INSTITUTE FOR DEFENSE ANALYSES

DATAWorks 2022: DebProp: Orbital Debris Collision Effects Prediction Tool for Satellite Constellations

Joel E. Williamsen, Project Leader

James F. Heagy
Daniel L. Pechkis
Steven W. Evans
Robert F. Stellingwerf

April 2022

IDA Document NS D-32942

Log: H 2022-000011

INSTITUTE FOR DEFENSE ANALYSES
730 East Glebe Road
Alexandria, Virginia 22305

The Institute for Defense Analyses is a nonprofit corporation that operates three Federally Funded Research and Development Centers. Its mission is to answer the most challenging U.S. security and science policy questions with objective analysis, leveraging extraordinary scientific, technical, and analytic expertise.

About This Publication
This work was conducted by the Institute for Defense Analyses (IDA) under contract HQ0034-19-D-0001, Task C9108, "Orbital Debris Risk Prediction," for the Office of the Director, Operational Test and Evaluation. The views, opinions, and findings should not be construed as representing the official position of either the Department of Defense or the sponsoring organization.

Acknowledgments
The IDA Technical Review Committee was chaired by Mr. Robert R. Soule and consisted of Peter M. Mancini, Jason P. Sheldon, and James E. Rhoads from the Operational Evaluation Division.

For more information:
Joel E. Williamsen, Project Leader
jwilliam@ida.org • (703) 578-2705

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

INSTITUTE FOR DEFENSE ANALYSES

IDA Document NS D-32942

DATAWorks 2022: DebProp: Orbital Debris Collision Effects Prediction Tool for Satellite Constellations

Joel E. Williamsen, Project Leader

James F. Heagy
Daniel L. Pechkis
Steven W. Evans
Robert F. Stellingwerf

Executive Summary

Based on observations gathered from the IDA Forum on Orbital Debris (OD) Risks and Challenges (October 8-9, 2020), DOT&E needed first-order predictive tools to evaluate the effects of orbital debris on mission risk, catastrophic collision, and collateral damage to DOD spacecraft and other orbital assets – either from unintentional or intentional [Anti-Satellite (ASAT)] collisions. This lack of modeling capability hindered DOT&E's ability to evaluate the risk to operational effectiveness and survivability of individual satellites and large constellations, as well as risks to the overall use of space assets in the future.

This presentation describes an IDA-derived technique (DebProp) to evaluate the debris propagating effects of large, trackable debris (>5 cm) or antisatellite weapons colliding with satellites within constellations. IDA researchers used a Starlink-like satellite as a case study and worked with Stellingwerf Associates to modify the Smooth Particle Hydrodynamic Code (SPHC). The result is a file format that is readable as an input file for predicting orbital stability or debris re-entry for thousands of thousands of created particles, and predict additional, short-term OD induced losses to other satellites in the constellation.

By pairing this technique with SatPen[1], IDA can conduct long-term debris growth studies.

[1] SatPen is an Excel-based tool for determining the probability and mission effects of >1mm OD impacts and penetration on individual satellites with Orbital Debris Engineering Model 3.1 as an input, supplemented with typical damage prediction equations to support mission loss predictions.

DebProp: Orbital Debris Collision Effects Prediction Tool for Satellite Constellations

Joel Williamsen (OED), Project Leader
Jim Heagy (STD)
Dan Pechkis (OED)
Jason Sheldon (OED)
Steven Evans (IDA Consultant)

January 2022

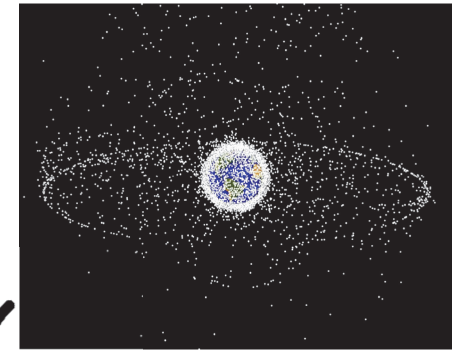
Institute for Defense Analyses
730 East Glebe Road ● Alexandria, Virginia 22305

What is the effect on a satellite or a constellation of satellites when a catastrophic collision occurs with orbital debris (OD), another spacecraft, or an anti-satellite (ASAT) weapon?

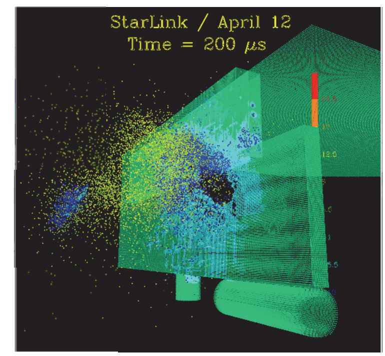
Outline

1. Overview of IDA's orbital debris assessment tools
2. Elements within large debris collision assessment approach
   a. Smooth Particle Hydrodynamics Code (SPHC) input
   b. DebProp (Debris Propagation) tool
3. Assessment of large debris hit on Starlink-like satellite
4. How DebProp fits into a larger assessment of the "Kessler effect"

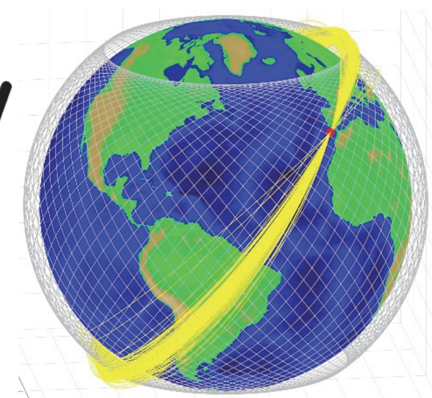
IDA is developing tools to evaluate the effects of orbital impacts from OD and ASAT weapons on satellites and constellations



SatPen is a tool for **debris penetration** that will determine the probability of satellite mission loss from orbital impact (outlined in a different DATAWorks presentation)



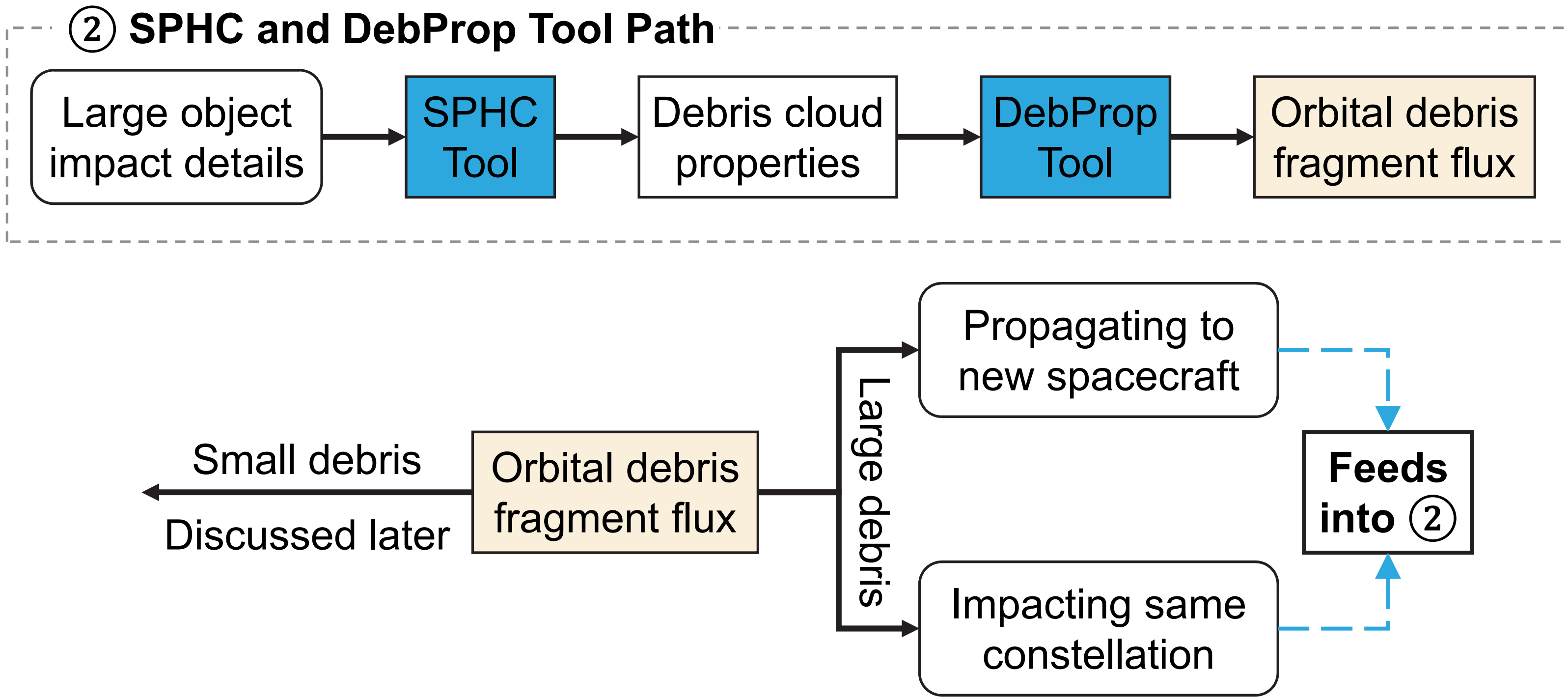
SPHC is a tool for **high-speed collisions** and **DebProp** is a tool for **debris propagation** that together determine the effect on a satellite or constellation from orbital impact



Iterating SatPen, SPHC, and DebProp in a loop will allow us to estimate the results from a cascade of orbital debris impacts

ASAT – Anti-Satellite; OD – Orbital Debris; SPHC – Smooth Particle Hydrodynamics Code

Examining debris propagation from a triggering event



SPHC is a tool for collisions that:

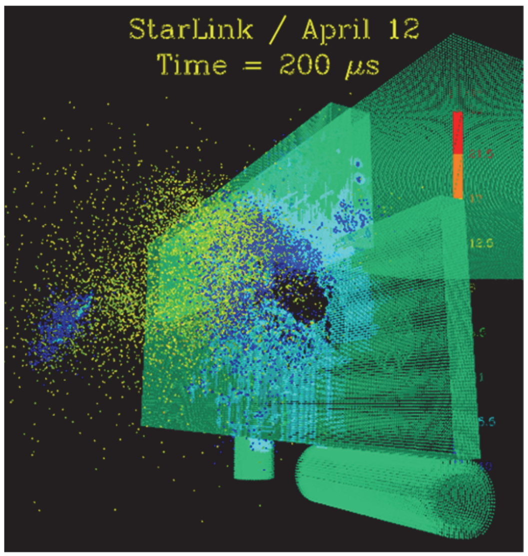
- Calculates cloud (mass, velocity, phase, etc.) of impacted materials created following hypervelocity impact by satellite model or orbital debris

DebProp is a tool for propagation that:

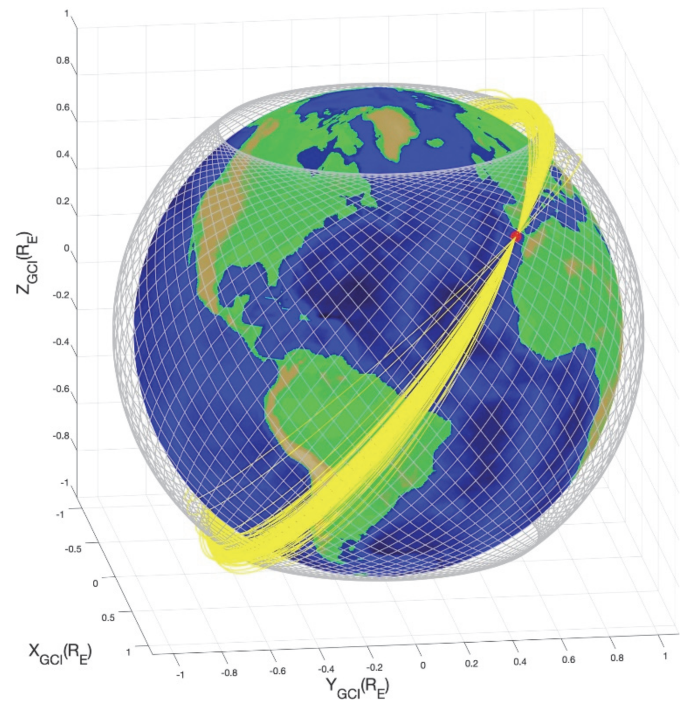
- Imports SPHC "cluster files" describing clouds of thousands of debris particles
- Predicts potential collision paths with other satellites for subsequent analyses

SPHC – Smooth Particle Hydrodynamics Code

We model collisions using SPHC and propagate the resulting fragments using DebProp to determine the cascading effects on satellites and constellations



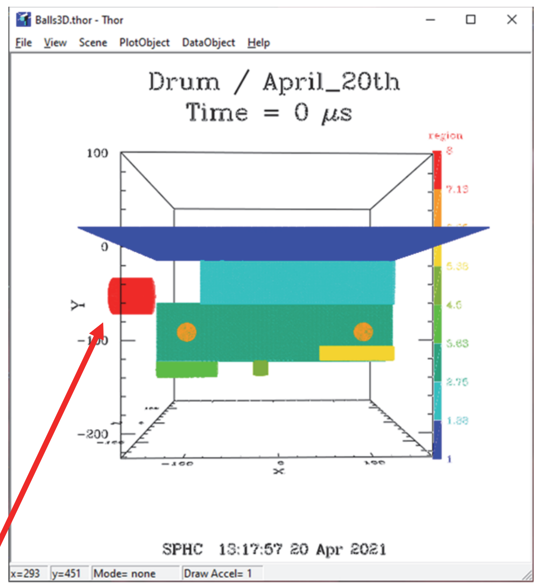
SPHC: Smooth particle hydrodynamic code

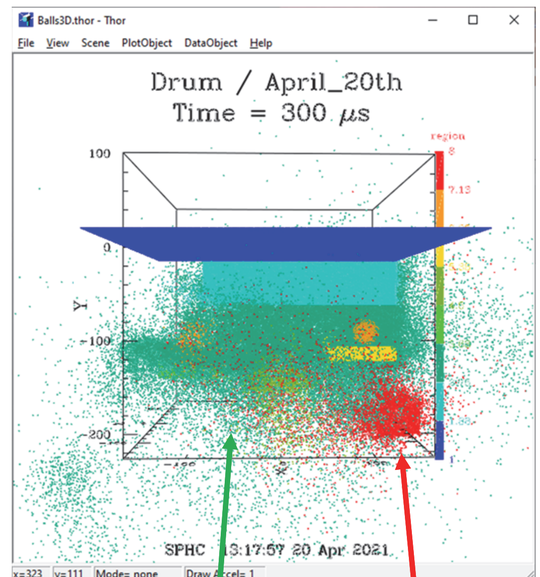


DebProp: IDA developed propagation tool

We used SPHC to predict fragment mass and velocity distributions emanating from a collision between an object and a Starlink satellite

ASAT Example





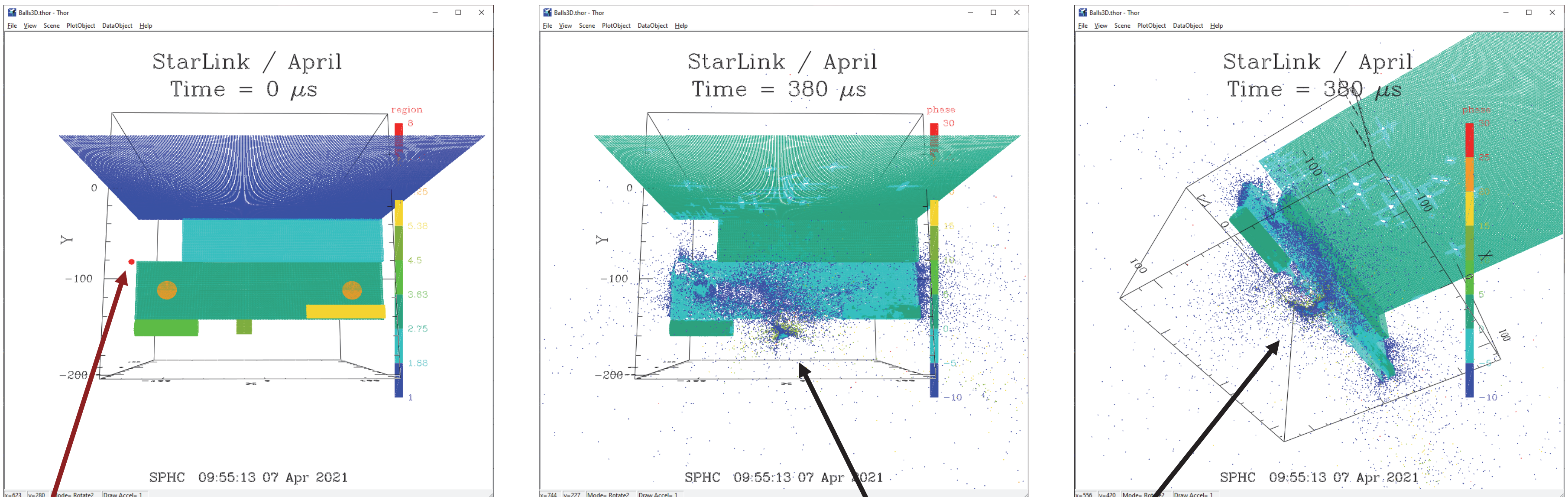
Conceptual cylindrical satellite fragment

Dots represent Starlink and ASAT fragments resulting from the impact

ASAT – Anti-Satellite; SPHC – Smooth Particle Hydrodynamics Code

We used SPHC to predict fragment mass and velocity distributions emanating from an object impacting a Starlink satellite

Debris Example



8 cm diameter debris
13 km/sec, 25 deg
just before impacting

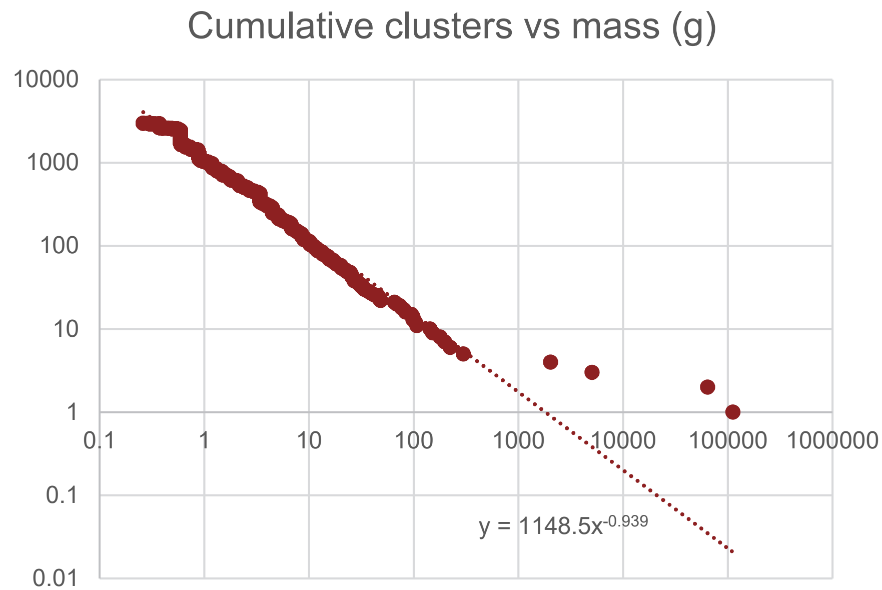
Blue dots represent fragments resulting from the impact
SPHC calculates mass and velocity for each fragment

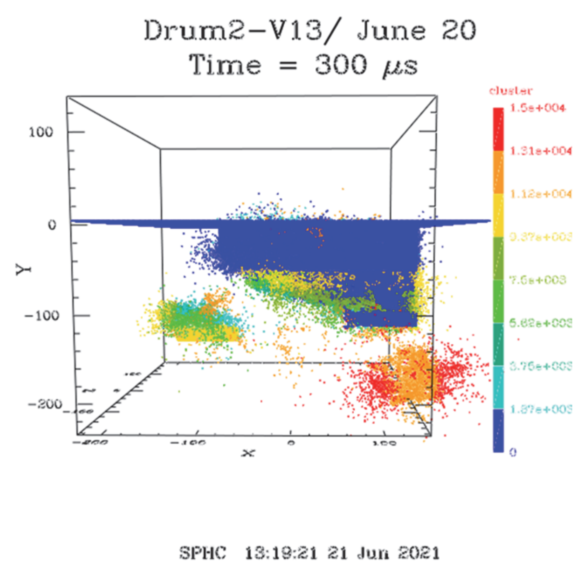
SPHC – Smooth Particle Hydrodynamics Code

SPHC cluster files predict material, velocity, and other physical properties of projectile and target satellites

mass | position | velocity | material & phase

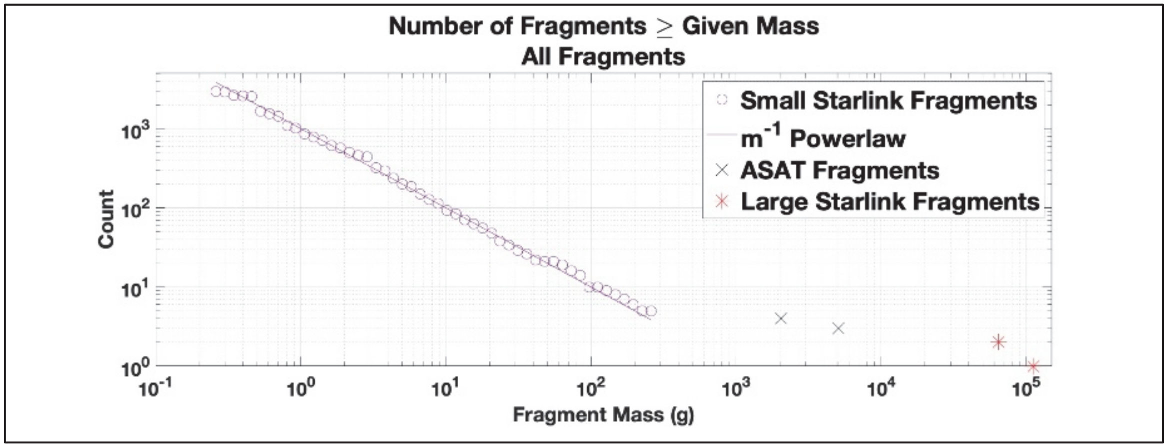
clusters	parts	mass	x	y	z	vx	vy	vz	material	av_phase
1	481048	111960	30.4458	-30.2673	-208.368	0.009567	0.005305	-0.01485	8	-1.4
2	35157	64259.2	-120.244	-152.477	5.82353	0.000409	-0.053	0.003266	26	-2
3	4985	5066.13	165.125	-219.55	-35.1532	11.8099	-5.52798	-0.9984	4	-7.5
4	2419	2033.24	175.595	-213.599	18.7856	11.6797	-5.35499	-0.01025	4	-9.5
5	176	298.714	145.781	-214.041	36.8822	11.8148	-5.38225	0.862407	4	-10
6	131	223.284	160.633	-189.265	17.9445	11.641	-4.72195	-0.00849	4	-10
7	89	197.234	-119.558	-115.199	-16.6393	0.13039	-0.28572	-0.75623	4	-9.8
8	105	178.968	156.792	-226.85	23.9326	11.7849	-5.64496	0.060413	4	-9.8
9	89	151.696	161.781	-207.211	28.7492	11.7716	-5.16358	0.376667	4	-10
10	84	143.174	140.676	-195.361	-52.9929	11.8301	-5.07279	-1.77794	4	-10
11	63	107.381	150.703	-232.406	19.1217	11.7489	-5.62068	-0.08781	4	-10
12	61	103.972	149.156	-230.308	29.5061	11.8637	-6.00049	0.410495	4	-9.9
13	92	98.4062	134.836	-221.183	-46.7537	11.7674	-5.6183	-1.4111	4	-9.9
14	118	98.2844	126.466	-209.325	29.6725	11.2103	-5.32581	0.377299	4	-10
15	56	95.4495	142.082	-202.544	37.8236	11.8275	-5.23109	0.788374	4	-10
16	49	83.5183	147.795	-185.915	24.7006	11.5715	-4.4771	0.351499	4	-10
17	95	80.6659	127.86	-237.851	15.0674	11.389	-5.941	-0.18231	4	-10
18	45	76.7005	138.385	-235.036	19.6006	11.7932	-5.6691	0.068662	4	-10
19	130	73.803	-97.8687	-52.5827	-12.3848	0.009733	0.039225	-0.16731	4	-7.5
20	327	68.7373	-159.083	-126.233	14.4483	-0.27513	-0.01974	0.352272	4	-8.6

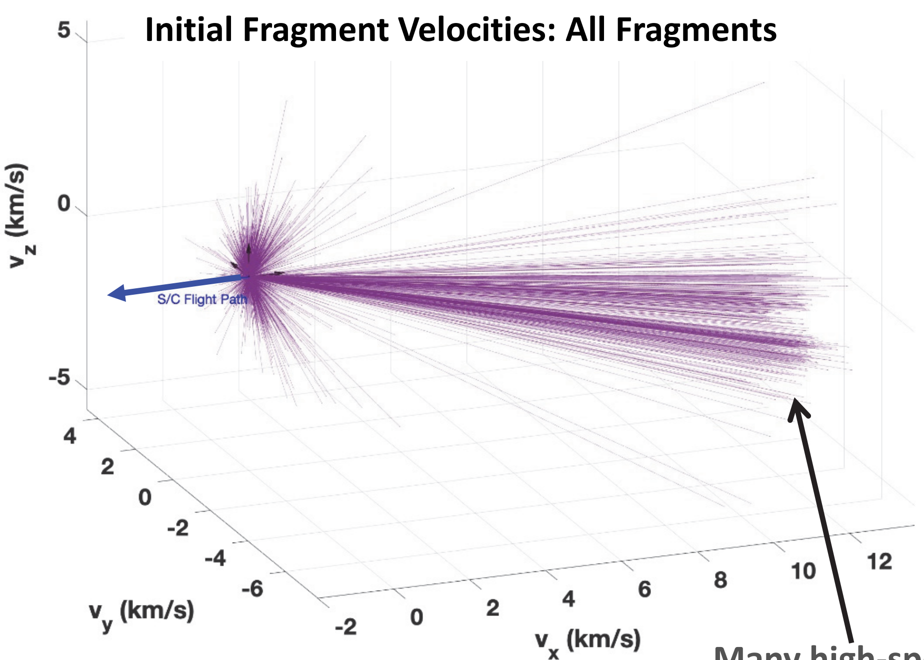




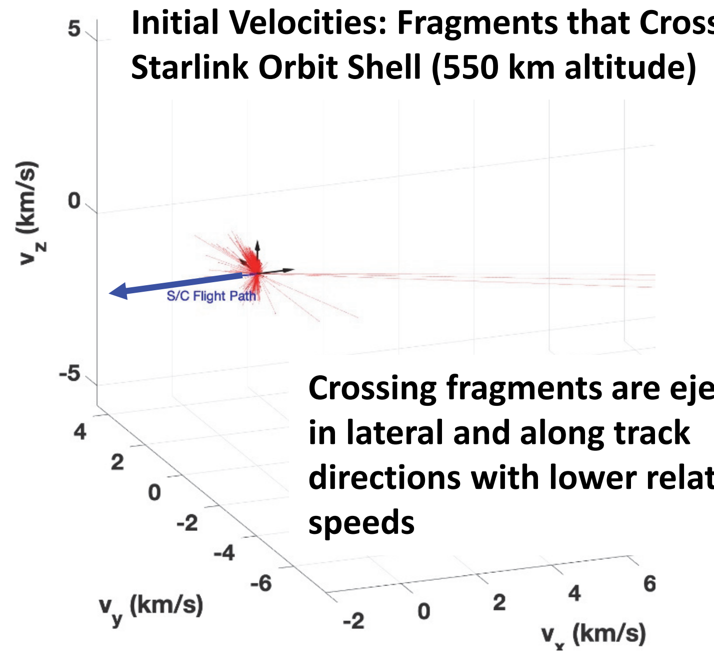
SPHC cluster file data are read into DebProp propagation tool for subsequent orbital analyses

Fragment masses, and position and velocity vectors from SPHC provide input to fragment propagation tool (DebProp)



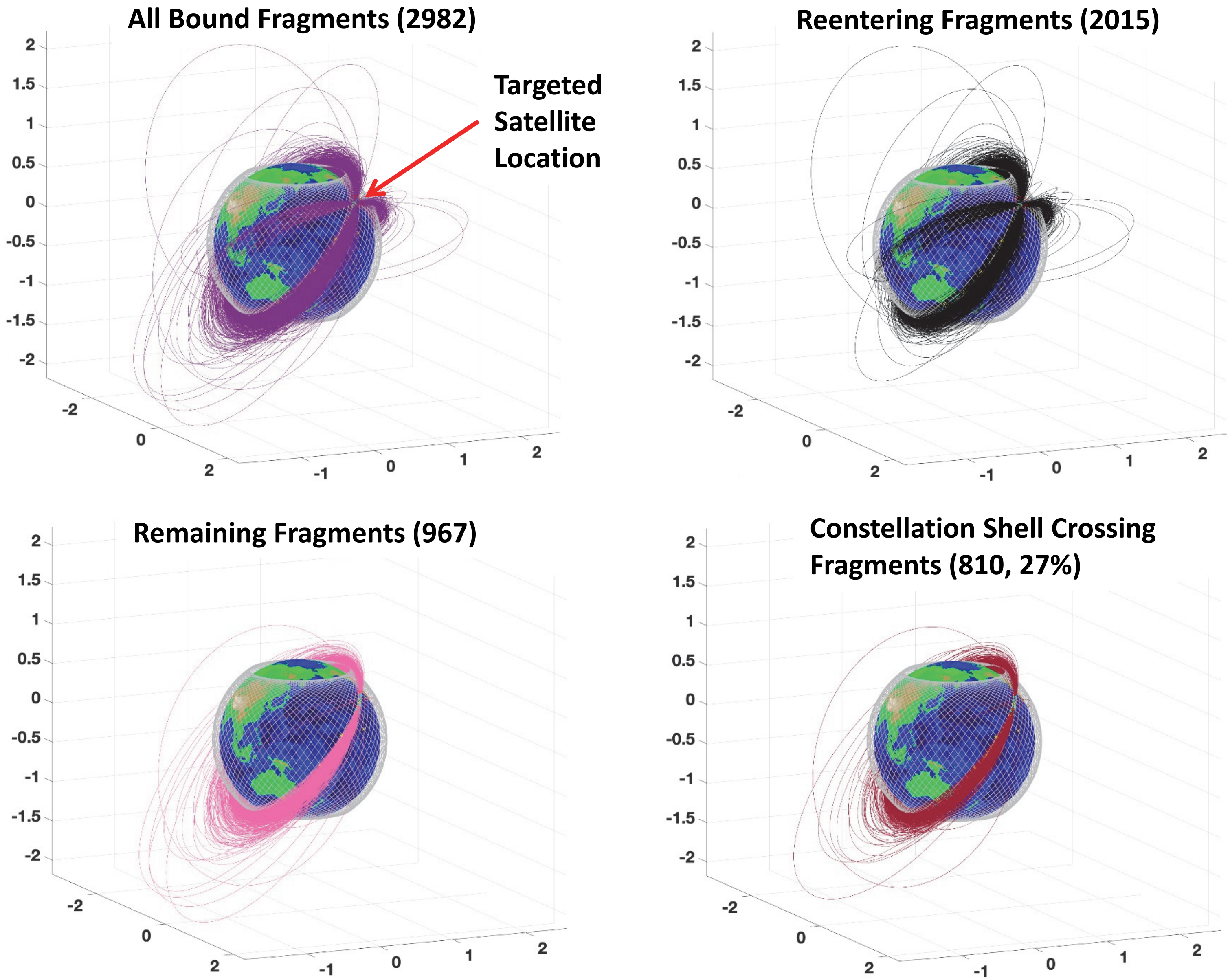


Many high-speed fragments are interceptor fragments



Crossing fragments are ejected in lateral and along track directions with lower relative speeds

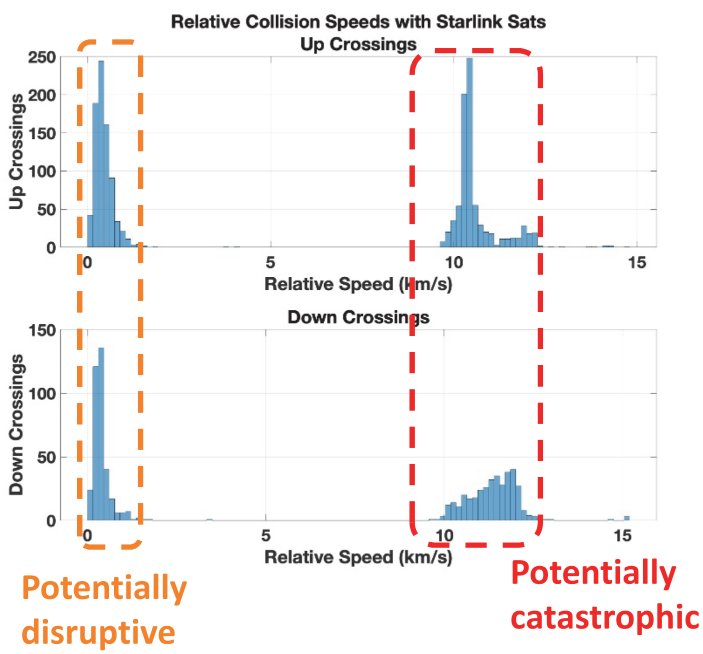
DebProp predicts where each debris fragment goes

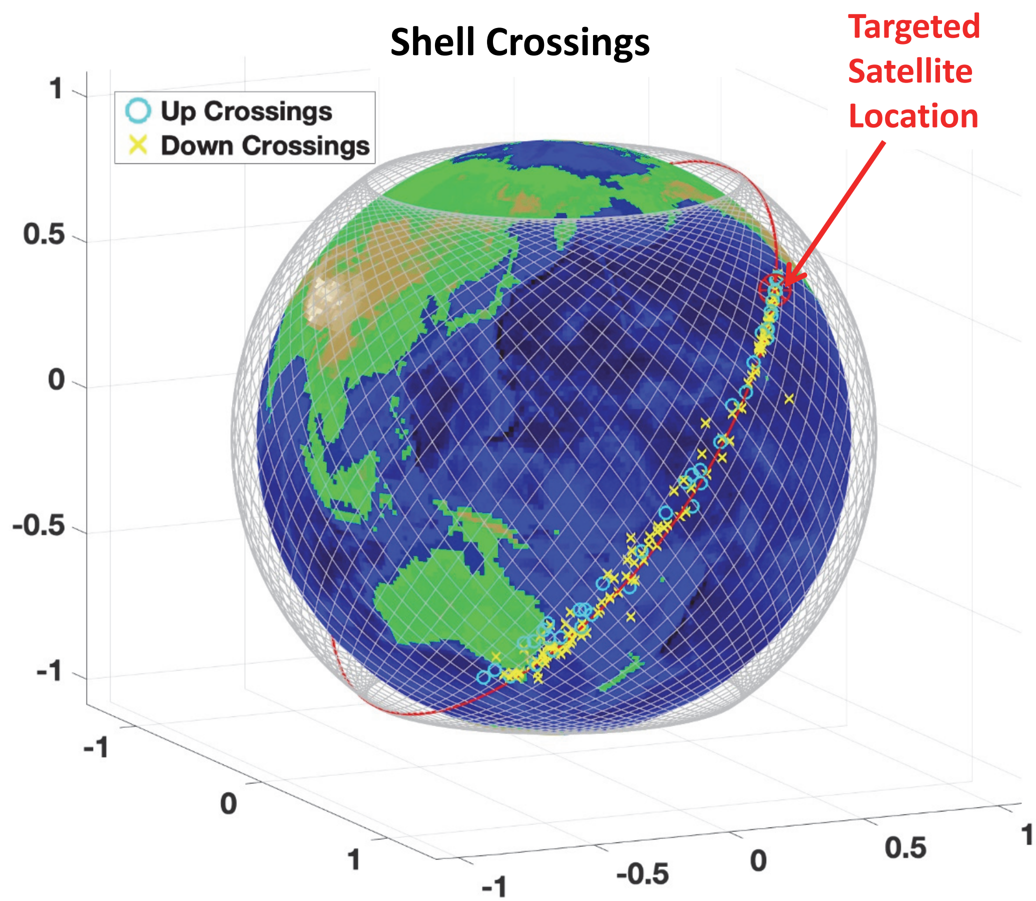


The debris is a threat to other Starlink satellites within the constellation

Fragments can cross the 550 km constellation shell either from above or from below

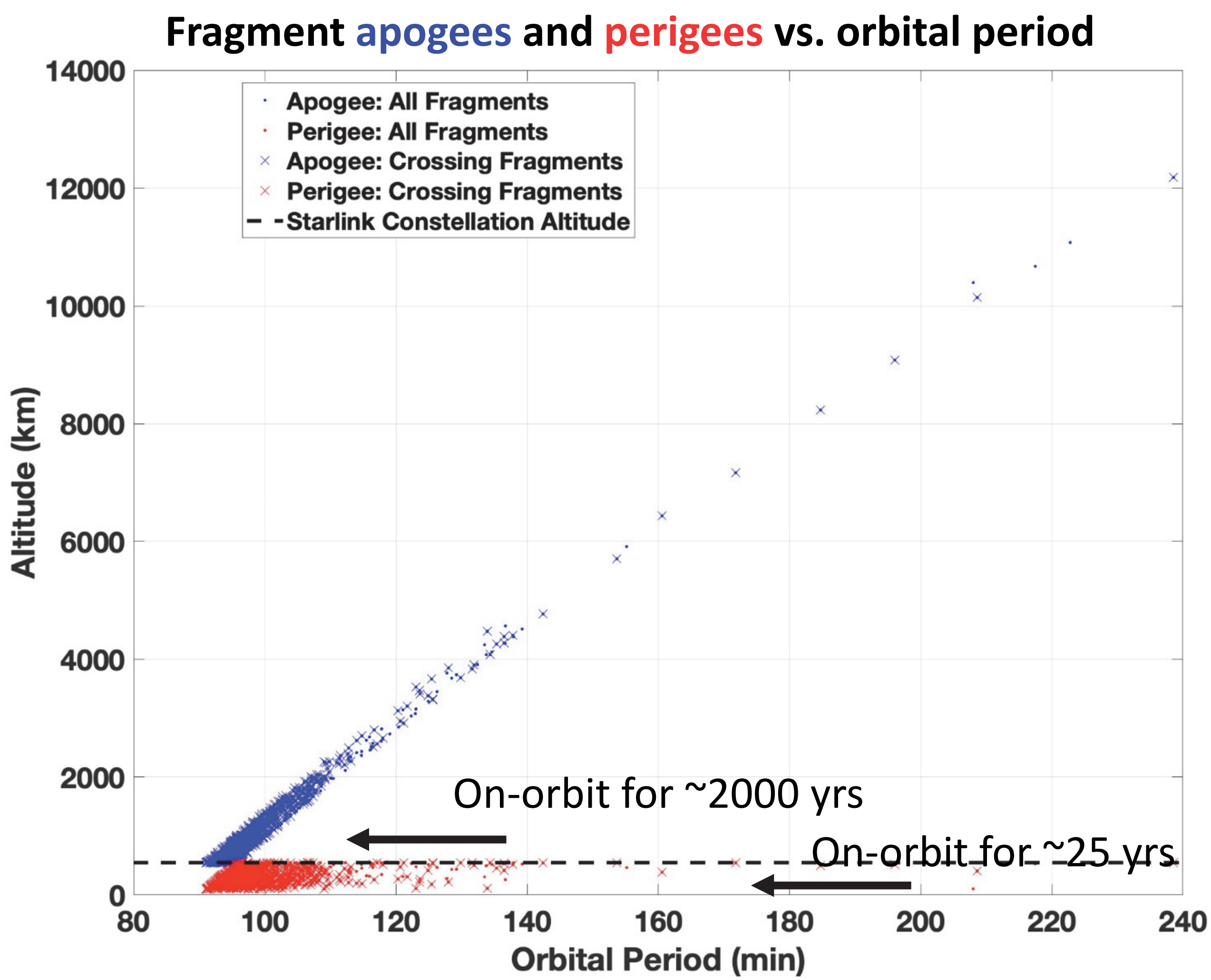
If there is a Starlink satellite at the location of a crossing, there are two possible relative collision velocities:
low for a receding satellite
high for an approaching satellite





Crossings are concentrated along the orbit of the targeted Starlink sat

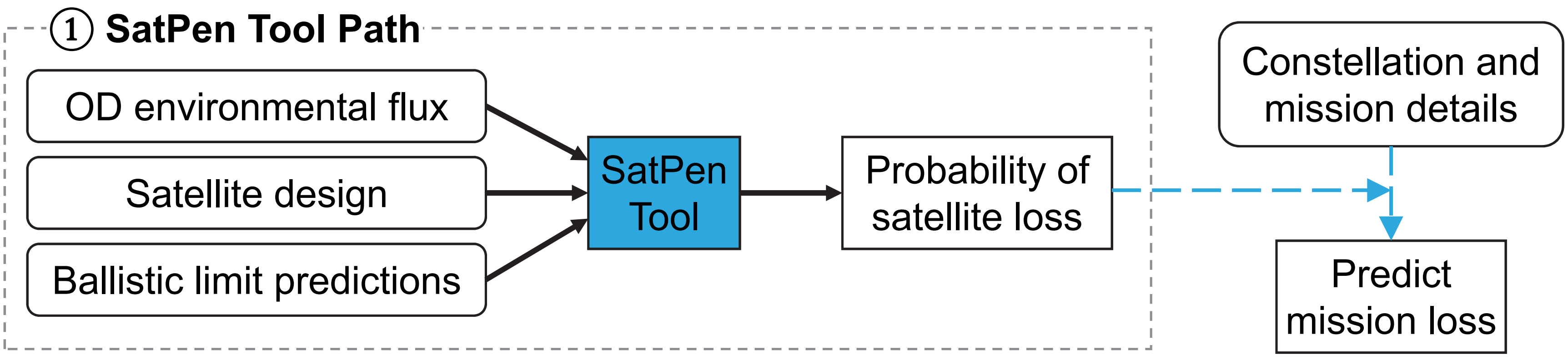
Debris from ASAT impact is a threat to non-Starlink operational satellites and has the potential to impact other "dead" objects, creating more debris



Starlink fragments are lofted to apogees as high as 12,000 km altitude and could be there for *1000s of years*

IDA

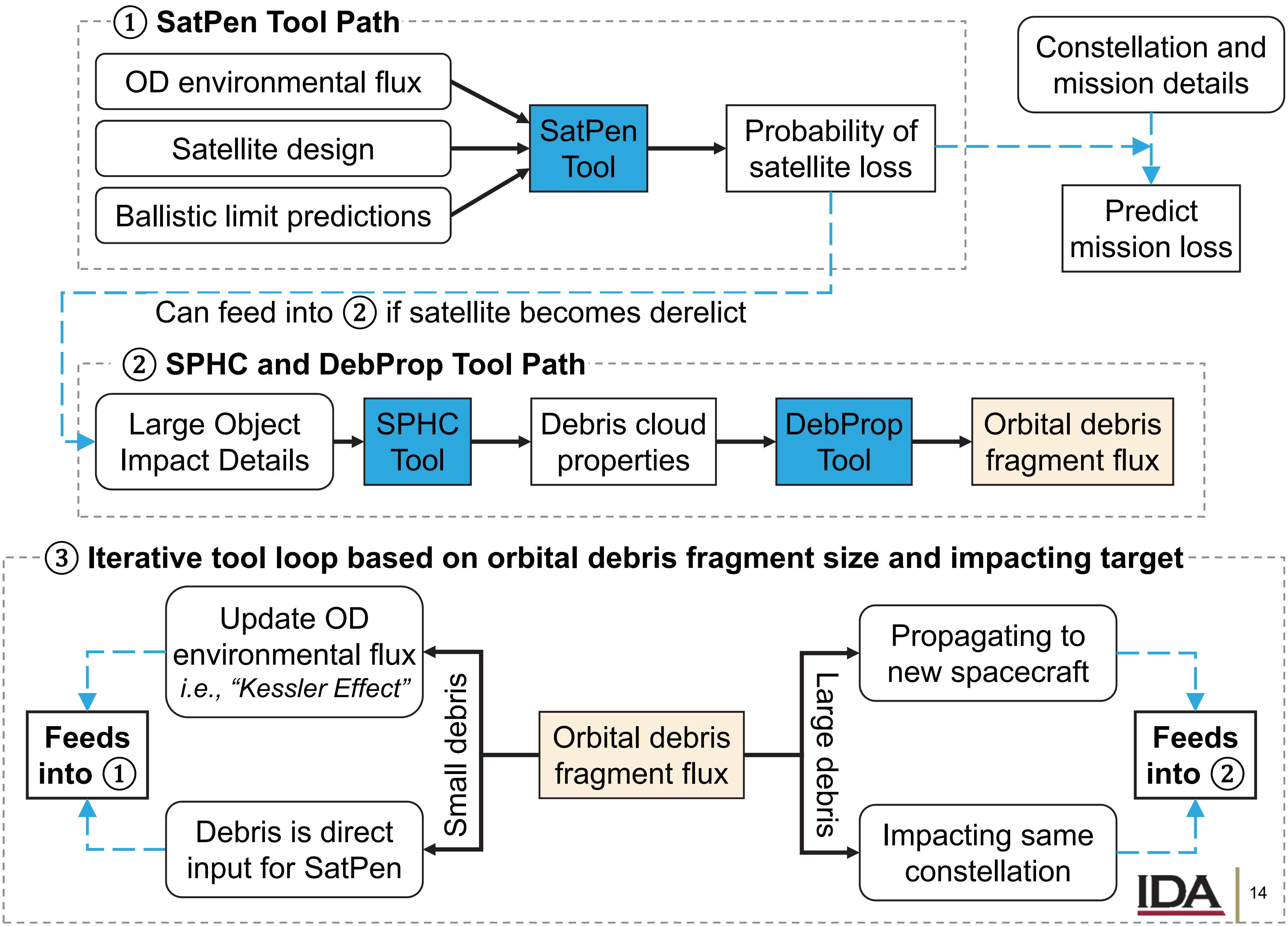
In case you weren't at the previous talk, IDA also developed a tool for debris penetration called SatPen



SatPen can be used iteratively with SPHC and DebProp to study a cascade of orbital debris impacts (the Kessler Effect).

OD – Orbital Debris; SPHC – Smooth Particle Hydrodynamics Code

IDA's tools can be combined to examine a variety of orbital impact scenarios



OD – Orbital Debris; SPHC – Smooth Particle Hydrodynamics Code

Backup

Abstract

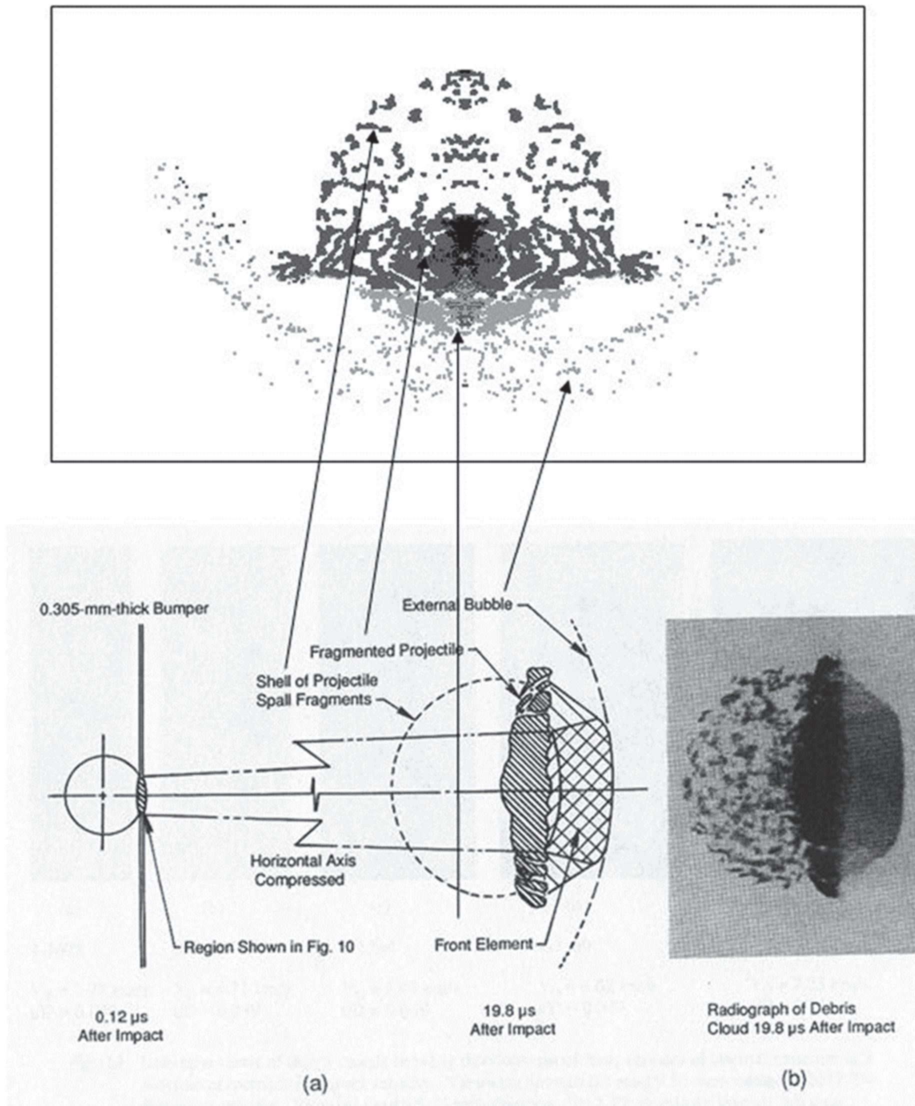
Based on observations gathered from the IDA Forum on Orbital Debris (OD) Risks and Challenges (October 8-9, 2020), DOT&E needed first-order predictive tools to evaluate the effects of orbital debris on mission risk, catastrophic collision, and collateral damage to DOD spacecraft and other orbital assets – either from unintentional or intentional [Anti-Satellite (ASAT)] collisions. This lack of modeling capability hindered DOT&E's ability to evaluate the risk to operational effectiveness and survivability of individual satellites and large constellations, as well as risks to the overall use of space assets in the future.

This presentation describes an IDA-derived technique (DebProp) to evaluate the debris propagating effects of large, trackable debris (>5 cm) or anti-satellite weapons colliding with satellites within constellations. IDA researchers used a Starlink-like satellite as a case study and worked with Stellingwerf Associates to modify the Smooth Particle Hydrodynamic Code (SPHC). The result is a file format that is readable as an input file for predicting orbital stability or debris re-entry for thousands of created particles, and predict additional, short-term OD-induced losses to other satellites in the constellation. By pairing this technique with SatPen (an Excel-based tool for determining the probability and mission effects of >1mm OD impacts and penetration on individual satellites with ORDEM 3.1 as an input, supplemented with typical damage prediction equations to support mission loss predictions), IDA can conduct long-term debris growth studies).

SPHC is a thoroughly vetted tool

- Developed at Los Alamos National Labs; technique in use for 30 years to examine fragments following hypervelocity impacts
- Used by Williamsen/Evans in a wide variety of OED studies for NASA; developed by Stellingwerf (formerly LANL, now IDA consultant)
- Produces comparable results to other collision tools used by NASA as well as light gas gun tests (validation case at right)
- Migrating use of this code into IDA with help of Stellingwerf/Evans for ongoing work of this nature

SPHC Run
9.8 mm AL Sphere, 6.8 km/sec



The spalled material, as well as the liquid frontal volume are clearly visible in each case, and the agreement between model and experiment is excellent.

UDRI Test Case
4-1360,
6.8 km/sec

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION

1. REPORT DATE	**2. REPORT TYPE**	**3. DATES COVERED** START DATE	END DATE
XX-04-2022	Draft Final		Apr 2022

4. TITLE AND SUBTITLE
DATAWorks 2022: DebProp: Orbital Debris Collision Effects Prediction Tool for Satellite Constellations Created By: Williamsen, Joel E 1/11/2022 10:38:43 AM

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER**
Separate Contract		
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**
C9108	C9108	

6. AUTHOR(S)
Williamsen, Joel, E.; Heagy, James, F.; Pechkis, Daniel, L.; Evans, Steven, W.; Stellingwerf, Robert, F.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Institute for Defense Analyses 4850 Mark Center Drive Alexandria, Virginia 22311-1882	NS D-32942 H 2022-000011

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**	**11. SPONSOR/MONITOR'S REPORT NUMBER**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Public release approved. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Based on observations gathered from the IDA Forum on Orbital Debris (OD) Risks and Challenges (October 8-9, 2020), DOT&E needed first order predictive tools to evaluate the effects of orbital debris on mission risk, catastrophic collision, and collateral damage to DoD spacecraft and other orbital assets – either from unintentional or intentional [Anti-Satellite (ASAT)] collisions. This lack of modeling capability hindered the ability of DOT&E to evaluate the risk to operational effectiveness and survivability of individual satellites and large constellations, as well as risks to the overall use of space assets in the future.

This presentation describes an IDA-derived Excel-based tool (SatPen) for determining the probability and mission effects of >1mm orbital debris impacts and penetration on individual satellites in low Earth orbit (LEO). Using a Starlink-like satellite as a case study and NASA's ORDEM 3.1 orbital debris environment as an input, supplemented with typical damage prediction equations to support mission loss predictions, IDA estimated the likelihood of satellite mission loss. By pairing this technique with DebProp (another IDA tool described at this forum for evaluating the debris propagating effects of large, trackable debris or antisatellite weapons colliding with satellites within constellations), IDA can predict additional, short term OD induced losses to other satellites in the constellation, and conduct long-term debris growth studies.

15. SUBJECT TERMS
orbital debris; spacecraft protection

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
Unclassified	Unclassified	Unclassified	SAR	27

19a. NAME OF RESPONSIBLE PERSON	**19b. PHONE NUMBER**
Joel Williamsen	703-578-2705