a smallsat bus to identify and examine asteroids for mining (of water, as a propellant for deep space missions).
- Through the Ceres constellation, the company had planned to launch their technology into LEO orbit to both test the technology in-flight and also serve the Earth observation market through thermographic infrared and hyperspectral payloads. The company has secured both public (Government of Luxembourg) and private funding.

Company Information

- Headquartered in Redmond, WA; opening and additional office in Luxembourg
- Founded in 2009
  – 60 staff in the United States
  – Plans to have 50 staff in Luxembourg by 2020

Leadership Heritage

- Chris Lewicki, President and CEO,
  – 10 years at NASA JPL; engaged in the systems engineering and operations of the NASA Mars Exploration Rovers and the Phoenix Mars Lander.
  – Flight Director for the Mars rovers Spirit and Opportunity, and the Surface Mission Manager for Phoenix.
- Chris Voorhees, COO and Chief Engineer
  – Over 10 years of experience at NASA JPL; served as chief engineer for NASA’s Mars Science Laboratory
- Peter Marquez, VP, Global Engagement
  – Served as Director of Space Policy for Presidents Bush and Obama

Organizational Mission and Goals

- "The company's vision is to establish a new paradigm for resource utilization that would bring the Solar System within humanity's economic sphere of influence."[67]
  - In developing a pathway to accessing and identifying commercially viable near-Earth, water-rich asteroids, the company has developed smallsat technologies useful for Earth observation and SSA applications
- Planetary Resources is vertically integrated in their manufacturing, with nearly 96% of their product made in house. The method is used to reduce costs relative to currently available COTS parts on the market.

Ongoing and Future Plans

- Planetary Resources has identified a number of near-Earth asteroids for future reconnaissance missions with water or metals (e.g., platinum), accessible for extraction.
- The Arkyd-3 spacecraft was launched in 2015 to demonstrate various technologies in development
- Until June 2017, Ceres, an Earth observation constellation, was in development. The project intended to both test key payloads and be used for commercial applications
  - The Arkyd 6 spacecraft platform had a planned launch of 2019, scheduled for SpaceX's Falcon 9.
  - The 10 smallsat constellation were meant to be equipped with two sensor payloads capable of mapping surface temperature (mid-wave IR) and water content (hyper-spectral imager)
- Further, "Planetary Resources is developing a multi-function main instrument for its Arkyd spacecraft platform, one that integrates remote imaging, optical navigation, and optical communications into a single, resource-efficient tool."[68]
- Long-term goals of Planetary Resources include the deployment of similar smallsats (with similar sensors) to identified asteroids for water (a potential fuel for future deep space missions) and metals (for in-space manufacturing).

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[67] Planetary Resources, "Planetary Resources and the Government of Luxembourg Partner to Advance the Space Resource Industry," http://www.planetaryresources.com/2016/06/planetary-resources-and-the-government-of-luxembourg-partner-to-advance-the-space-resource-industry/.

[68] Planetary Resources, "Space Communications,"http://www.planetaryresources.com/technology/#space-communications.

Customers and Partners

- Large agriculture companies have signed MOUs with Planetary Resources, to use insight gained from the EO Ceres mission
  – In mid-2016, Bayer and Planetary Resources signed an MOU for the development of applications and products derived from satellite data; the insight would be used to inform new and improve existing agriculture products for better irrigation practices, crop yields, and soil health.[69]
- Additional partnerships include:
  – The Government of Luxembourg—provided funding to Planetary Resources, in a move to bring operations to Luxembourg[70]
  – University of Nebraska's School of Natural Resources, Israel Institute of Technology, Technion, Bechtel Corporation, 3D Systems, and AGI Strategic Partner[71]

Financial

- Planetary Resources has received $60 million; they closed $25 million in Series A funding (private investors, VCs and Angels) and received a $25 million grant from the Government of Luxemburg
  – An initial effort to crowdfund ARKYD was attempted but not carried through due to limited follow-on funding from business and educational institutions[72]

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69 Planetary Resources, "Bayer and Planetary Resources Intend to Collaborate to Improve Agriculture with Space Data," http://www.planetaryresources.com/2016/05/bayer-and-planetary-resources-intend-to-collaborate-to-improve-agriculture-with-space-data/.

70 Planetary Resources, "Planetary Resources and the Government of Luxembourg Partner."

71 Planetary Resources, "Team," http://www.planetaryresources.com/company/#team.

72 Kickstarter, "Arkyd, a Space Telescope for Everyone," accessed February 20, 2017, https://www.kickstarter.com/projects/arkydforeveryone/arkyd-a-space-telescope-for-everyone-0/posts/1584844.

SpaceX

Type: Manufacturer, operator, launch
Sells: Launch, broadband internet (future)
Operational: yes (launch), in development phase (broadband constellation)

Company Overview

- SpaceX currently operates launch vehicles that have been used to launch smallsats (either as secondary payloads or as primary payloads).[73]
- SpaceX also seeks to develop and deploy a constellation of 4,425 smallsats (~400–500 kg each) to provide broadband internet access across the globe. Satellites would be built, launched and operated in-house. A 5–7 year lifetime of the satellites would allow for replacement with updated technologies as the SOTA progresses.

Company Information

- Headquartered in Hawthorne, CA
  - Operate offices in California, Washington (Seattle), Texas, Florida, and Washington, D.C
- Founded in 2002

Leadership Heritage

- Elon Musk, CEO and lead designer
  - Internet entrepreneur
- Gwynne Shotwell, President and COO
  - R&D at Aerospace Corporation

Organizational Missions and Goals

- In the smallsat realm, SpaceX seeks to develop and deploy a constellation of smallsats to provide broadband internet access across the globe. The constellation, if successful, would be an additional revenue stream to support R&D ventures with high upfront costs (e.g., missions to Mars).

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[73] SpaceX launches small, medium, and intermediate payloads with the Falcon 9, and it launches heavy payloads with the Falcon Heavy. Operations are not limited to small satellites.

Ongoing and Future Plans

- Launch vehicles
  - Falcon 9
    - Falcon 9 has had 27 successful launches through 2016
    - Smallsats launched either as a primary payload using a dispenser (Orbcomm, Iridium) or as a secondary, through rideshare accommodations
    - Known for testing "re-usability" of first stage to decrease the cost of launch, with 6 successful recoveries.
  - Falcon Heavy - the first launch of Falcon Heavy is expected in 2017
  - An earlier generation rocket, Falcon 1, was retired several years ago
- SpaceX broadband constellation
  - The constellation would comprise 4,425 smallsats in LEO, and deployed over a period of 5 years beginning in 2019.
    - The satellites would be built by SpaceX, using proprietary technology developed and designed in house.
  - "The SpaceX network would feature user terminals fitted with phased-array antennas inexpensive enough—$100 to $300—to be purchased the world over to deliver broadband to areas that are unlikely to be served by terrestrial broadband anytime soon"[74]
  - According to a license application filed with the FCC in Nov. 2016[75]
    - Each satellite would provide aggregate downlink capacities of 17–23 Gbps. The total aggregate capacity would reach 32 tbps. Targeted latency of 25–35 ms
    - Constellation can commence broadband service with deployment of as few as 800 satellites, remaining satellites would augment capacity and redundancy
    - Satellites would have a lifetime of 5-7 years. This allows for replacement of assets as the state of the art in technology progresses

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[74] P. B. de Selding, "SpaceX to Build 4,000 Broadband Satellites in Seattle," *SpaceNews*, http://spacenews.com/spacex-opening-seattle-plant-to-build-4000-broadband-satellites/.

[75] Mosher, "SpaceX Just Asked Permission to Launch 4,425 Satellites."

- If able to reach low latency and a global distribution of satellites, SpaceX's goal is to provide worldwide consumer broadband services, as well as long-distance internet access (e.g., Paris to LA) and other services such as cellular backhaul and business traffic.[76]

Customers and Partners

- Most of the constellation technology (satellite and on-ground gateways), is being designed and developed in-house.
- For broadband services, SpaceX would work with distributors or partners as needed in countries that would not allow for SpaceX to directly provide consumer broadband. Otherwise SpaceX is vertically integrated and interested in operating internally.

Financial

- The broadband project is funded internally. SpaceX is supported by Google ($1 billion) and Fidelity; investments are not tied to any specific project.[77]
- Project is expected to bring in over $30 billion in revenues annually, to generate an operating profit of $15–$20 billion annually by 2025.[78]
- There are claims that SpaceX would not go public until it is routinely launching people to Mars. [79]

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[76] Ibid.

[77] D. R. Schilling, "4,000 SpaceX Satellites to Launch Between 2017 and 2019," Industry Tap, http://www.industrytap.com/4000-spacex-satellites-launch-2017-2019/33721.

[78] R. Winkler and A. Pasztor, "Exclusive Peek at SpaceX Data Shows Loss in 2015, Heavy Expectations for Nascent Internet Service," *Wall Street Journal*, January 13, 2017, https://www.wsj.com/articles/exclusive-peek-at-spacex-data-shows-loss-in-2015-heavy-expectations-for-nascent-internet-service-1484316455.

[79] de Selding, "SpaceX to Build 4,000 Broadband Satellites."

Tyvak International

Type: Smallsat manufacturer, launch integrator/broker, space systems operator
Sells: platforms, subsystems, mission operations and launch vehicle integration services
Operational: Yes

Company Overview

- Tyvak works with U.S. Government (DOD, IC, and Civil), commercial, and international customers on end-to-end smallsat/space vehicle solutions, subsystems and services (support with system design/studies, integration, testing, launch integration, and mission operations).

Company Information

- Headquartered in Irvine, CA; office in Torino, Italy (opened 2015)
  - The European office works closely with the U.S. office, but "will operate independently and grow in response to European Union (EU) and European Space Agency (ESA) commercial needs, as well as requirements from other European-based smallsat programs."[80]
  - "In the past 10 years, the global satellite industry has more than doubled to a $195.2 billion dollar business. Our new European office is poised to meet this growing demand."[81]
- Founded in 2011
  - Subsidiary of Terran Orbital (parent/holding company formed in 2014)
  - 47 employees (300 years, collective experience); 100% U.S.-owned

Leadership Heritage

- Anthony Previte, CEO
  - Entrepreneur and engineer
- Dr. Marco Villa, COO
  - Previous director of Mission Operations at SpaceX
- Jordi Puig-Suari, CSO and co-founder

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80 Tyvak, "Terran Orbital Opens First Tyvak International Office in Turin, Italy," accessed February 20, 2017, http://tyvak.eu/newoffice.html.

81 Ibid.

    - 20 years of experience at Cal Poly State University, a co-inventor of the CubeSat standard
- Roland Coelho, VP Lunch Services, Co-founder
    - 10 years of experience at Cal Poly State University

Organizational Mission and Goal

- Tyvak seeks to be a "worldwide provider of nanosatellite and microsatellite vehicles, services and solutions"[82]

Ongoing and Future Plans

- Consulting and integration
    - Continue to provide "mission compatibility and feasibility studies" to offer full mission design and analysis, as well as systems engineering support and requirements development to customers
    - Tyvak also operates testing facilities
- Launch services
    - Launch coordination, licensing and documentation; advise on payload accommodations and deployment systems
    - Satellite replacement insurance
        - Designed and implemented an insurance offering partnership with Aon Risk Solutions' International Space Brokers
    - CubeSat deployer
        - Developed a CubeSat dispenser system to eject MarCO satellites from Atlas 5's upper stage (for NASA)[83]
- Ground stations
    - Tyvak's ground command and control software (C2D2) provides support for ground control of the spacecraft during integration and test, and for operations when in orbit.[84]

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[82] Tyvak, "Tyvak: A Terran Orbital Corporation,"http://www.tyvak.com/.

[83] Tyvak, "In NASA First, Cubesats Headed to Mars with Insight Lander," accessed February 20, 2017,http://www.tyvak.com/in-nasa-first-cubesats-headed-to-mars-with-insight-lander/.

[84] Tyvak, "Capabilities," accessed February 20, 2017, http://www.tyvak.com/capabilities/.

- Strategic partnership with KSAT and the KSAT Worldwide Ground Station network
- Mission Operations Center coordinates ground stations to communicate with their satellites
- Flight software "capabilities range from C&DH house-keeping and radio interfaces, to complex formation flight, rendezvous and docking algorithms."[85]

- Components and subsystems
  - Tyvak builds payload systems depending on customer needs in addition to partnering with other payload developers on a case-by case basis. Tyvak does not sell individual subsystem COTS.
  - Examples of products built and services delivered include guidance and navigation control, RF design and integration, PCB design
- Platforms: currently build up to 80 kg
  - Tyvak is an end-to-end space systems provider. Smaller platforms (e.g., 1-12 U CubeSats) leverage the Tyvak Endeavor basic building block components including high power, precision attitude determination and control, rad-tolerant avionics, communication, and autonomous operations capabilities.
  - Tyvak is currently building 50–80-kg class satellites and space vehicles for performing SAR and EO missions in support of multiple customers.
  - Tyvak has built multiple types of space system platforms for various applications and a variety of customers. Applications have included (but not limited to) RF beacons, communications/data exfiltration, GPS radio occultation, space situational awareness, and rendezvous/ proximity operations.
  - Currently Tyvak is developing space platforms for SAR, EO/IR, precipitation monitoring (Ka-band radar), along with applications involving orbital regimes other than LEO (e.g., GEO).
- Future Capabilities and Technology; Goals

85 Ibid.

- Signed on with ESA for a feasibility demonstration program for nanosatellites providing autonomous inspection and support systems to the ISS[86]
- Cubesat dispenser system would be used for NASA's Mars Cube One program (MarCO), CubeSats going with the next mars lander mission[87]
- NASA partnership for CubeSat Proximity Operations Demonstration for docking 2 3U CubeSats, SSTP STMD project[88]
- Tyvak is moving into a much larger facility (still in Irvine CA) late summer 2017. This new facility would not only allow support for its growing staff, but would also increase the amount of manufacturing, laboratory and testing space needed to support the growing number and diversity of mission applications desired by Tyvak's customers.

Customers and Partners

- Roughly 80 percent of portfolio is for the U.S. Government (DOD, IC, and Civil (e.g., NASA) including international (e.g., further work with ESA (Tyvak was selected to use LIDAR and IR to map the ISS). The remaining 20 percent supports commercial clients.
- Tyvak works closely with MMA Design for deployable systems, increasing packing efficiency for solar panels and radio antennas

Financial

- Received 3 SBIR grants[89] in 2013, 2014, and 2015 from NASA and DOD/Army
  - Received 3 SBIRs in 2016 alone to:
    - develop star-trackers and control algorithms for JPL,
    - develop low-risk, medium gain Ka-band reflect array,
    - develop high-power, high efficiency power systems for smallsats.

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86 Tyvak, "European Space Agency Selects Tyvak International for ISS CubeSat Study," http://www.tyvak.com/european-space-agency-selects-tyvak-international-for-iss-cubesat-study/.

87 NASA JPL, "Mars Cube One," http://www.jpl.nasa.gov/cubesat/missions/marco.php.

88 Tyvak, "To Serve+ Protect: Autonomous Space Drones?"http://www.tyvak.com/to-serve-protect-autonomous-space-drones/.

89 SBIR STRR, "Tyvak Nano-Satellite Systems LLC," accessed February 20, 2017, https://www.sbir.gov/sbc/tyvak-nano-satellite-systems-llc.

Chandah Space Technologies

Type: Operator
Sells: On Orbit Observation
Operational: Future

Company Overview

- CST plans to put smallsats (called “InsureSats”) in orbit above geosynchronous orbit (GSO) to come down and inspect client GSO satellites; CST seeks to commercialize space.

Company Information

- Headquartered in Houston, TX, with an office in Mountain View, CA.
- Founded in April 2012.

Leadership Heritage

- Adil Rahim Jafry, Co-founder, President and CEO,
  - Prior work in mergers and acquisitions, entrepreneurship, and infrastructure development; CST is his first venture in the space arena.
  - Part of a Google Lunar X Prize Team in 2008.
  - Member of the Academic Council at International Space University (ISU); Chair of Business and Management for the Space Studies Program (SSP) organized by ISU.
- Helen Reed, Co-founder, CTO and VP Engineering,
  - Prior work has covered IDA, U.S. GIF, and a variety of satellite and aerospace work; currently member of National Academies’ Intelligence Science and Technology Experts Group (ISTEG)
  - Currently Professor of Aerospace Engineering at Texas A&M
- Lee Graham is CST’s lead technical advisor through a reimbursable Space Act Agreement with NASA.
- Christian Fadul is Co-founder and Commercial Manager for Business Development, and Andrew Tucker is Systems Engineer, both with degrees from Texas A&M.

Organizational Mission and Goals

- “Our vision is to transform space economics for satellite owners and operators, and enable them to manage their asset portfolio efficiently. Our team and partners include marquee aerospace organizations and individuals with deep domain expertise and a passion for space."[90]

Ongoing and Future Plans

- Chandah intends to build smallsats ("InsureSat") for SSA applications. The smallsats would orbit about 200km above GSO (circular graveyard orbit), and come down to 5km standoff distance from client GSO satellites to inspect them.
- Constellation would have (on average) separation between InsureSat satellites of 18–20 degrees.
- Individual InsureSat satellite mass would be low (below 50 kg) to start, eventually reaching approximately 80 kg, with eventual 1cm resolution capability.

Customers and Partners

- Prospective customers include any owners of GSO satellites and include additional interested parties such as the government (e.g., DARPA and NASA), space insurers, underwriters, and manufacturers. Chandah currently has signed 6 letters of interest.
- Chandah is working with a reimbursable Space Act Agreement from NASA.

Financial

- Founders and outside angel investors have contributed $1 million in cash, >$2 million in cash and resources to date.
- CST is raising money from U.S. VCs and Private Equity interested in commercial space with a funding goal of $15 million for capital and operating expenditures for the first InsureSat satellite "InsureSat 1."

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[90] Chandah, "Chandah," http://www.chandah.com/.

HawkEye 360

Type: Operator, Data Analytics
Sells: RF Data
Operational: future; flight tested; launch in Q4 2017

Company Overview

- HawkEye 360 is a developing a network to provide data analytics based on RF signals. They are looking to operate their own smallsat constellation; first launch is booked on a Falcon 9 for the first half of 2018.
- Internally the company is focused on operations and analytics, the remaining (construction, integration and launch) has been contracted out. The government is seen as a primary customer.

Company Information

- Headquartered in Herndon, VA
  - Subsidiary of Allied Minds, a company that forms, funds, manages and builds startups based on early-stage technology
  - Founded in 2015 by Chris DeMay and Charles Clancy
- Number of employees in 2016: 8 (as of 12/1/2016)

Leadership Heritage

- John Serafini, CEO[91]
  - Senior Vice President of Allied Minds, HE360's parent company
  - Former Army infantry officer
- Russ Matijevich, Vice President, Sales
  - Retired Air Force Lt Colonel
  - Worked at SAIC and Northrop Grumman
- Rob Rainhart, Vice President, Engineering
  - Various engineering and technical leadership roles with RT Logic and Harris Corporation
- Chris DeMay, COO and Founder

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91 HawkEye 360, "About Us," http://www.he360.com/about/.

- Led programs for satellite development at the NRO

- Charles Clancy, Board member and Founder
    - Director of the Hume Center for National Security and Technology at Virginia Tech

Organizational Mission and Goals

- Build and launch a constellation of smallsats (Pathfinder Mission), capable of geolocation, detection, and analysis of wireless signals
  - The goal is to operate seven satellite constellations in three separate orbital inclinations (21 smallsats total), dependent on expanding smallsat launch capabilities
- HawkEye 360 believes commercial RF frequency survey can augment government capabilities, especially in the unclassified realm, and can introduce data analytics that utilizes insights provided by geolocation of signals.
- The business model is similar to that of a large GEO communications satellite company; HawkEye 360 goes out to manufacturers to build their smallsats. The company serves as a satellite operator/owner and analytics company.

Ongoing and Future Plans

- Sensor and analytic technologies have been demonstrated on proof of concept Cessna flights, correctly geolocated a ship that was deliberately transmitting the wrong location with AIS.
- Pathfinder mission
  - 15 kg, 20U volume (does not conform to CubeSat standard). First three satellites are scheduled to launch in 2017.[92] Launch contract with SpaceX, on a Falcon 9.
  - Spacecraft has been through CDR, and all components have flight heritage. After Pathfinder is complete, can go from order to orbit in 6 months. Manufacturing of satellite done externally by the following,
    - Deep Space Industries (DSI): providing water thruster with 100m/s ΔV

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92 HawkEye 360, "HawkEye 360 Selects GomSpace to Manufacture Pathfinder Mission Payload," http://www.he360.com/hawkeye-360-selects-gomspace/.

    - University of Toronto Space Flight Laboratory (SFL): providing bus in conjunction with DSI (CanX-4/CanX-5)[93]
    - GomSpace: providing payloads (software defined radio and antennas)
    - Chinese textbook purchased on Amazon.com—key algorithms
    - [To Be Competed]: operating ground stations
  - The mission's goal would be to track and monitor global transportation networks and comprehensively map spectrum resources
    - Enabling detection of RF signals to allow accurate location and characterization of difficult-to-visualize spectrum information
    - Will monitor global transportation networks, support government requirements, assist with emergencies
    - Orbit at less than 600km from Earth; 3-year lifespan
  - The constellation would take RF data and turns it into usable intelligence, monitors frequency usage to identify trends and areas of interference[94]
- Long-term goals:
  - Increase autonomy of satellites, identify targets and pick out multiple signals associated with them, cross-talk with other satellites
  - Improve aggregation with other satellite data, and increase on board data processing. Key limitation is onboard processing capabilities.
  - Increase machine learning, visualization, and predictive analytics capabilities

Customers and Partner

- First contracts are with the U.S. Government and an NGO acting in support of government
- HawkEye 360 is moving towards supporting commercial enterprises and governments, both U.S. and eventually internationally, with proposed constellation; they have interest in selling outside the United States

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[93] Deep Space Industries, "DSI selected as manufacturer for HawkEye 360 pathfinder constellation," http://deepspaceindustries.com/dsi-selected-as-manufacturer-for-hawkeye-360-pathfinder-constellation/.

[94] HawkEye 360, "Application: Spectrum Mapping and Use," http://www.he360.com/applications/spectrum-mapping-and-use/.

- Targeting the communications, transportation, and data analysis markets
  - Applications include tracking ships and identifying bad actors, tracking development and identifying areas of high activity

Competitors and Major Actors

- SPIRE, IridiumNEXT, are both involved in commercial maritime awareness
- SARSat and Argos (both from NOAA) use signals tracking for maritime tracking, humanitarian aid, search and rescue, and other applications

Financial

- Seed round funding through Allied Minds, currently finishing series A funding intended to last through 2018

Kongsberg Satellite Services (KSAT)

Type: Ground Systems Operator
Sells: Ground System Operations, Data
Operational: Yes, including KSAT Lite smallsat network

Company Overview

- KSAT owns and operates a Global Ground Station Network (Figure G-1) with full motion antennas distributed on a global basis on over 20 locations, and serving a global portfolio of space agencies, government institutions, as well as commercial companies. The antenna systems vary in sizes and technical specifications and are in the range of 2, 4 to 13 meter in diameter.
- The KSAT Lite network is adapted with several years of empiric knowledge from the industry from operations of larger satellite grounds systems, and is designed specifically for the low-cost needs of smallsat operators (cost optimized, standardized service level agreements, more generic interfaces etc.).
- An additional business division provides data analytics.

Company Information

- Headquartered in Tromso, Norway; offices in Silicon Valley, Oslo, Stockholm and at Svalbard
  - Subsidiary of Kongsberg[95] (50%) and SpaceNorway (50%) (SpaceNorway is 100% owned by the Norwegian Ministry of Trade, Industry and Fisheries).
- Operating since 1960s, KSAT Lite started in 2014; 150 employees
  - First antenna was a bi-lateral agreement between the United States and Norway to track NASA sounding rockets; have grown to operate at 20 locations world-wide

Organizational Mission and Goals

- Maintain position as leading global ground station service provider, allowing access to any satellite anywhere, anytime.

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95 Kongsberg is a Norwegian international technology conglomerate company (70 offices, over 8,000 employees).

- Leverage current ground network to deliver data and imagery in 15min for the artic region, or within one hour globally.[96] Seek to get data to customers in near real time.
- In regards to smallsats and KSAT lite, KSAT seeks to make operations "10-times smaller, 10-times cheaper, 10-times faster…."[97]

Source: J. Van Wagenen, "KSAT Launches 20 Ground Station Network for SmallSats," Via Satellite, January 21, 2016, http://www.satellitetoday.com/technology/2016/01/21/ksat-launches-20-ground-station-network-for-smallsats/.

Figure G-1. Global Distribution of KSAT's Total Ground Station Network

Ongoing and Future Plans

- KSAT Lite dedicated smallsat ground system network (20 operating locations)

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[96] Ibid.

[97] J. Van Wagenen, "KSAT Launches 20 Ground Station Network for SmallSats," *Via Satellite*, January 21, 2016.

- Minor augmentations to the KSAT network enable smallsat operators. Many stations are polar and optimized towards Polar Orbiting Satellites in low Earth orbit (LEO) but the rest of the global network is able to support satellites in lower inclination, launches from International Space Station (ISS) orbits. The network (not KSAT lite, currently) is also capable of supporting other orbits as well as MEO, GEO, and HEO satellites.
  - "KSAT lite has standardized capabilities in X and S band, which are great frequencies. KSAT has also added Ka band capability for the small sat market, which is first in the world. KSAT also offers capabilities in UHF and VHF, but this is more limited as of challenges on interference."[98]
- Data aggregation, analytics, and delivery
  - "KSAT supplements SAR imagery with data from medium- and high-resolution optical satellites through a network of targeted reseller agreements."[99]
  - Applications are focused on maritime issues, specifically oil spills and tracking ships, with possible expansions to tracking ice coverage and northern passages for cruise ships; this is working mostly with SAR and AIS data
  - Human image analysts are still a large part of their process, which they don't see changing in the next 2-4 years, although machine algorithms augment efforts
  - Analytics are agnostic to data source (i.e., large versus small satellite)

Customers and Partners

- KSAT has a global customer base of space agencies, government institutions, as well as commercial companies. The U.S. customers range from NASA, NOAA, and USGS on the civil side, and commercial actors such as Terra Bella (Google) on the commercial side. Globally, customers include JAXA, ESA, and Canadian MDA.[100]
- KSAT works with approximately 15–20 smallsat operators, this represents roughly 10% of their consumers (the rest being larger satellites and space

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98 Ibid.

99 Konsberg, "Multi-Mission Data," http://www.ksat.no/en/services%20ksat/multi%20mission%20near%20real%20time%20page/.

100 C. Henry, "Terra Bella Evaluating Launches for Eight SkySats by 2017," *Via Satellite*, April 6, 2016.

agencies, which is served primarily has been served by their polar-based network)

- Customers of archival and new satellite imagery and data come from a range of sectors (defense and intelligence community, national security actors, civil mapping and charting agencies, natural resource management organizations, NGOs, and any other end-users who require timely and accurate insight), all with unique requirements.[101]

Competitors and Major Actors

- Spaceflight Networks (1st operational system in Seattle, more to come across the world through 2017 in 6 continents)[102]
- Leaf Space (Italian start-up, received $1.1 million in funding, working to develop a 20 ground station network to support smallsats called "Leaf Line")[103]
- Spire, Planet and other operators have invested in their own ground stations

Financial

- Overall more than 50% of revenue is from the United States, including NASA, and Canada; about 30% is from Europe; just a few percentage points from Norway; and the rest from Asia, primarily Japan, India, South Korea, and Taiwan.

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[101] Konsberg, "Multi-Mission Data,"

[102] Spaceflight, "Spaceflight Networks," http://www.spaceflight.com/spaceflight-networks/.

[103] C. Henry, "Leaf Space Raises $1.1 Million for Dedicated SmallSat Ground Station Network," *Via Satellite*, July 11, 2016. http://www.satellitetoday.com/publications/st/2016/07/11/leaf-space-raises-1-1-million-dedicated-smallsat-ground-station-network/.

OneWeb

Type: Operator
Sells: Broadband internet (future)
Operational: In development

Company Overview

- OneWeb seeks to develop and deploy a constellation of about 720 smallsats (~140–200 kg each) to provide broadband internet access across the globe, by 2020. Satellites would be built and integrated by OneWeb Satellites. The company has raised roughly $1.7 billion.

Company Information

- Headquartered in Channel Islands, UK; officeso in the United States (Tysons, VA; Florida, and California)
    - Opening manufacturing facility in Florida in 2017.
- Founded in 2012, staff currently numbers at over 100 employees with 300+ full time employees at partner locations.

Leadership Heritage

- Greg Wyler, Founder and Chairman
    - Founded satellite communications provider O3b Networks, Ltd. in 2007
- OneWeb board includes,
    - Paul Jacobs, Executive Chairman of Qualcomm Inc.
    - Richard Branson, Founder of Virgin Galactic
    - Sunil Bharti Mittal, Founder and Chairman of Bharti Enterprises
    - Thomas Enders, CEO of Airbus Group

Organizational Mission and Goals

- OneWeb seeks to deliver "high speed, low latency internet access with the global reach of satellites to the underserved and unserved starting in 2020."[104]

[104] P. Karingufu, "One Web, Access for Everyone: Future-SAT Africa: Connecting Everyone Everywhere," Slideshare, http://www.slideshare.net/MylesFreedman/one-web-overview-for-future-sat-africa.

- The company aspires to support multiple downstream markets, as shown in Figure G-2.

Market	Segment	Description
Satellite Broadband	Corporate Small Enterprise	• Business-to-business (B2B), business-to-market (B2M) communications • Scalable to meet capacity needs
	Integrated Small Cells	• Connectivity for smartphone demand • Major growth sector in telecommunications
	Consumer Residential	• Direct to home internet and data • Exceptional data speeds
Enterprise	Maritime	• On and off-shore communications • Global coverage of shipping routes
	Aeronautical	• Low profile antenna • Front and rear-of aircraft services (e.g. media, health monitoring of aircraft)
	Government	• First Responder applications • Military applications
	Oil and Gas	• Reliable and secure communications • High resiliency, low latency enhances monitoring solutions
	Connected Car	• Trusted communications for over-the-air updates • Driver assistance systems and passenger connectivity
Cellular Backhaul	Macro-cell Satellite Trunking	• Low cost expansion of mobile networks • Not-spot fill-in

Source: OneWeb.

Figure G-2. Prospective Downstream Markets Met by a LEO Broadband Satellite Constellation

Ongoing and Future Plans

- OneWeb plans to operate a constellation of about 720 smallsats in eighteen 1200-km orbital planes to provide global coverage of wireless Internet. Each satellite would generate 6 gigabits per second of throughput.[105]
  - Satellite would have a mass of 140–200 kg, with a production run of 900 in the first generation to include ground spares
  - Communication rights have been secured for the Ka/Ku band, from the ITU.
  - User speeds are planned to be over 50 Mbps

[105] P. B. de Selding, “Competition to Build OneWeb Constellation Draws 2 U.S., 3 European Companies,” *SpaceNews*, http://spacenews.com/competition-to-build-oneweb-constellation-draws-2-u-s-3-european-companies/.

- The total cost of the OneWeb system, including the satellites themselves, launch, operations, and ground systems is expected to be $3.5 billion.[106]
  - Manufacturing cost target is less than $500,000 per satellite
- Satellites would be built by OneWeb Satellites—a joint venture between OneWeb and Airbus. Components would be sourced externally by undisclosed partners.
  - Over 150 RFPs have been released, with a +85% supplier response rate
- Satellites would be launched through Arianespace (21 launches) and Virgin Galactic (39 launches, with option for 100 more)
  - A launch contract signed with Arianespace is valued at $1–2 billion.[107] Inclusive of 21 launches, one is planned for the end of 2017 to carry the first 10 satellites to orbit.
    - Each Arianespace Soyuz rocket can carry 32–36 satellites a time, enough to fill one orbital plane per launch.
- Satellites would operate with a Ku/Ka downlink

Customers and Partners

- OneWeb has developed partnerships with a variety of actors across the supply chain to foster strategic and commercial relationships; key partners are shown in Figure G-3.
- In June 2017, proposed merger with Intelsat failed due to Intelsat bondholders not agreeing to "the terms of a debt exchange that SoftBank, having already invested $1 billion into OneWeb in December, made a prerequisite to approving the merger."[108]

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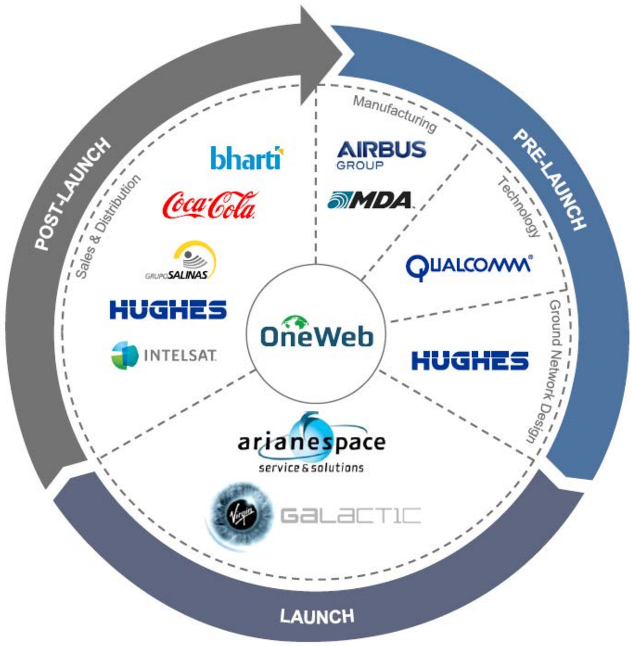
[106] P. B. de Selding, "One Year after Kickoff, OneWeb Says its 700-Satellite Constellation Is on Schedule," *SpaceNews*, http://spacenews.com/one-year-after-kickoff-oneweb-says-its-700-satellite-constellation-is-on-schedule/.

[107] P. B. de Selding, "Launch Options Were Key to Arianespace's OneWeb Win," SpaceNews, http://spacenews.com/launch-options-were-key-to-arianespaces-oneweb-win/.

[108] http://spacenews.com/oneweb-formally-ends-intelsat-merger/



Source: OneWeb. 2016. "OneWeb Presentation." ITU Symposium and Workshop https://www.itu.int/en/ITU-R/space/workshops/2016-small-sat/Documents/OneWeb-SSS-16.pdf

Figure G-3. OneWeb Partnerships Span across Supply Chain

Competitors and Major Actors

- Direct competitors include SpaceX and Boeing (both who are planning LEO broadband constellations). Other competitors include ground broadband providers (i.e., fiber, DSL etc.) and other UAV/balloon projects being developed by actors such as Facebook.

Financial

- OneWeb has raised $1.7 billion to date.[109]
  - $1.2 billion raised, and announced, at the end of 2016 ($1 billion alone from Japan-based Softbank); $500 million raised prior in summer 2015.
  - Additional investors include: Airbus Group, Intelsat, Bharti Enterprises, Totalplay, Hughes Network Systems, Qualcomm, Coca-Cola Co., and the Virgin Group

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[109] C. Henry, "OneWeb Gets $1.2 Billion in SoftBank-Led Investment," *SpaceNews*, December 19, 2016, http://spacenews.com/oneweb-gets-1-2-billion-in-softbank-led-investment/.

Vertical Air-Breathing Launch Technology (VALT) Enterprises, LLC

Type: Launch Service Provider, Launch Vehicle Manufacturer
Sells: Small satellite launch
Operational: Future

Company Overview

- VALT Enterprises provides hypersonic delivery systems for both orbital and suborbital applications. VALT is a low-cost, mobile, flexible, dedicated nanosatellite launch vehicle (to LEO) ready for launch as soon as 2019, (contingent upon funding).
- VALT LV would be capable of launching from land, sea and air platforms to provide optimal flexibility to nanosatellite customers, in terms of launch locations, schedule and orbit. Further the launcher could be used as an anti-satellite weapon, or for rapid and precise deployment of satellites taken out by anti-satellite weapons, damage or use. Initial funding is sourced through U.S. defense and intelligence agencies; expansion to the commercial sector is dependent on lowering cost (based on automation of production) and need for "when and where" space access.

Company Information

- Headquartered in Sanford, ME
- Founded in 2015, VALT Enterprises, LLC
  - VALT is a spinoff technology from Maine R&D company Applied Thermal Sciences, Inc.
  - Collaboration with USRA (Universities Space Research Association)

Organizational Mission and Goals

- Provide low-cost launch vehicle to emerging nano/micro-satellite community with on-demand (i.e., when and where in LEO) space access.[110]

Leadership Heritage

- Karl Hoose
  - CEO/CTO and Founder of VALT, LLC.

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[110] Valt, "Valt Enterprises,"http://www.valt-ent.com/.

- Previously President and owner of Applied Thermal Sciences, Inc. that developed concept of VALT for low-cost hypersonic delivery systems. Worked with the Office of Naval Research

Ongoing and Future Plans

- Currently at 22 test launches for VALT, looking to push this from Mach 5 to Mach 8 over next few test launches
- Vertical Air-Breathing Launch Technology (VALT)
  - 25 kg to max 500km LEO, 50º-90º inclinations from their Maine launch site
  - Could launch from a submarine, F18, land, sea, air, any U.S. spaceport, non-traditional site could work; could access a wide range of orbits
  - Hypersonic Delivery Systems: Suborbital and Orbital Missions (Commercial, Government, Academic)
  - To increase affordability, VALT utilizes the oxygen in the atmosphere to dramatically reduce the size, weight, and cost of dedicated space access for micro/nanosatellites.
  - VALT would maximize launch frequency to help build a resilient space architecture. VALT would assure space access to establish and replenish micro/nanosatellite constellations when and where needed.

Customers and Partners

- Air Force, Navy, DARPA
- Interest in selling to commercial customers requiring “when and where” space access, dependent on lowering costs
- Some non-U.S. customers interested in the ability to launch their own smallsats without having to wait on rides from other countries, such as India’s PSLV
- VALT Enterprises has teamed with Draper for GN&C of VALT launch systems

Financial

- In the process of finalizing funding from DIUX, DARPA, AFRL
- Current funding internal from VALT Enterprises, Maine Space Grant Consortium, and Finance Authority of Maine (FAME)
- Applied Thermal Sciences, Inc. invested approximately $4 million
  - Office of Naval Research supported at $750,000

BlackSky (Spaceflight)

Type: Operator
Sells: Data/insight
Operational: Yes; currently buying other satellite data, plans to launch constellation

Company Overview

- BlackSky intends to provide insight based on their upcoming network of satellites, improving revisit rates (sub-hourly) and lowering the cost of satellite imagery and intelligence. In addition to small satellite imagery, data is sourced externally from other terrestrial and airborne technologies, and social media.

Company Information

- Based in Herndon, VA, and Seattle, WA
  - Subsidiary of Spaceflight Industries
- Founded in 2013, about 150 people on staff

Leadership Heritage

- Peter Wegner, Chief Technology Officer
  - Worked for the Air Force Research Laboratory, directed the Operationally Responsive space Office at DOD, and was the Director of Advanced Concepts at Space Dynamics Laboratory

Organizational Mission and Goals

- "BlackSky is reinventing how we see and interact with our planet."[111]

Ongoing and Future Plans

- Pathfinder 1 (45 kg)
  - BlackSky's planned constellation of 60 satellites, 6 on orbit by 2017, would provide revisit rates (40–70 times per day, 10–45 min between revisits—dependent on latitude) to cover 95% of Earth's population
    - Color imagery with resolution of 1 meter; 10 orbital planes, two SSO, 8 52 degree inclination
  - User defined tasking, with automated predictive tasking

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[111] BlackSky, "Transforming How We Look at the Planet."

  - On-orbit cost of a satellite is <$10 million

- BlackSky is currently building out their own ground stations
- Goal of web/app ordering at $90 an image with 90 minute delivery times
- Will synthesize data from other satellites and sources to provide insight

Customers and Partners

- Customers include, UNITAR, World Bank, RS Metrics (Early Adopter Program), among others
- Company partnerships allow their data analytics and integration platform to provide access to more than 10 high-resolution imaging small and large spacecraft (i.e., 21AT's TripleSat, SIIS's KOMPSAT, and UrtheCast's Deimos-2), as well as using data from common social media platforms
- BlackSky is considering partnerships with niche data providers that have unique sensors and payloads (e.g., Hawkeye 360) to provide insight

Competitors and Major Actors

- BlackSky seeks to bring down costs from Digital Globe's state-of-the-art service of $2,500/image with 4-week delivery, and undercut it with $90 in 90 minutes
- Generally don't see other imagery companies, such as Planet, UrtheCast, and Astroscale as competition; rather BlackSky may buy from them to help acquire insight for their customers

Financial

- Investors: Mithril Capital Management, RRE Ventures, Vulcan, Razor's Edge Ventures, In-Q-Tel
- Six satellites already funded through series B funding, Goal of next 20 being funded through series C

Spire

Type: Operator
Sells: Data/Insight
Operational: Yes

Company Overview

- Spire is providing weather tracking, maritime domain awareness, and plans to provide aircraft tracking based on their satellite constellations, using GPS-RO, AIS, and ADS-B.

Company Information

- Headquartered in San Francisco, CA
- Other offices
  - Glasgow, Scotland, UK
  - Singapore
  - Boulder, CO
- Founded in 2012
- Number of employees in 2016: 117[112]

Leadership Heritage

- Peter Platzer, CEO
  - Completed an internship on nanosatellites at NASA in 2012
  - Long career in business (strategy consultant/banking), including over a decade at Harvard Business school, and 3 years at Deutsche Bank

Organizational Missions and Goals

- Spire provides unique data for any point on Earth in near real time to provide competitive advantages for organizations in areas like global trade, air-traffic, weather, shipping, supply chain, illegal fishing, and maritime domain awareness.
- Spire aspires to build and operate the first commercial weather satellite network

112 LinkedIn, "Spire Global, Inc,"https://www.linkedin.com/company-beta/3506863?pathWildcard=3506863.

Ongoing and Future Plans

- Spire is building a constellation of CubeSats (Lemur-1 was a prototype launched in 2014, now launching Lemur-2 satellites for the constellation, 20 launched so far)
  - Satellites are designed, built and tested in-house at a rate of 1-2 satellites a week; launch rate is 4–8 each month, and operated through Spire's global ground station network; mass of ~5 kg, no propulsion carried
  - Carry two payloads for meteorology and ship traffic tracking
    - A GPS-RO imaging payload
    - SENSE AIS payload (receives automatic identification signals (AIS) from ships)
  - Listen for GPS signals and performs GPS-RO in order to measure the change in GPS signal readings and calculate profiles for temp, pressure, humidity on Earth
- Spire has built and tested a majority of its nanosatellites in house, at its manufacturing and testing plant in Glasgow, UK. Manufacturing abroad helps to avoid U.S. ITAR law complications; "we chose European suppliers for our first mission for that very reason. We have built ourselves a nice competitive advantage there."[113]
- The constellation would have up to 120 operational in constellation at a given time
- 25 ADS-B satellites for aircraft tracking planned for launch in 2017

Customers and Partners

- Spire primarily works with clients concerned with global trade, weather, shipping, supply chain, illegal fishing, and maritime domain awareness.
- "Data generated from the Spire system would provide critical near real-time data of interest to shipping companies, harbor operators, governments, vessel traffic service data providers, and financial services companies."
- The constellation would also add capacity to track aircraft as well[114]

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[113] D. Werner, "Lofty Aspirations for Spire's Weather-watching Cubesats," *SpaceNews*, September 17, 2015.

[114] J. Van Wagenen, "Spire Releases CubeSat-Based Flight Tracking Solution," *Via Satellite*, December 6, 2016, http://www.satellitetoday.com/technology/2016/12/06/spire-releases-cubesat-based-flight-tracking-solution/?hq_e=el&hq_m=3313064&hq_l=6&hq_v=bb2d7aae54.

Competitors and Major Actors

- Major competitors includes Hawkeye 360

Financial

- Satellites cost under $1 million according to CEO
- Investors include
  - Bessemer Venture Partners, Promus Ventures, Shasta Ventures, RRE Ventures—William Porteous, Fresco Capital, Jump Capital, Moose Capital, Beamonte Investments
  - E-Merge, Grishin Robotics, Lemnos Labs, Mitsui and Co. Global Investment, Qihoo 360 Technology, Scottish Enterprise

Terra Bella (formerly Skybox Imaging)

Type: Operator, Analytics
Sells: Data, Intelligence
Operational: Yes

Company Overview

- Terra Bella is a smallsat operator and data analytics firm. The company has a constellation of 7 Earth observation satellites in orbit with additional satellites planned for launch. Planet's acquisition of Terra Bella was announced in February of 2017.

Company Information

- Headquartered in Mountain View, CA
- Founded in 2009 (Skybox Imaging), acquired by Alphabet (Google) in 2014, acquired by Planet in 2017
- 125 employees, prior to Planet's acquisition

Leadership Heritage

- Thomas Ingersoll, President and CEO
  - Aerospace veteran with more than 25 years of experience in space and communications industry
  - Prior CEO of Universal Space Network which provided ground station services to NASA and the DOD.

Organizational Mission and Goals

- Terra Bella seeks to pioneer the search for patterns of change in the physical world to address global economic, environmental, and humanitarian challenges
  - High revisit rates would enable change detection efforts; seek to be the first commercial providers of high-res video of Earth from satellite
- Terra Bella provides insight from satellite imagery, serving both as an operator of a smallsat constellation for Earth observation and data analyzer.

Ongoing and Future Plans

- Using SOTA deep learning and computing resources, combined with an array of geospatial and web information, Terra Bella identifies economic indicators
- SkySat Constellation

- Satellites would cost between $2 to $5 million per unit; total cost projected to be below $50 million
- Space Systems Loral has signed a contract to build the satellites Terra Bella would operate.[115] The smallsats are around 120 kg.
- The smallsat imaging constellation would include the following,
    - Optical payloads with Panchromatic, RGB, Near infrared imagery with 90cm resolution
    - 1.1m video resolution at 30 fps from 600 km
    - Two-dimensional sensor array would take multiple frames per second, images would be strung together on-ground
    - SkySat-3 offers several improvements over 1 and 2
    - Propulsion module to support orbit-stationing (from Swedish company ECAPS), further improvements in resolution (HPGP system), smaller pixels and increased agility to collect more area (better reaction wheels); production would be scalable
- Satellite constellation's high revisit rates are a key advantage

Customers and Partners

- Terra Bella would provide data commercially to organizations involved in economics, humanitarian, and environmental efforts
- Constellation (occupying four different polar-orbit planes) would provide high-resolution imagery and full-motion video for commercial sale
- Terra Bella has signed a contract to provide imagery to Japan Space Imaging

Financial

- Alphabet (which bought Terra Bella in 2014 for an estimated $500 million) has sold Terra Bella to Planet; although financial terms are not disclosed, the acquisition would include a multi-year contract between Planet and Google for satellite imagery.[116]

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[115] D. Werner, "SSL Lends a Hand to Smallsat Startups," *SpaceNews Magazine*, November 21, 2016.

[116] A. Knapp, "Google Is Selling Its Satellite Business Terra Bella To Satellite Startup Planet," Forbes, http://www.forbes.com/sites/alexknapp/2017/02/07/google-is-selling-its-satellite-business-terra-bella-to-satellite-startup-planet/#c3cf932f4b5c.

- Prior to both acquisitions, Terra Bella raised over $180 million in funding rounds and debt financing; VC firms that invested in Terra Bella include:
  - Asset Management Ventures; Bessemer Venture Partners; Canaan Partners; CrunchFund; Draper Associates; Khosla Ventures; Norwest Venture Partners

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