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How Big is Too Big? Using SAL (Smallsat Affordability in LEO) to Evaluate the Small Satellite Tradespace

Vincent A. Lillard, Project Leader

Matthew R. Avery
Alexander J. Slawik
Geoffrey M. Koretsky

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INSTITUTE FOR DEFENSE ANALYSES
4850 Mark Center Drive
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For more information:
Vincent A. Lillard, Project Leader
vlillard@IDA.org • (703) 845-2230

Robert R. Soule, Director, Operational Evaluation Division
rsoule@ida.org • (703) 845-2482

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Executive Summary

The public sector is increasingly making use of satellites in Low Earth Orbit (LEO) for a variety of applications, including imagery. Because the Department of Defense (DoD) also uses satellites to collect imagery, decision-makers are interested in whether the DoD also could find cost savings by using large constellations of small satellites. IDA created the Satellite Affordability in LEO (SAL) model to facilitate CAPE inquiries into the small satellite tradespace. SAL identifies the cheapest constellation capable of providing a desired level of performance within a set of design parameters. SAL achieves this using a combination of analytical models, statistical emulators, and geometric relationships. SAL is flexible and modular, allowing users to easily customize certain components while retaining default behavior in other cases. This tool allows users to quickly and responsively address questions about the utility of proliferated LEO constellations.

SAL uses a multi-step process to build a set of candidate constellations that meet user-specified performance requirements. Based on customizable assumptions about constellation cost, SAL determines the most cost-effective constellation size for the desired performance level. Figure 1 shows optimal constellation size as a function of desired access time for SAL's default cost assumptions.

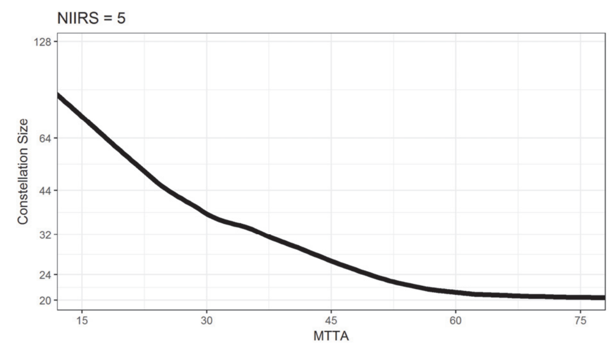


Figure 1. Constellation size as a function of Mean Time to Access (MTTA) using the default cost assumptions in SAL

SAL generates these outputs using the following algorithm:

1. For a desired MTTA and National Imagery Interpretability Rating Scale (NIIRS) value, select a candidate set of constellation sizes.

2. For each constellation size, identify the swath of ground each satellite would have to cover to achieve the desired MTTA.
3. Identify the collection of satellite configurations (altitude and sensor size combinations) that would achieve the desired swath width and NIIRS.
4. Of this set, choose the cheapest.
5. Repeat for each constellation size in the candidate set.
6. Select the constellation size that has the cheapest constellation.

Many steps in this algorithm are subject to user adjustment and customization, allowing SAL to incorporate new information and remain flexible and responsive in the rapidly-changing environment of proliferated smallsat constellations.

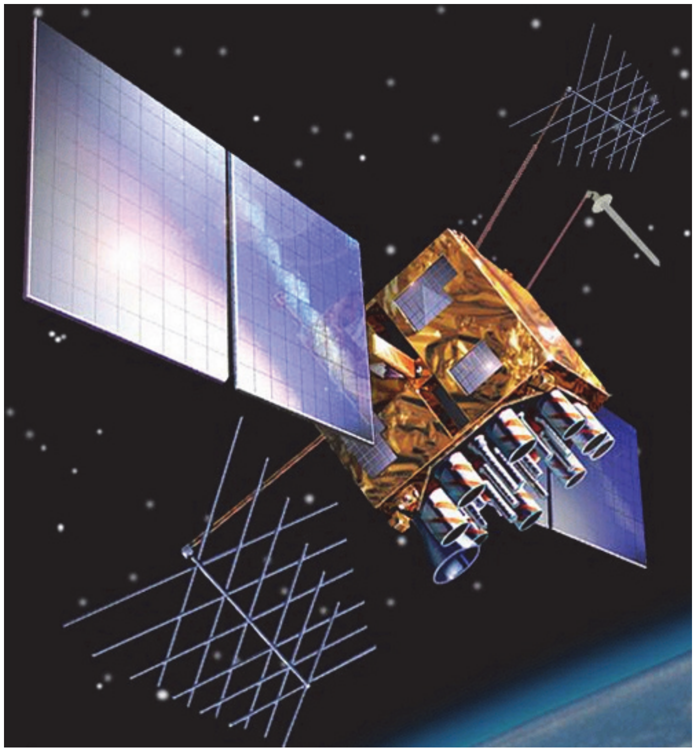
How Big Is Too Big?

Using SAL (Satellite Affordability in LEO) to Evaluate the Small Satellite Tradespace

Matthew Avery

April 10, 2019

Historically, the DoD has bought a few big satellites that orbit very far away



Global Positioning System

Orbits around 20,000 km above Earth

Currently 31 in orbit

Each weighs around 2,000 kg

Most other constellations are smaller!

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The current industry trend is large constellations of small satellites

Starlink

SpaceX's global communications constellation

4,425 satellites planned

Orbits around 1,300 km

Each will weigh less than 400kg

OneWeb

Airbus global communications constellation

600-700 satellites planned

Orbits around 1,200 km

Each will weigh about 150 kg

SAL overview

What to use SAL for

- Determining the optimal constellation size for a given level of performance
- Comparing the effect of different cost assumptions on optimal constellation size
- First-order estimates of constellation cost

What NOT to use SAL for

- Decision-level constellation cost calculations
- Determining whether a mission is feasible
- Evaluating the accuracy of cost functions

SAL accounts for key constellation characteristics

- Constellation Size
- Altitude
- Satellite Look Angle
- Swath Width
- Other Orbital Characteristics
  - F-number
  - Number of orbital planes
- Sensor Aperture Size
- Image Quality (NIIRS rating)
- Mean Time to Access (MTTA)
- Cost
  - Sensor cost
  - Bus cost
  - Launch cost
  - Transmission cost

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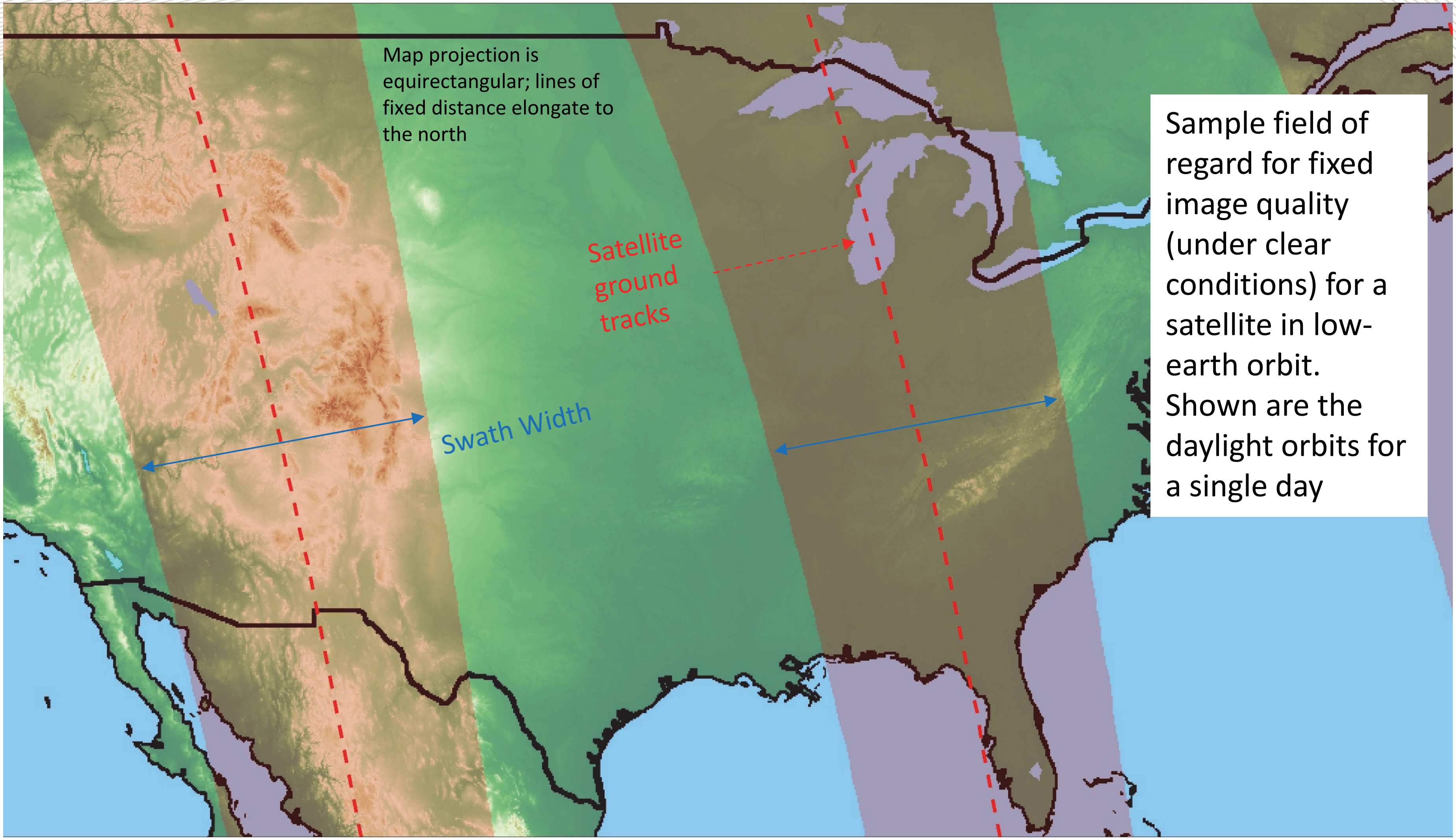
Illustration of swath width



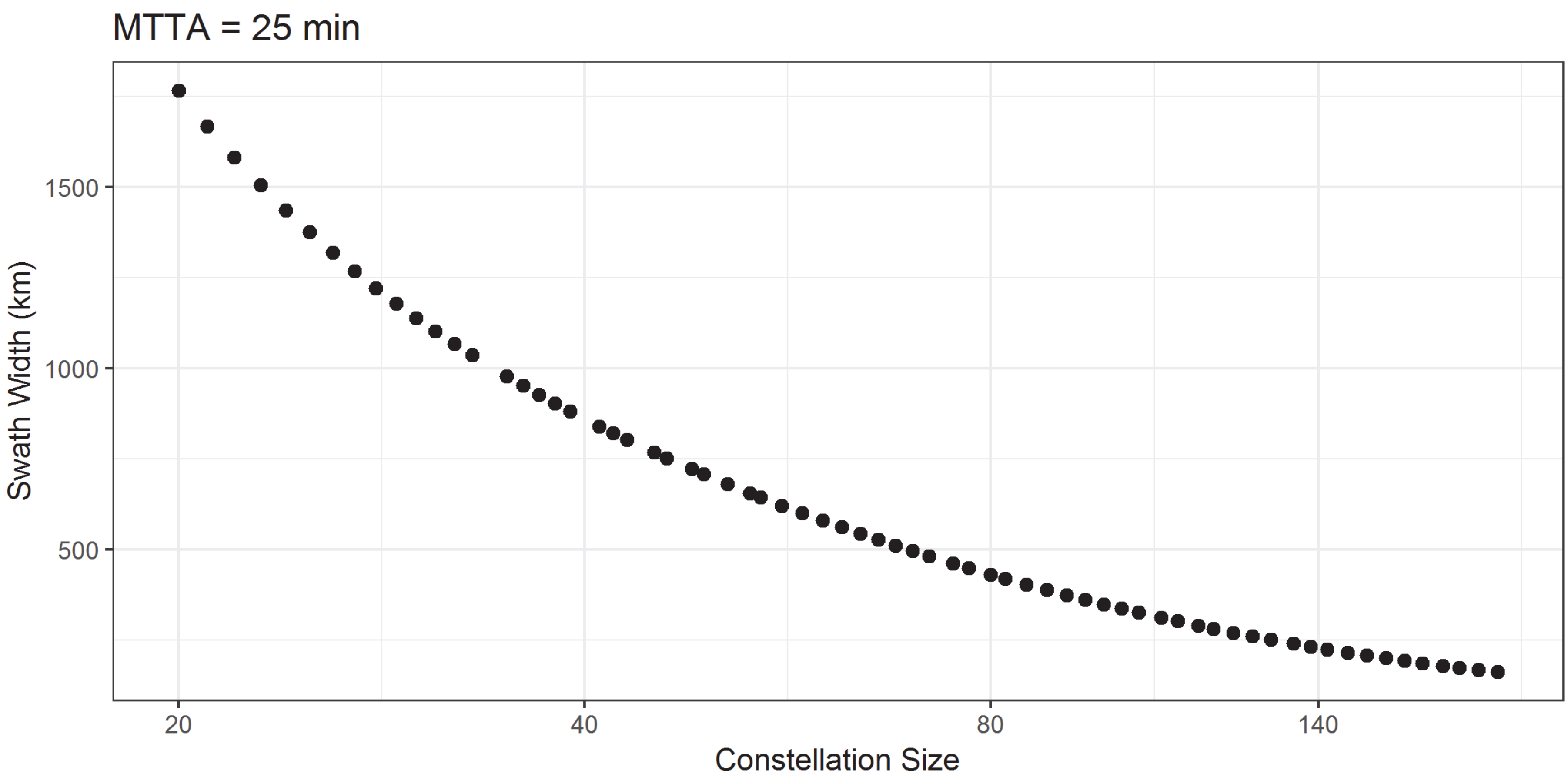
Sample field of regard for fixed image quality (under clear conditions) for a satellite in low-earth orbit. Shown are the daylight orbits for a single day

How does SAL find the optimal constellation size?

The algorithm employed by SAL is flexible and modular. New cost models can easily be substituted for default ones. The general approach used by SAL is described below:

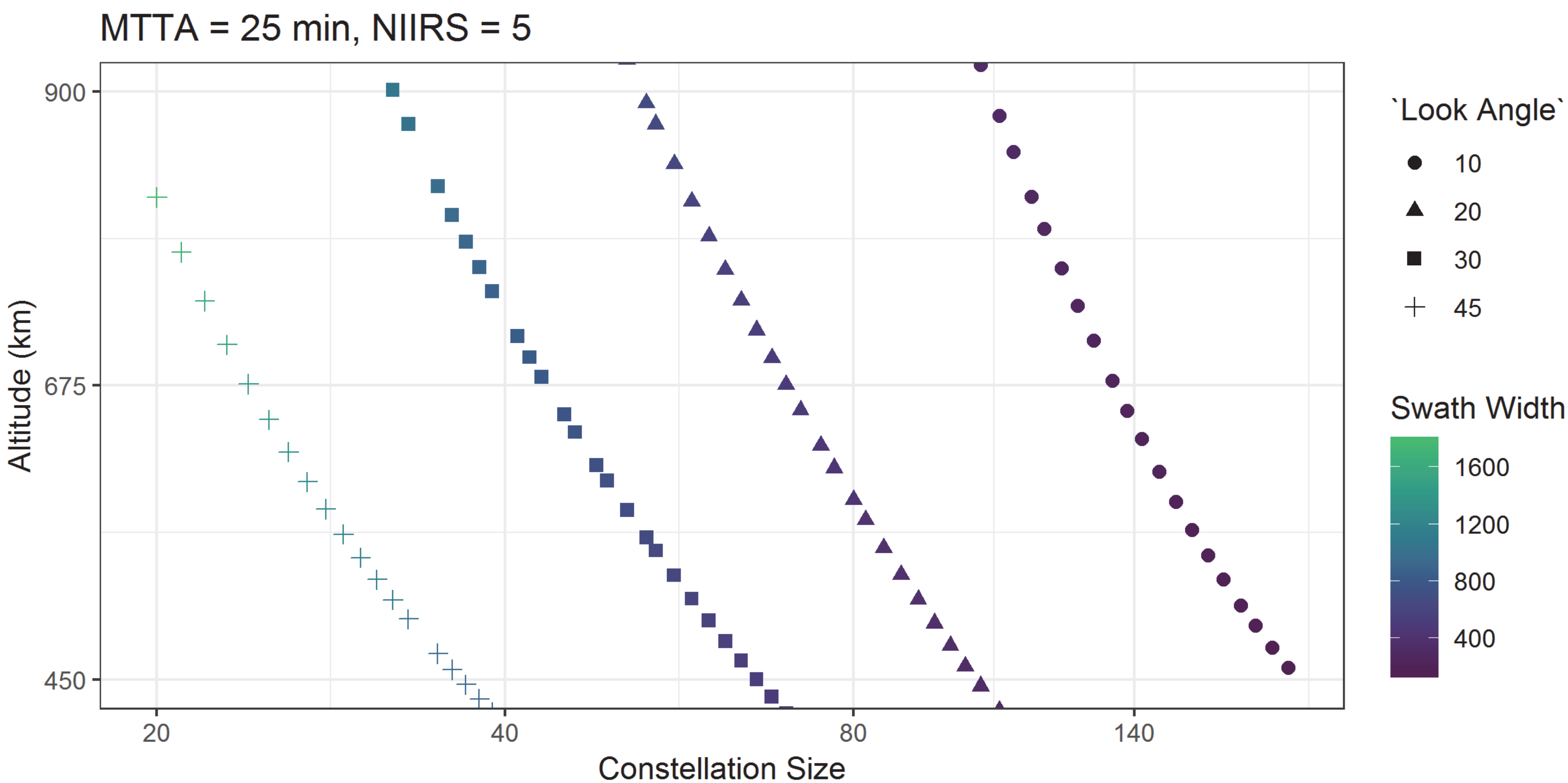
1. For a desired MTTA and NIIRS rating, select a candidate set of constellation sizes.
2. For each constellation size, identify the swath of ground each satellite would have to cover to achieve the desired MTTA.
3. Identify the collection of satellite configurations (altitude/sensor size combinations) that would achieve the desired swath width and NIIRS.
4. Of this set, choose the cheapest.
5. Repeat for each constellation size in the candidate set.
6. Select the constellation size that has the cheapest constellation.

For a given MTTA, SAL first identifies constellation requirements



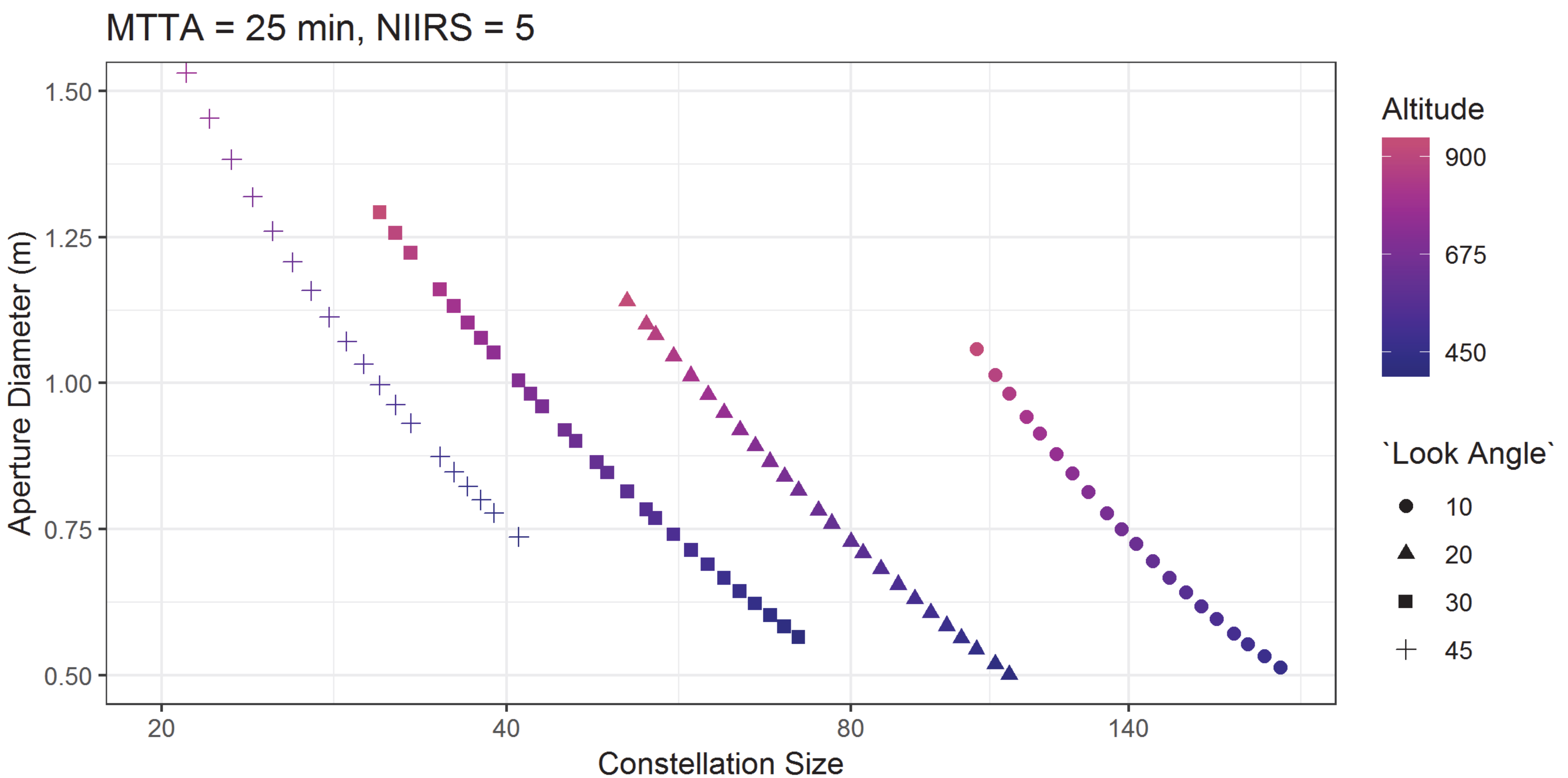
Many combinations of constellation size and swath width can achieve a desired level of performance (MTTA).

Next, SAL determines which constellations can meet these requirements



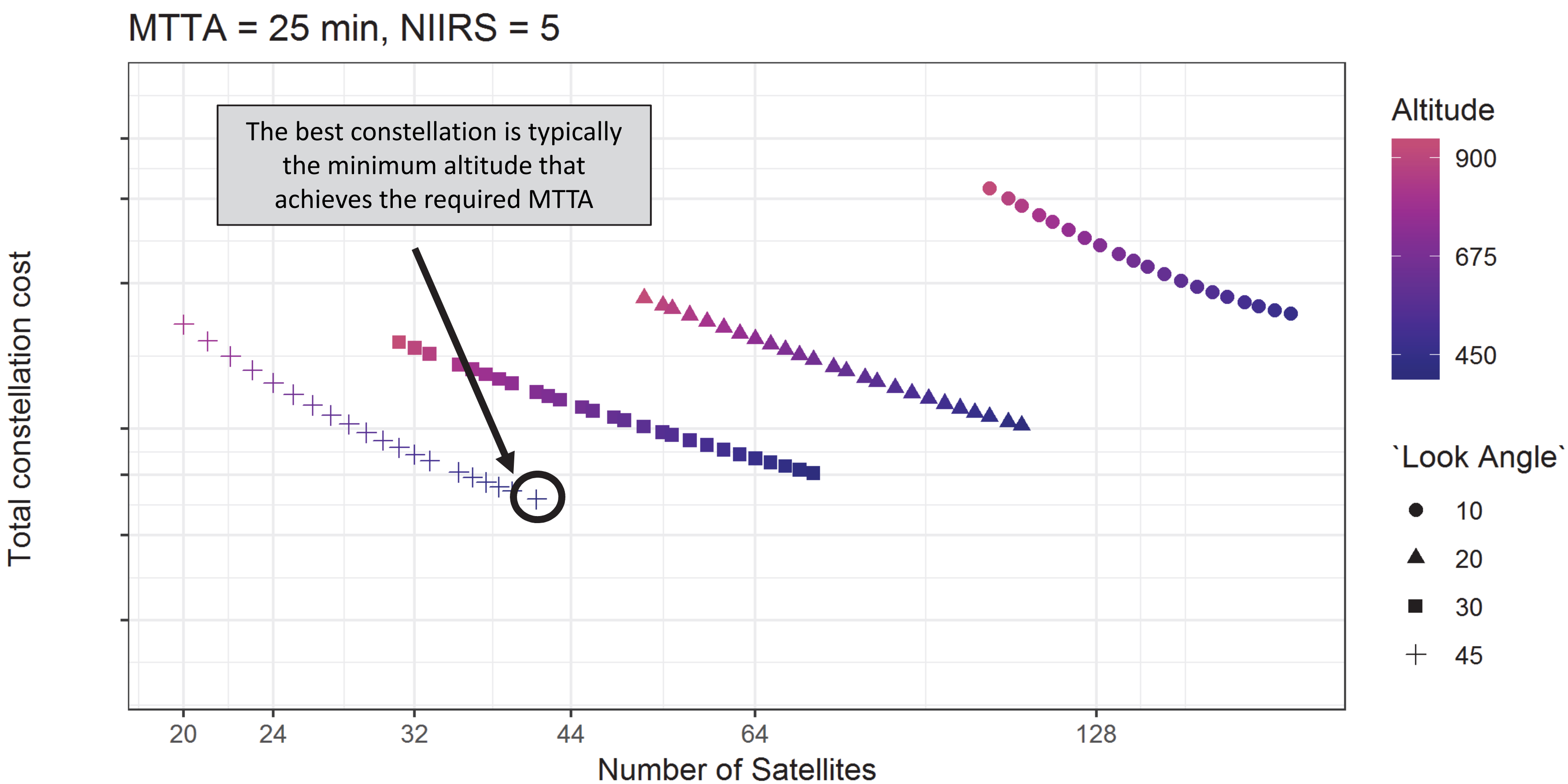
These constellations achieve the desired swath width via different combinations of altitude and look angle.

For each candidate constellation, SAL estimates the aperture size



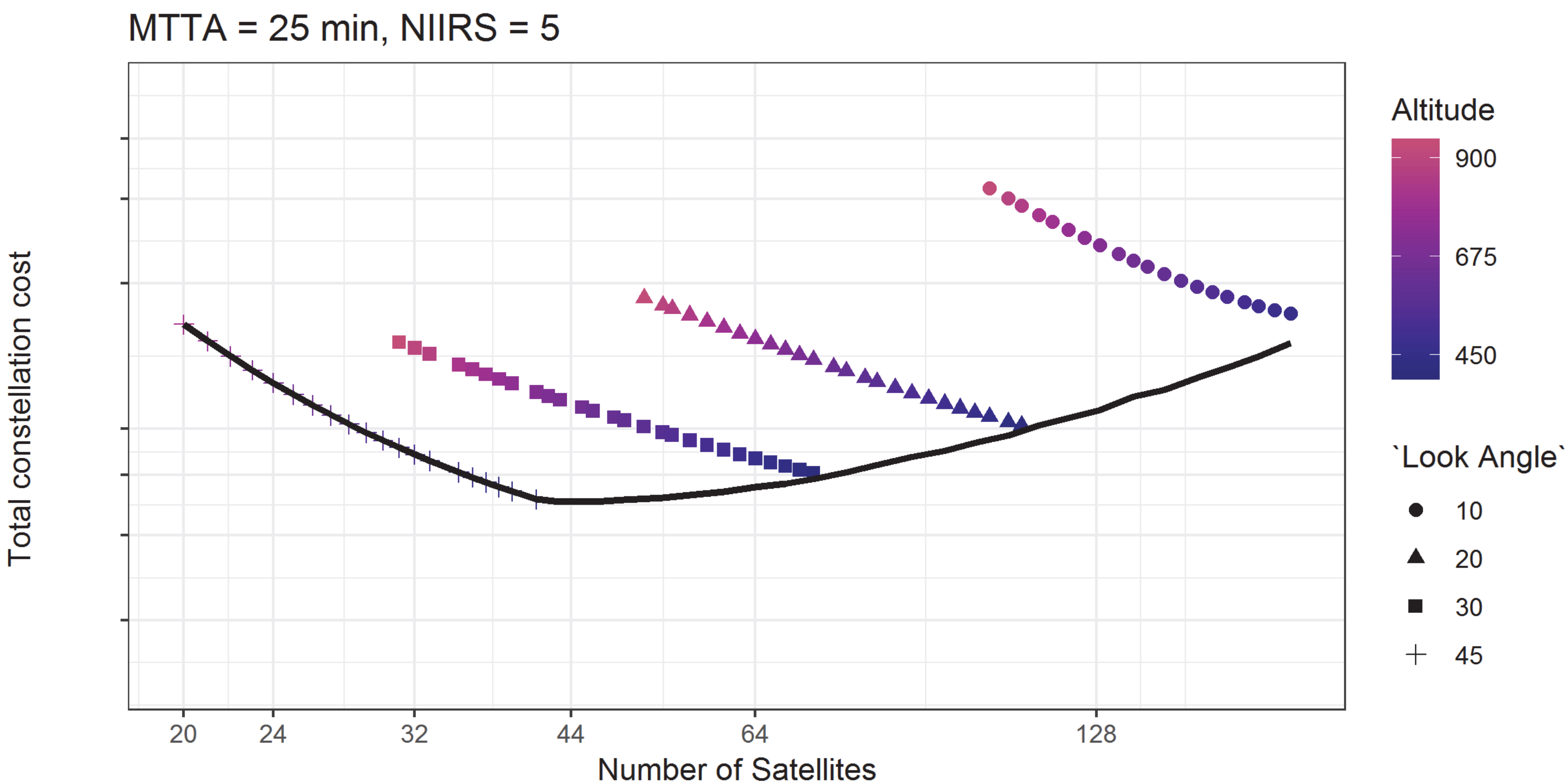
These trends look similar to those in the previous plot because aperture size is determined based on swath width, altitude, and look angle.

Using these aperture sizes and the default cost functions, SAL estimates the cost of each candidate



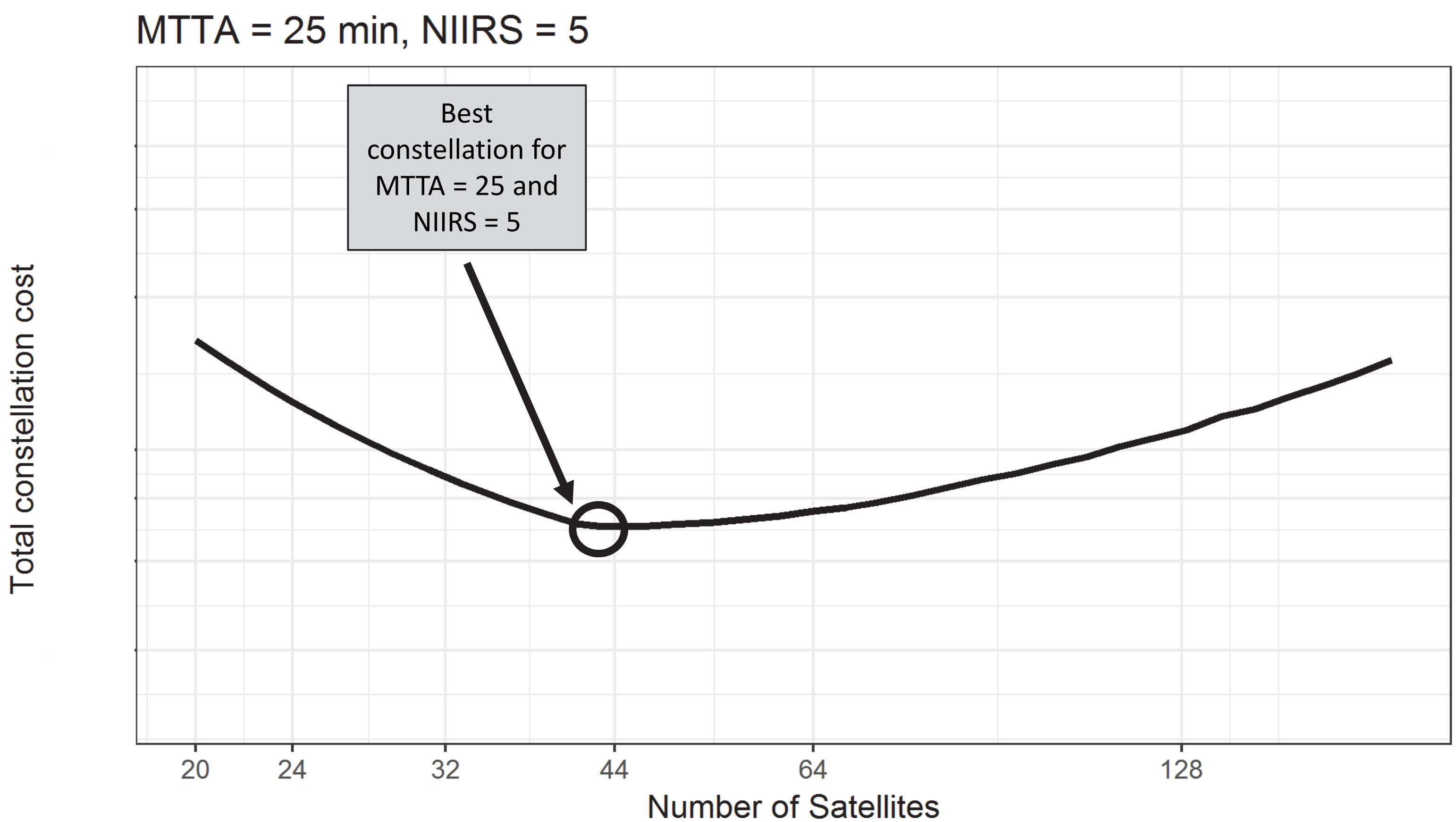
Because each constellation provides equivalent performance, the desired choice is the minimum cost option.

By searching across a fine grid of look angles and altitude, we can find the cheapest constellation for each constellation size



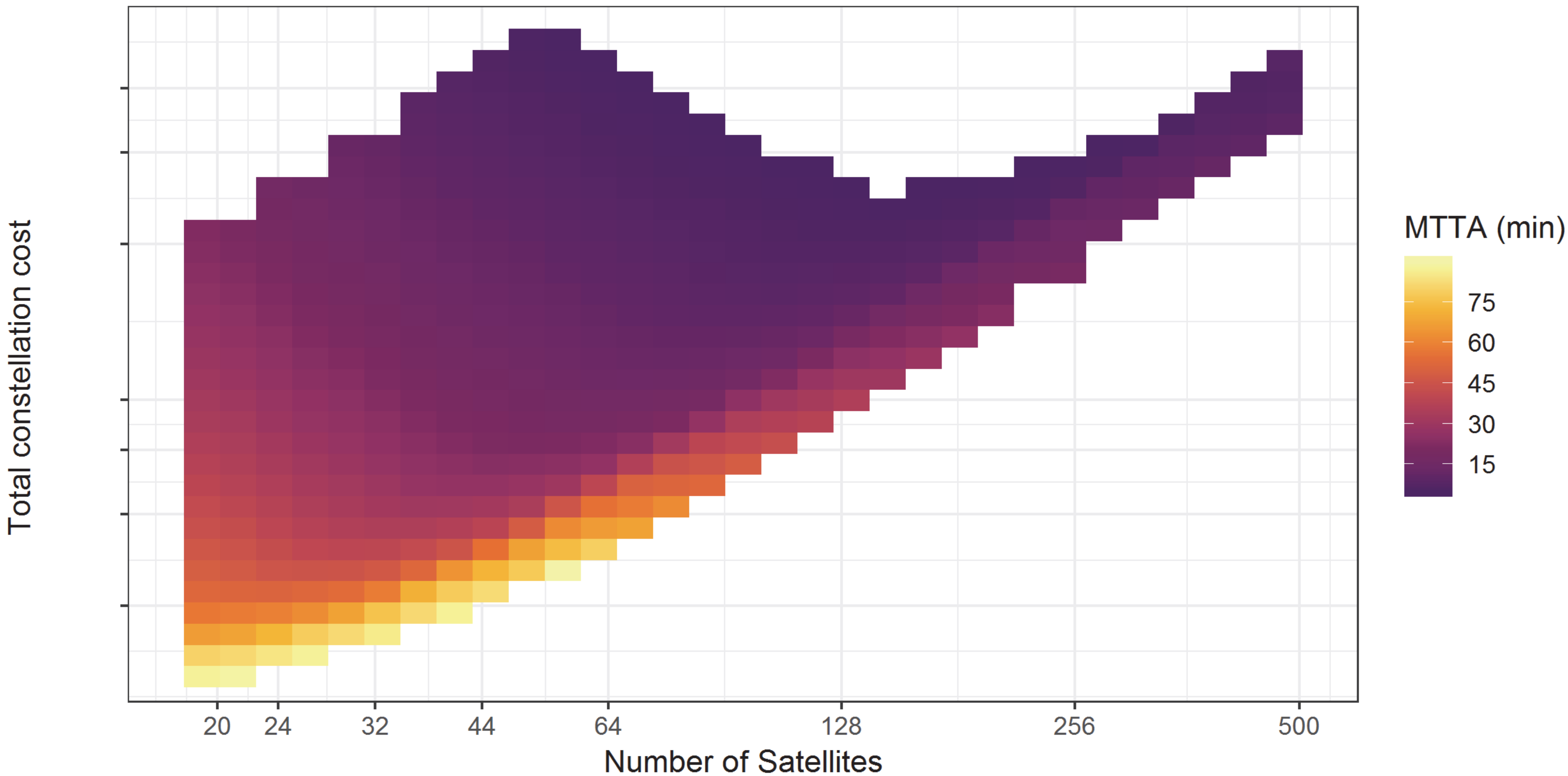
This plot only shows four look angles, but SAL considers all options between 10 and 45 degrees.

The nadir of this curve is SAL's estimate of the cheapest constellation that will provide an MTTA of 25 minutes with NIIRS 5 image quality

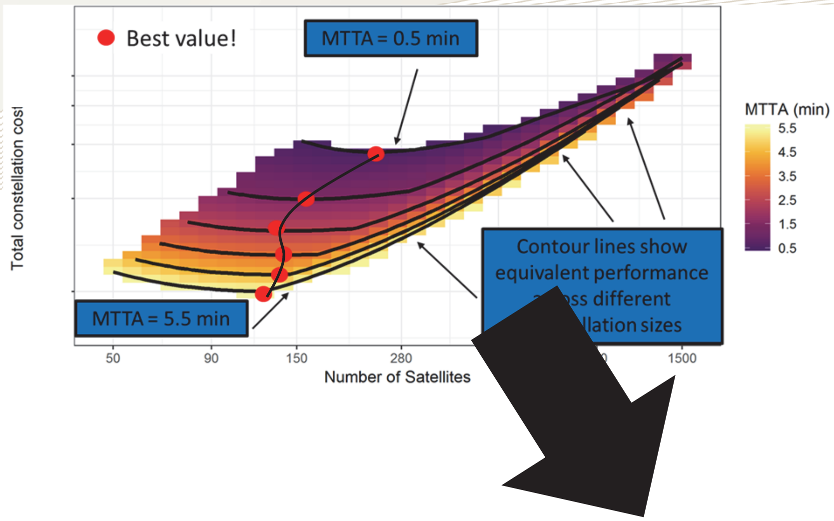


This optimal value is specific to the chosen level of performance (NIIRS quality, MTTA)

Repeating this process across different MTTAs allows us to look at the full space of choices

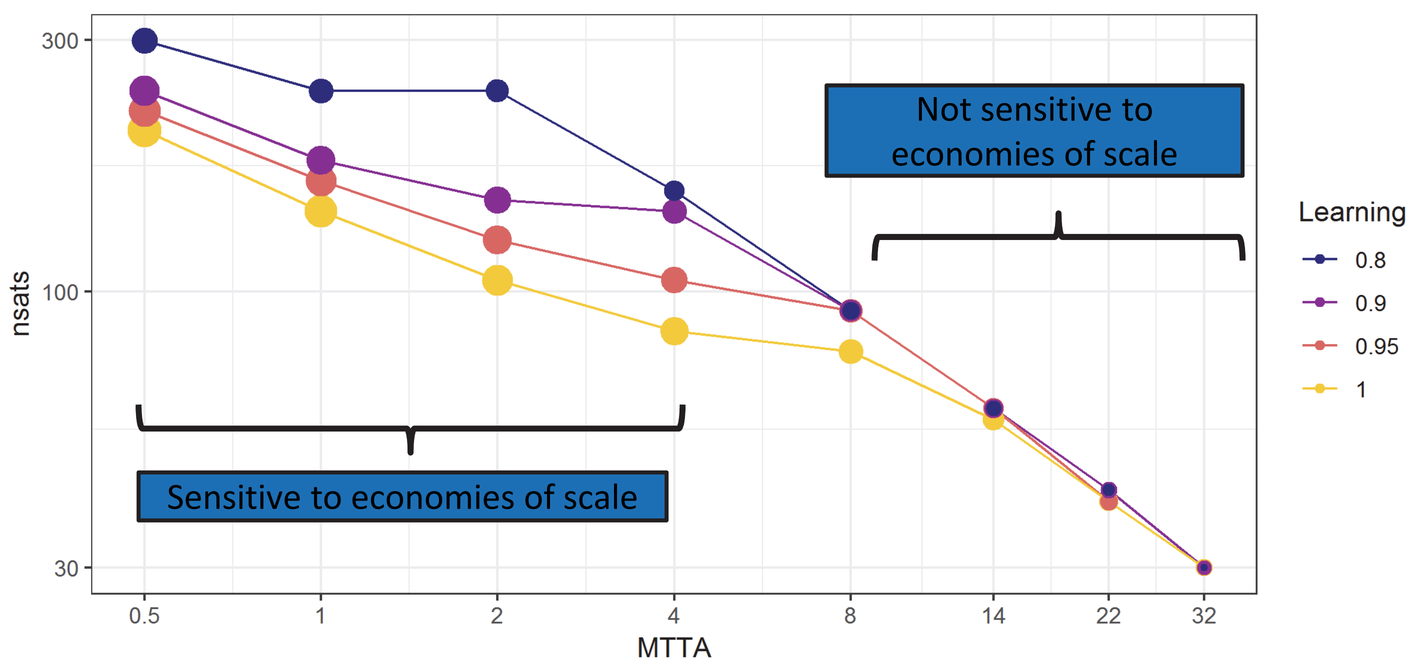


This plot only shows four look angles, but SAL considers all options between 10 and 45 degrees.

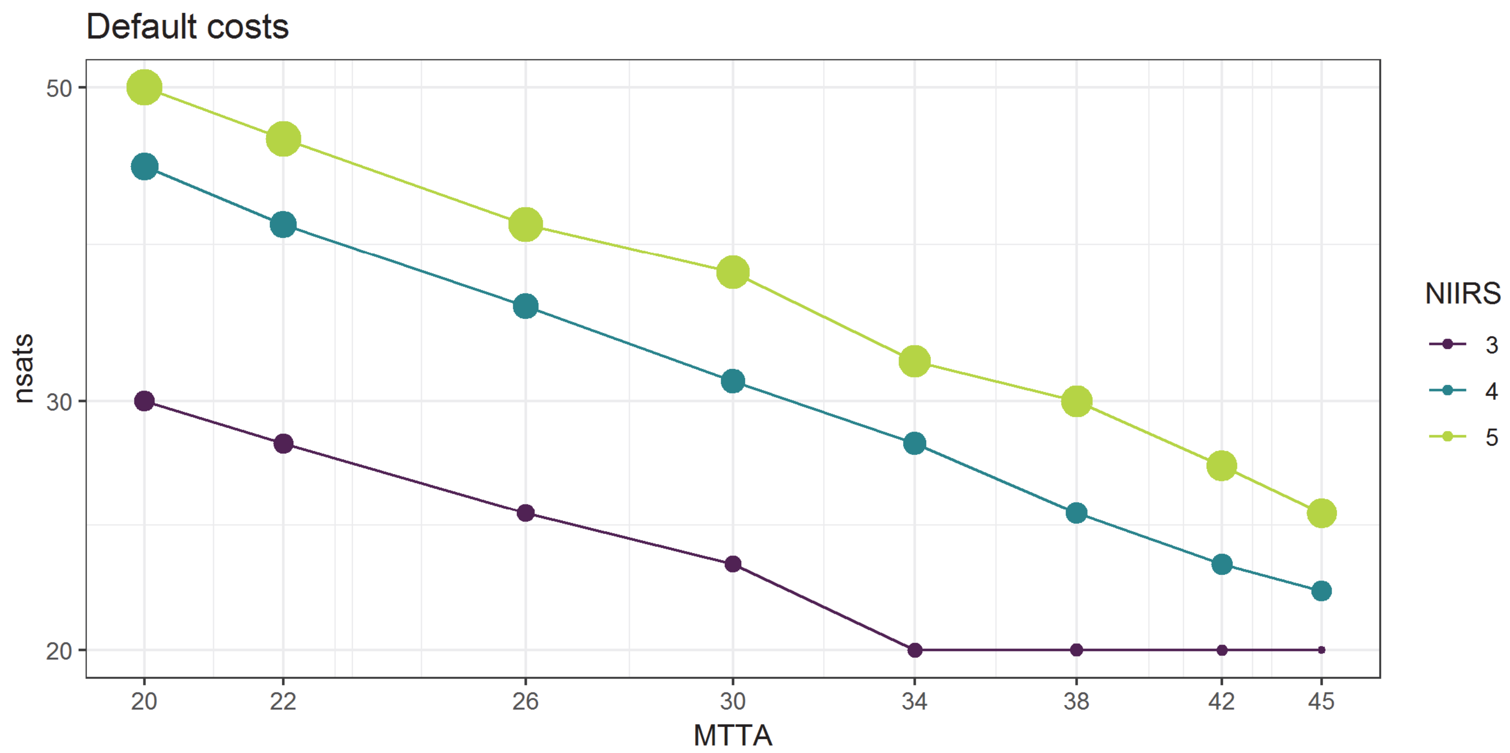


By finding the best constellation size under different design constraints or cost assumptions, we can determine what factors matter for optimizing a smallsat LEO constellation

Size of optimal constellation for different levels of economies of scale

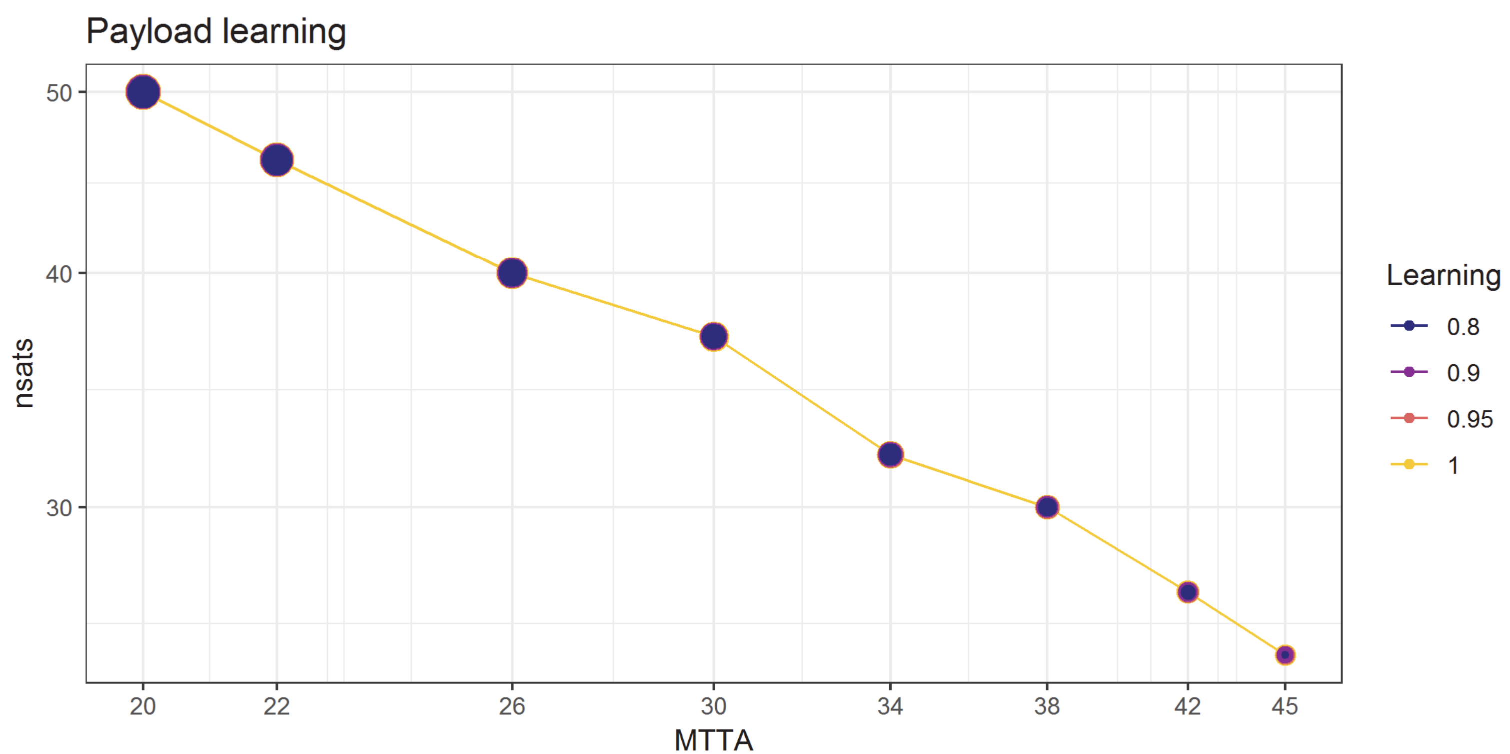


Constellation size sensitivity to NIIRS



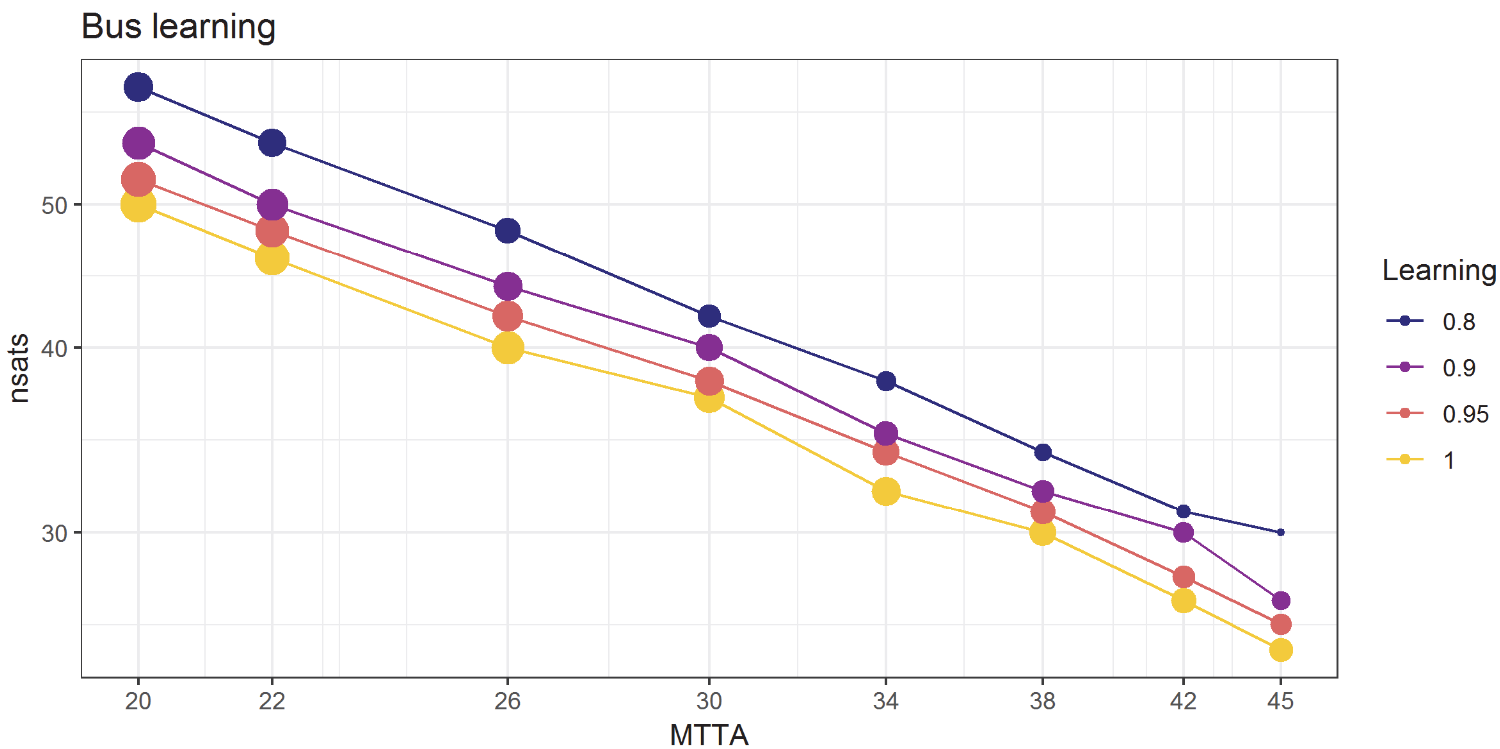
NIIRS rating makes a dramatic difference in the optimal constellation size. For lower MTTA (<30), lower NIIRS rating constellations will be substantially smaller than higher NIIRS rating constellations.

Constellation size sensitivity to learning (payload only)



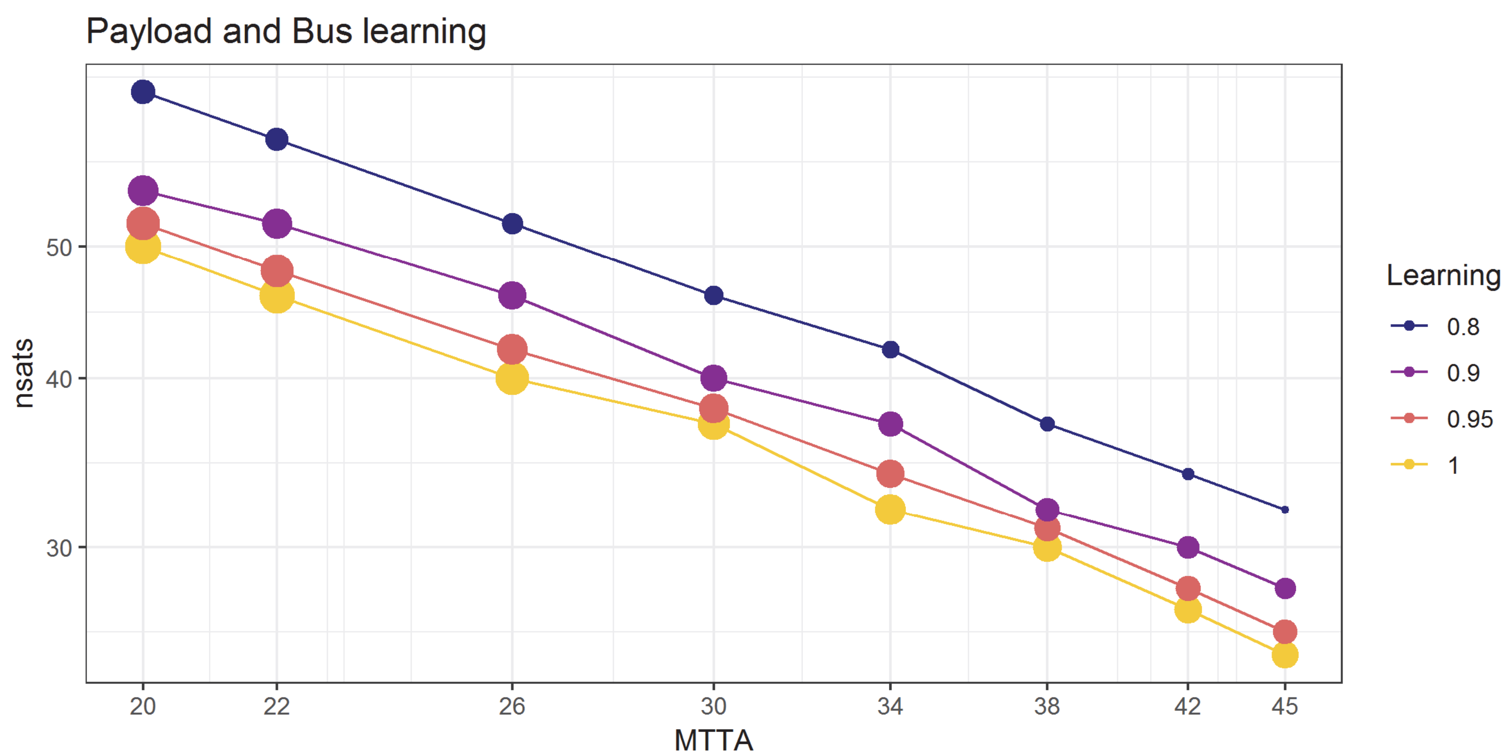
Efficiencies in payload production have no impact on optimal constellation size.

Constellation size sensitivity to learning (satellite bus only)



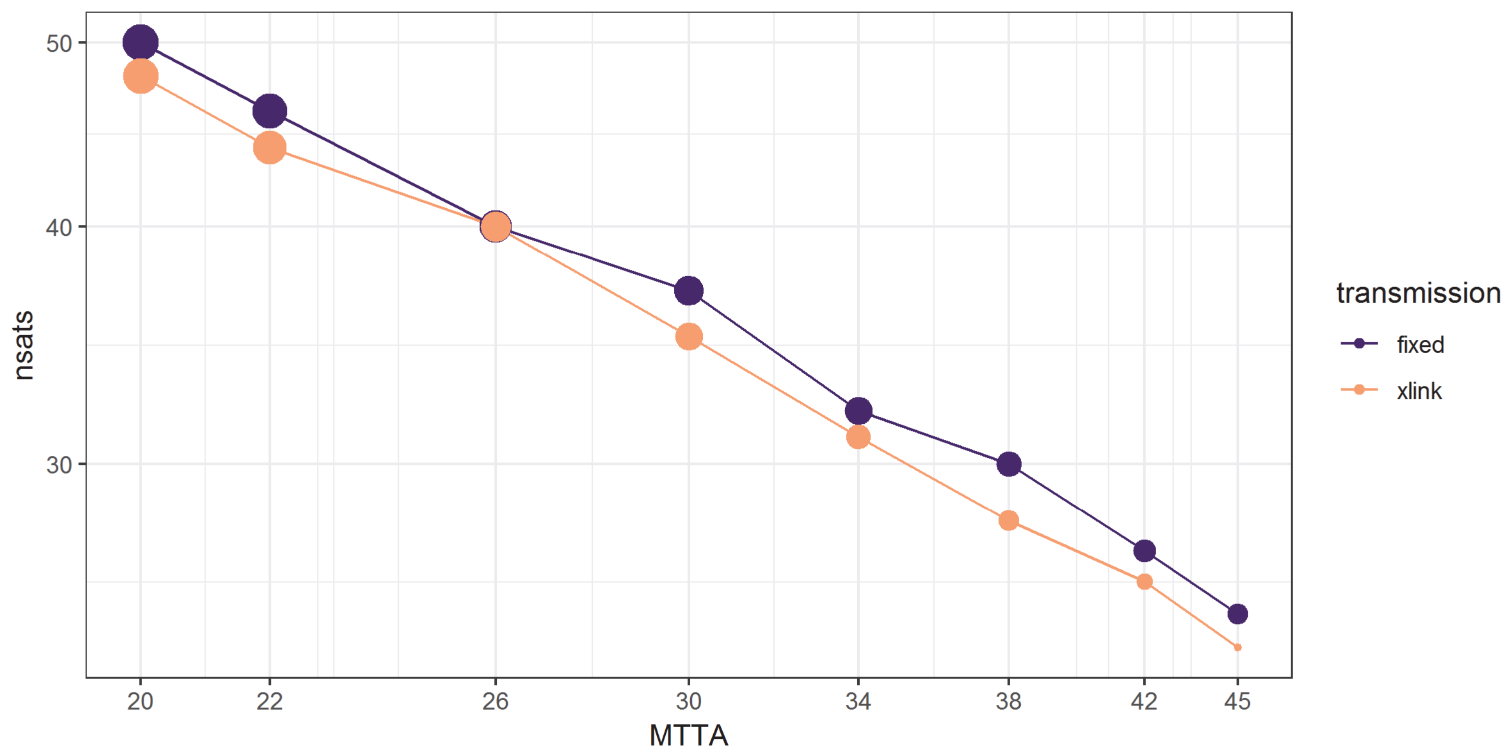
Efficiencies in satellite bus production make a small and consistent difference in optimal constellation size.

Constellation size sensitivity to learning



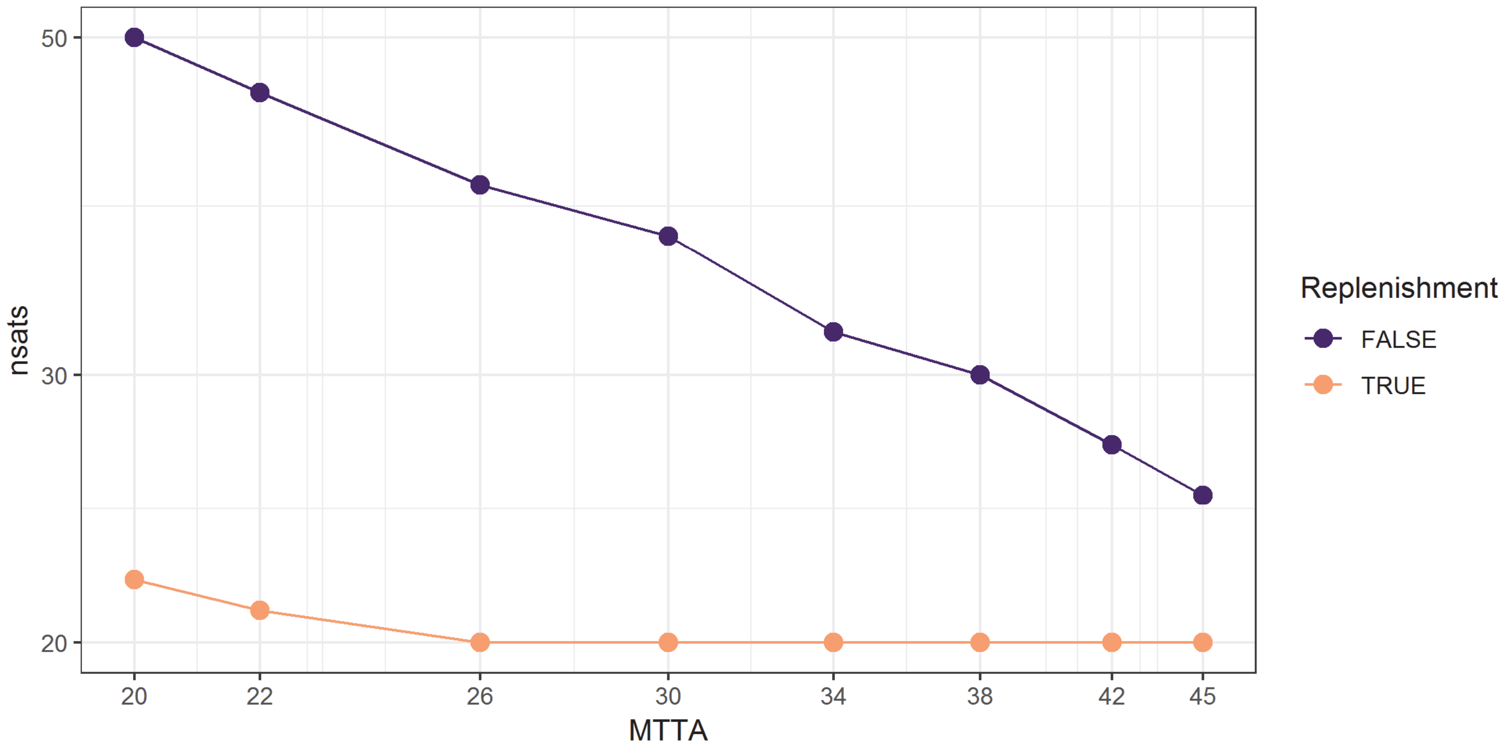
Similar to the bus-only picture, we see sustained and minor differences in constellation size when economies of scale are increased.

Constellation size sensitivity to transmission model



Cross-linked constellations will tend to be a bit smaller than constellations with large numbers of fixed ground stations.

Constellation size sensitivity to inclusion of replenishment costs

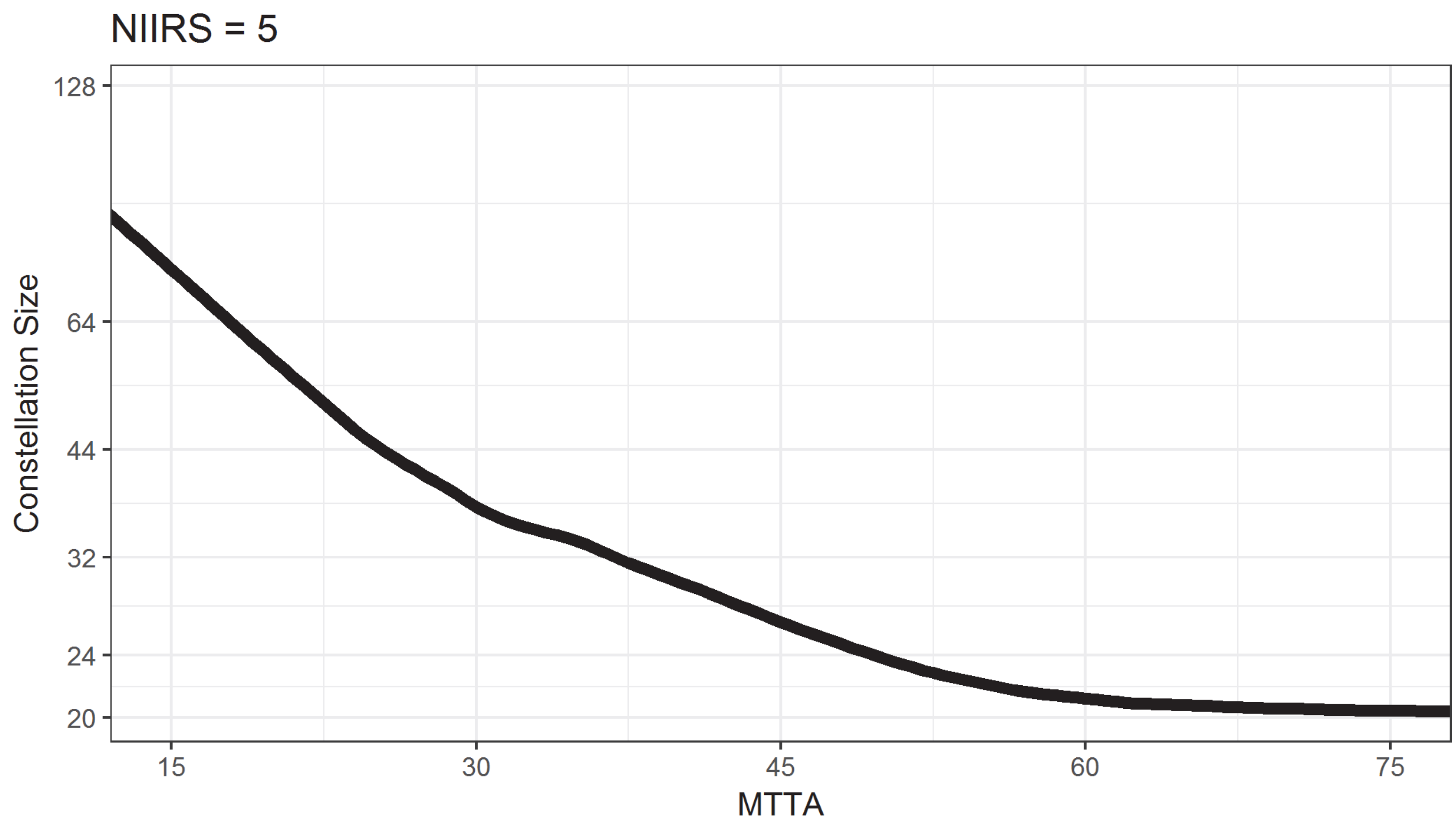


When we take replenishment into account, we almost invariably want a smaller constellation of large, long-lived satellites.

Important considerations for SAL

- SAL assumes monotonic relationships for most factors
  - Performance as a function of constellation size
  - Cost as a function of most factors
- Sensor aperture size and total weight are the main drivers of cost
- MTTA is chosen metric, though data exist to use others (max gap, etc.) if desired
- “Access” measured by constellation ability to look at a point at a given time, not ability to look at *all* points simultaneously
- Optical sensors only (for now….)

SAL estimates the cheapest constellation size as a function of performance level



This plot shows SAL's best estimate of constellation size under the default cost settings. Under different assumptions, the cheapest constellation size for a given performance level may change!

Conclusions

- SAL can tell us a lot about the most important considerations for planning smallsat constellations
  - How far from the optimal constellation size will we be if we overestimate our economies of scale?
  - How much do mission considerations (e.g., image resolution requirements) drive us toward larger or smaller constellations?
- Higher fidelity cost models can improve the raw cost estimates from SAL, although this isn't SAL's primary function
- Expanding the set of orbits (beyond polar sun-synchronous) considered by SAL might show new tradeoffs and possibilities
- Future work comparing proliferated LEO constellations to "large sats" should be **mission focused** in terms of having realistic mission requirements
  - Comparisons within LEO are useful, but MEO and GEO are still out there
  - Without a set of mission requirements, there are too many degrees of freedom to get definitive answers about whether small is better than large

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14. ABSTRACT
The Satellite Affordability in LEO (SAL) model identifies the cheapest constellation capable of providing a desired level of performance within certain constraints. SAL achieves this using a combination of analytical models, statistical emulators, and geometric relationships. SAL is flexible and modular, allowing users to customize certain components while retaining default behavior in other cases. This is desirable if users wish to consider an alternative cost formulation or different types of payload. Uses for SAL include examining cost tradeoffs with respect to factors like constellation size and desired performance level, evaluating the sensitivity of constellation costs to different assumptions about cost behavior, and providing a first-pass look at what proliferated smallsats might be capable of. At this point, SAL is limited to Walker constellations with sun-synchronous, polar orbits.

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