Analytic Space Domain Awareness

Darren McKnight, Erin Dale, Chris Gates, Owen Marshall, Rachit Bhatia, Mohin Patel, and Adam Marsh
LeoLabs

Abstract

Space domain awareness (SDA) is the “identification, characterization and understanding of any factor, passive or active, associated with the space domain that could affect space operations and thereby impact the security, safety, economy or environment of our nation.”[1] While the metric observations of tracking and monitoring are essential for characterizing patterns of life and anomalistic behavior, non-metric data helps to unlock more subtle but potentially more important operational features.

The rich corpus of data generated from the persistent surveillance and capture of metric data provides the foundation for a new generation set of SDA tools. The LeoLabs tracking & monitoring (T&M) service and a suite of analytic tools provide foundational insights for enduring space safety and space behavior awareness to prevent surprise in space. The LeoLabs T&M service will be shown how it contributes to SDA by characterizing non-physical interactions between space systems.

The fragmentation of Cosmos 1408 will be used to illustrate the functionality of the three standalone analytic tools (LeoMap, LeoCat, and LeoBreakup). These three analytic assessment dimensions create a coherent, mutually supportive means to leverage tracking & monitoring data to not only prevent strategic and environmental surprise in space but also provide predictive and forensics insights.

1. MOTIVATION

The term space situational awareness (SSA) has morphed for non-commercial applications into space domain awareness (SDA). However, the key is more about what problems these solutions, techniques, and services solve. As such, LeoLabs recently tried to add clarity to this dialogue by adding yet another term – space behavior awareness. Being aware that a new term may not be the best way to rally a community to be more precise, we are doubling down on this term as being more useful as it starts to hint at problems that we are trying to solve; we are trying to understand how space objects behave through superior object custody to prevent surprise in space as indicated in Fig. 1.

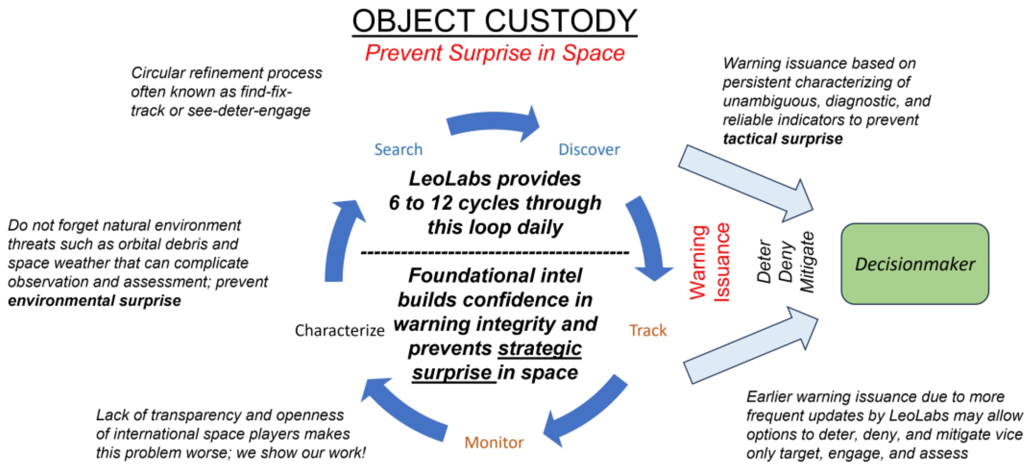


Fig. 1. Object custody provides a means to prevent surprise in space – environmental, tactical, and strategic.

---

[1] Air Force: SSA is no more; it’s ’Space Domain Awareness’ - SpaceNews

SDA is all about preventing conflict through timely warning issuances based on persistent surveillance of high interest objects. By achieving revisit rates of 6 to 12 times a day, warning issuance may enable the use of deterrence, denial, and threat mitigation measures to counter threats potentially obviating the need to target, engage, and assess. These benefits are realized by our awareness of the factors that lead to strategic, tactical, and environmental surprise in space. More importantly, we facilitate the handoff between these three "domains of surprise".

2. LEVERAGING COMMERCIAL SDA SERVICES AT SCALE

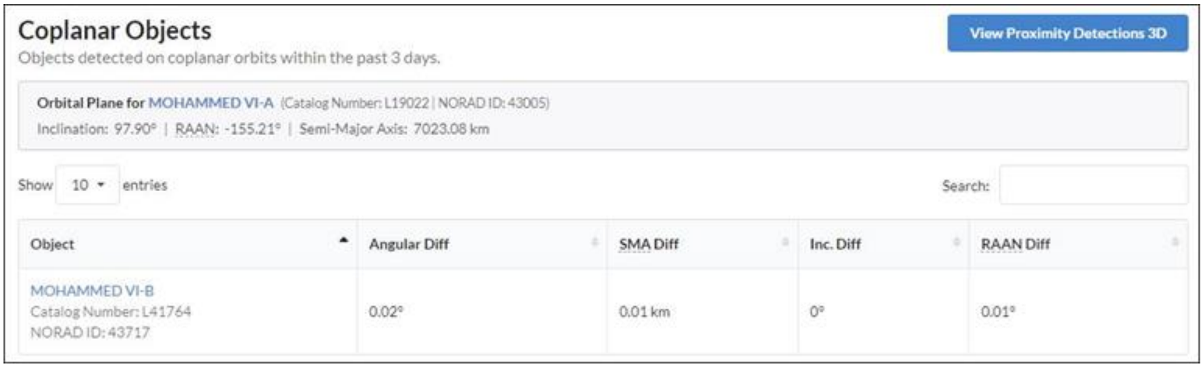
LeoLabs is part of a rapidly growing US commercial SDA capability. Our proliferated system and high-volume approach provide a "basemap" upon which other technologies and services can build to address unique problems. Leveraging LeoLabs' rich data set in combination with other systems can reveal novel insights and enable space behavior awareness.

Note: the following vignette is comprised of both real and simulated data, each clearly identified. The simulated data is meant to be realistic, but intentionally lacks detail for brevity.

The Mohammed VI-A and Mohammed VI-B satellites are Moroccan Earth observation and reconnaissance satellites launched in November 2017 and 2018, respectively. They are based on a common commercial satellite bus, so what makes them interesting? Utilizing LeoLabs' dense data set and advanced algorithms allows analysts to gain operational insights that may not be available without persistent, global coverage.

<u>Relative orbits</u> [source: LeoLabs tracking data]

Mohammed VI-A/B are in nearly identical orbits, as shown in Fig. 2, but 180° out of phase (see Fig. 3).



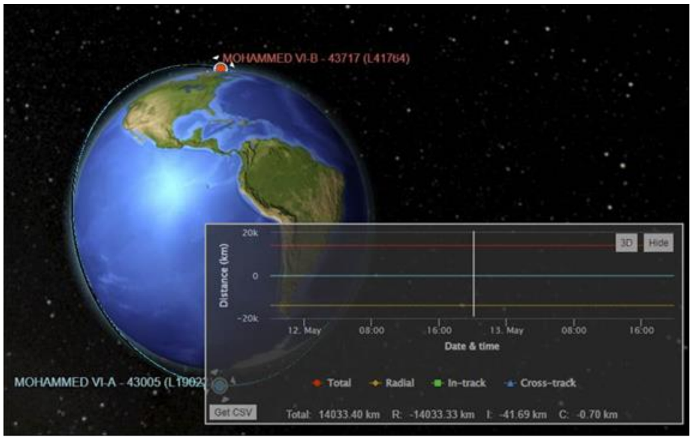
Coplanar Objects

Objects detected on coplanar orbits within the past 3 days.

Orbital Plane for MOHAMMED VI-A (Catalog Number: L19022 | NORAD ID: 43005)
Inclination: 97.90° | RAAN: -155.21° | Semi-Major Axis: 7023.08 km

Object	Angular Diff	SMA Diff	Inc. Diff	RAAN Diff
MOHAMMED VI-B Catalog Number: L41764 NORAD ID: 43717	0.02°	0.01 km	0°	0.01°

Fig. 2. LeoLabs co-planar analysis of Mohammed VI



Total: 14033.40 km R: -14033.33 km I: -41.69 km C: -0.70 km

Fig. 3. Mohammed VI phasing

<u>Orbital maintenance sequencing</u> [source: LeoLabs maneuver detection]

They perform frequent station keeping maneuvers, maintaining their sun-synchronous 640 km orbits. This is noteworthy as it indicates common and repeatable operations for both satellites as a constellation. LeoLabs monitors the satellite pair with a revisit rate of 7 to 8 passes per day. This data, when evaluated in conjunction with a reliable maneuver characterization model, can illuminate patterns of operational life. Utilizing this method LeoLabs assesses that both satellites are performing orbital maintenance burns with a periodic and predictable behavior.

Figures 4 and 5 present orbital elements over the same week for each satellite, with potential changes based on measurement residuals represented by vertical dashed lines. Note that maneuver campaigns for each satellite appear to be performed serially during this time.

Fig. 4. Potential orbit changes for Mohammed VI-A

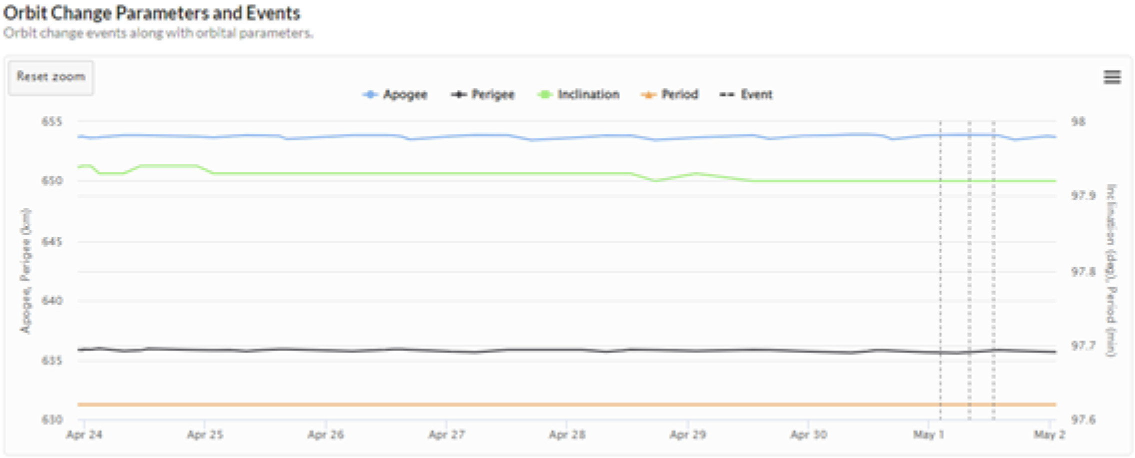


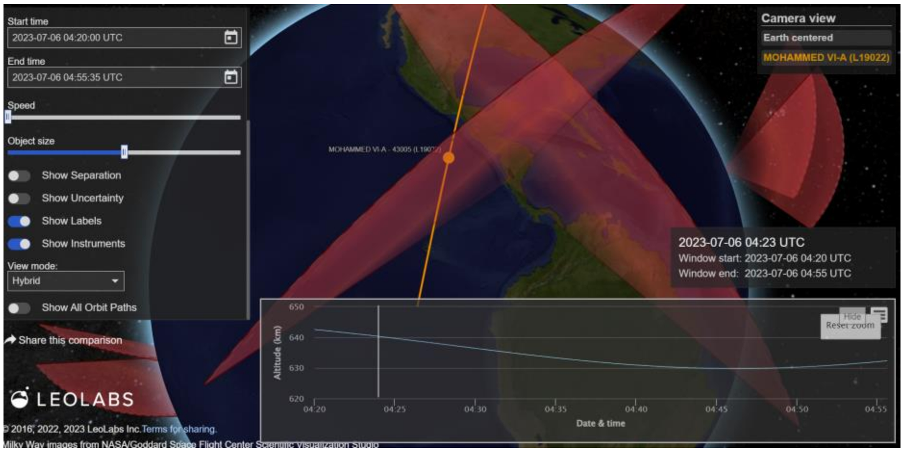
Fig. 5. Potential orbit changes for Mohammed VI-B

This information may be indicative of the operational capacity of the Moroccan space operations team. It is possible that the team is only capable of performing single maneuver campaigns for technical reasons such as ground infrastructure constraints. Another reason could be their risk tolerance, choosing not to overlap maneuvers in case anomalies need to be addressed. Or, they may only have the staffing available to support single maneuvers during normal operating hours.

While no definitive understanding of Moroccan operations can be determined with only this information, an analyst may be able to begin to draw an understanding of operational capability which, paired with further context, may result in deeper insights.

Maneuver timing [source: LeoLabs tracking data and open sources]

Let’s examine a single maneuver for one of the satellites. LeoLabs data indicates a potential orbit change for this vehicle at 2023-07-06 05:59UTC and generated a new state vector with 15 m RMS uncertainty just prior to this at 2023-07-06 04:22 UTC. At this time, it was located over the west coast of South America with no line of sight to Morocco, as illustrated in Fig. 6.



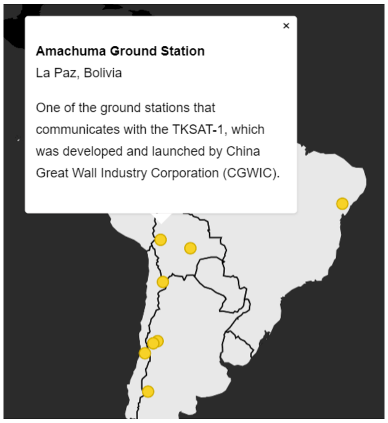
Start time 2023-07-06 04:20:00 UTC
End time 2023-07-06 04:55:35 UTC
○ Show Separation
○ Show Uncertainty
● Show Labels
● Show Instruments
View mode: Hybrid
○ Show All Orbit Paths

2023-07-06 04:23 UTC
Window start: 2023-07-06 04:20 UTC
Window end: 2023-07-06 04:55 UTC

Fig. 6. Mohammed VI-A location during potential maneuver

This information allows for several theories of the Moroccan concept of operations (CONOPS). Three distinct possibilities, assuming no knowledge of actual command & control (C2) links, are:

1. They only have a C2 link in Morocco. This may indicate that the Mohammed VI satellites are capable of storing and executing maneuver plans without direct access to a C2 link and maneuvers are performed out of view.
2. A ground station in the Americas is utilized for direct C2. China, for example, has significant space infrastructure in South America, with several ground assets illustrated in Fig. 7.



Amachuma Ground Station
La Paz, Bolivia

One of the ground stations that communicates with the TKSAT-1, which was developed and launched by China Great Wall Industry Corporation (CGWIC).

Fig. 7 Ground stations in South America utilized by China[2]

3. The Mohammed VI satellites are capable of crosslink communications with non-Moroccan satellites.

---

[2] Center for Strategic and International Studies, Hidden Reach Issue No. 1 https://features.csis.org/hiddenreach/china-ground-stations-space/

As indicated in Fig. 7, the Bolivian geosynchronous communications satellite TKSAT-1 downlinks to this region. China Satellite Launch & Tracking Control General (CLTC) is responsible for the ground segment[3]. Additionally, Tianlian-1 is a relay satellite operated by China[4], with a line of site to Mohammed VI-A during this part of its orbit, as depicted in Fig. 8.

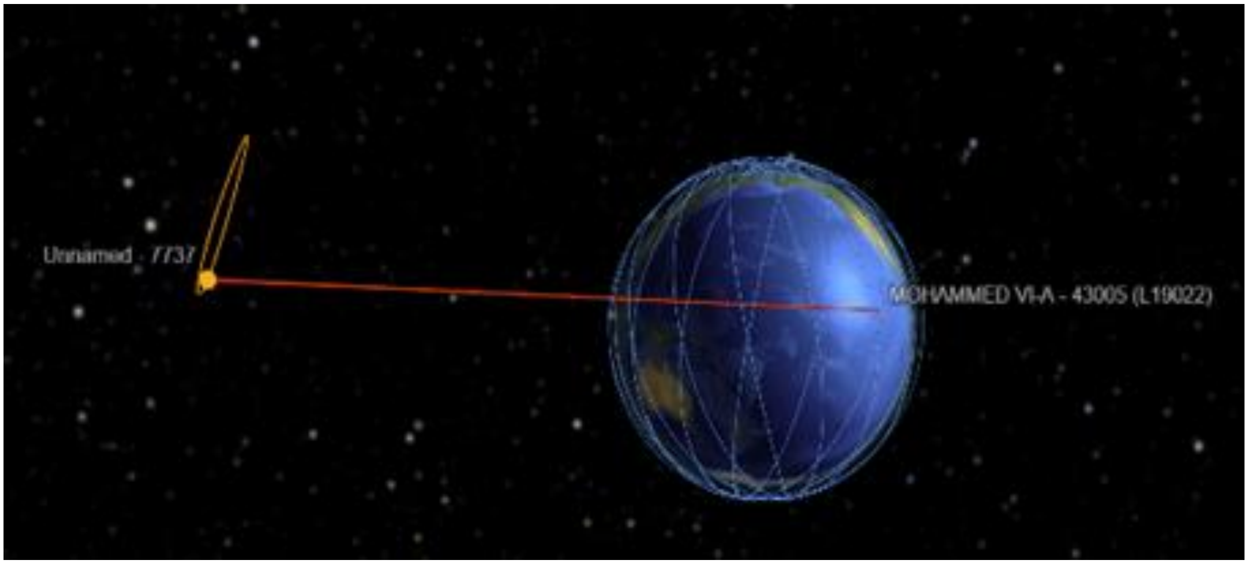


Fig. 8 Line of sight (red) between Tianlian-1 and Mohammed VI-A during maneuver

<u>Maneuver command and control</u> [source: open source and notional commercial data]

This brief investigation is nowhere near exhaustive and meant to only introduce some of the possible analytical threads that can be pursued to establish understanding of space behaviors and capabilities using commercial SDA. For this vignette, several different analyses could be performed to gain a more complete picture:

1. Commercial SAR imagery could be used to inspect suspected ground stations for tracking of Mohammed VI-A/B.
2. Optical and RF uplink and downlink analysis could be performed to identify associated telemetry, tracking, & control (TT&C) links and determine what level of support other assets (e.g., GEO satellites) may be providing.
    a. Imagery of satellites involved may provide pointing knowledge.
3. Ownership and connectivity between satellite developers, owner/operators, and ground station operators can be open sourced to identify interesting relationships (e.g., political, industrial, etc.).
4. Iterating over a period of time, vice the single snapshot presented here, can discern a pattern of life based on maneuvering and eliminate erroneous assumptions and associations made.

The real-time space behavior awareness vignette just reviewed highlights the utility of a real-time assessment of temporal, spatial, and geographic features. However, to truly ascertain the importance of this information this behavior can be compared to the ensemble of data collected by LeoLabs for all objects in low Earth orbit (LEO) and accessed through the LeoLabs analytic tool suite.

---

[3] https://space.skyrocket.de/doc_sdat/tupak-katari-1.htm
[4] https://space.skyrocket.de/doc_sdat/tl-1.htm

3. ANALYTIC TOOL SUITE

LeoLabs' four analytic tools work in harmony to provide forensic, diagnostic, and predictive space behavior awareness as well as life cycle space safety services. They use historical data that is consistently updated data from LeoLabs' global network of phased array radars to provide the most accurate and complete information. The main uses of the analytic tools are for planning space missions and providing context of the space environment to operators. The four tools LeoLabs uses to achieve these goals are LeoCat, LeoMap, LeoRisk, and LeoBreakup.

LeoCat examines the makeup of the current satellite catalog. It uses the same catalog as the 18th Space Defense Squadron (SDS) for consistency. Fragment clouds, which comprise more than 60% of the LEO catalog, are further decomposed by examining the total number of fragments created by breakup, the remaining fragments on orbit, the cause of each event, and country of origin. LeoCat has the least novel data but provides some of the most relevant insights for this paper. By stratifying the catalog by country, object type, inclination, and more, LeoCat allows the user to extract inferences that are otherwise hard to see. LeoCat also illustrates the breakdown of the catalog by country and object type, "spike plots" of the spatial or mass density of objects across LEO, metrics on fragment clouds, and features of orbital capacity.

Fig. 9. LeoLabs analytic tools provide life cycle space safety services.

LeoMap identifies and examines dangerous objects and orbits by their debris-generating potential. LeoLabs issues Conjunction Data Messages (CDMs) identifying encounters between two objects and displays the probability of collision (PC) at the time when the objects are closest (i.e., time of closest approach, TCA). LeoMap analyzes conjunctions with high PC broken down by type of object, country, number of times an object has had a conjunction with a certain threshold, and risk (i.e., PC x mass involved). This helps identify which objects pose the greatest collision risk and which are exposed to the greatest collision risk. It also permits identification of targets for active debris removal (ADR), quantification of effects of fragment clouds, and focuses space traffic management (STM) efforts. LeoMap is unique because it is built on CDM data only LeoLabs can produce. LeoLabs tags all intact objects with mass to enable calculations of risk which further differentiates LeoMap.

LeoRisk determines the statistical PC between any existing or hypothetical object or constellation against the current landscape of trackable and lethal nontrackable (LNT) objects. It allows the user to determine what would happen if an object was launched or resided in an orbit and the effect on it from likely fragmentation events in LEO. Characteristics of the constellation and the evolving collision hazard can be modified to examine operational tradeoffs. LeoRisk is useful for determining constellation architecture, what would happen without collision avoidance capabilities, and setting space insurance rates. LeoRisk uses ESA's Meteoroid And Space Debris Terrestrial Environment Reference (MASTER) to depict LNT population.[5] LeoRisk will not be further discussed in

---

[5] McKnight, D.; Dale, E., Patel, M.; and Kunstadter, C., "Modeling Empirical Orbital Capacity," Space capacity allocation for the sustainability of space activities" Workshop, Milan, June 2023.

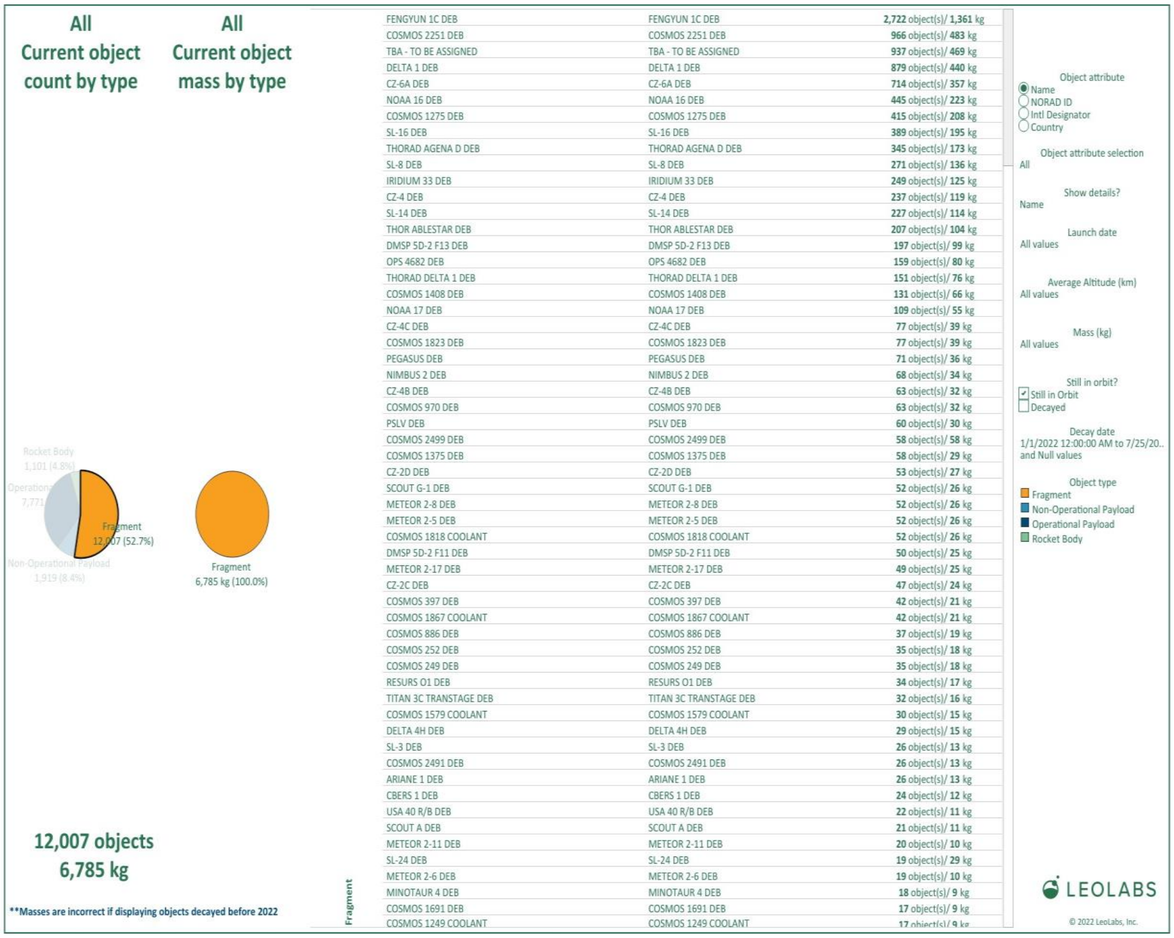
this paper as it has limited contribution to SDA but it is vitally critical for constellation mission design and space safety.

LeoBreakup determines the cause of breakup events by analyzing the initial object and the resulting fragment cloud. LeoLabs uses 40 years of hypervelocity impact phenomenology and anomaly attribution experience to inform its algorithms. The cause of a breakup event is essential in space debris mitigation because it informs the operator and the community what to avoid in designing and operating systems in space and provides forensic insights to be used in preventing future breakup events. The breakup cause is determined by answering a series of logic and scientific questions to assemble evidence in discerning the likely cause of the breakup between low intensity explosion, high intensity explosion, low intensity (i.e., non-catastrophic, non-hypervelocity) collision, and high intensity (i.e., catastrophic, hypervelocity) collision.

The three SDA-related analytic tools will be reviewed with the examination of the fragmentation of Cosmos 1408 as a common thread of analysis.

LeoCat

Cosmos 1408 fragmented on November 15, 2021, as the result of a direct ascent ASAT test conducted by Russia. Eventually a total of ~1,800 fragments were cataloged and monitored by the 18th SDS and LeoLabs but LeoCat shows that as of 31 July 2023 only ~130 fragments remained in orbit from the event as shown in Fig. 10.



All Current object count by type

All Current object mass by type

12,007 objects
6,785 kg

****Masses are incorrect if displaying objects decayed before 2022**

FENGYUN 1C DEB	FENGYUN 1C DEB	**2,722** object(s)/ **1,361** kg
COSMOS 2251 DEB	COSMOS 2251 DEB	**966** object(s)/ **483** kg
TBA - TO BE ASSIGNED	TBA - TO BE ASSIGNED	**937** object(s)/ **469** kg
DELTA 1 DEB	DELTA 1 DEB	**879** object(s)/ **440** kg
CZ-6A DEB	CZ-6A DEB	**714** object(s)/ **357** kg
NOAA 16 DEB	NOAA 16 DEB	**445** object(s)/ **223** kg
COSMOS 1275 DEB	COSMOS 1275 DEB	**415** object(s)/ **208** kg
SL-16 DEB	SL-16 DEB	**389** object(s)/ **195** kg
THORAD AGENA D DEB	THORAD AGENA D DEB	**345** object(s)/ **173** kg
SL-8 DEB	SL-8 DEB	**271** object(s)/ **136** kg
IRIDIUM 33 DEB	IRIDIUM 33 DEB	**249** object(s)/ **125** kg
CZ-4 DEB	CZ-4 DEB	**237** object(s)/ **119** kg
SL-14 DEB	SL-14 DEB	**227** object(s)/ **114** kg
THOR ABLESTAR DEB	THOR ABLESTAR DEB	**207** object(s)/ **104** kg
DMSP 5D-2 F13 DEB	DMSP 5D-2 F13 DEB	**197** object(s)/ **99** kg
OPS 4682 DEB	OPS 4682 DEB	**159** object(s)/ **80** kg
THORAD DELTA 1 DEB	THORAD DELTA 1 DEB	**151** object(s)/ **76** kg
COSMOS 1408 DEB	COSMOS 1408 DEB	**131** object(s)/ **66** kg
NOAA 17 DEB	NOAA 17 DEB	**109** object(s)/ **55** kg
CZ-4C DEB	CZ-4C DEB	**77** object(s)/ **39** kg
COSMOS 1823 DEB	COSMOS 1823 DEB	**77** object(s)/ **39** kg
PEGASUS DEB	PEGASUS DEB	**71** object(s)/ **36** kg
NIMBUS 2 DEB	NIMBUS 2 DEB	**68** object(s)/ **34** kg
CZ-4B DEB	CZ-4B DEB	**63** object(s)/ **32** kg
COSMOS 970 DEB	COSMOS 970 DEB	**63** object(s)/ **32** kg
PSLV DEB	PSLV DEB	**60** object(s)/ **30** kg
COSMOS 2499 DEB	COSMOS 2499 DEB	**58** object(s)/ **58** kg
COSMOS 1375 DEB	COSMOS 1375 DEB	**58** object(s)/ **29** kg
CZ-2D DEB	CZ-2D DEB	**53** object(s)/ **27** kg
SCOUT G-1 DEB	SCOUT G-1 DEB	**52** object(s)/ **26** kg
METEOR 2-8 DEB	METEOR 2-8 DEB	**52** object(s)/ **26** kg
METEOR 2-5 DEB	METEOR 2-5 DEB	**52** object(s)/ **26** kg
COSMOS 1818 COOLANT	COSMOS 1818 COOLANT	**52** object(s)/ **26** kg
DMSP 5D-2 F11 DEB	DMSP 5D-2 F11 DEB	**50** object(s)/ **25** kg
METEOR 2-17 DEB	METEOR 2-17 DEB	**49** object(s)/ **25** kg
CZ-2C DEB	CZ-2C DEB	**47** object(s)/ **24** kg
COSMOS 397 DEB	COSMOS 397 DEB	**42** object(s)/ **21** kg
COSMOS 1867 COOLANT	COSMOS 1867 COOLANT	**42** object(s)/ **21** kg
COSMOS 886 DEB	COSMOS 886 DEB	**37** object(s)/ **19** kg
COSMOS 252 DEB	COSMOS 252 DEB	**35** object(s)/ **18** kg
COSMOS 249 DEB	COSMOS 249 DEB	**35** object(s)/ **18** kg
RESURS O1 DEB	RESURS O1 DEB	**34** object(s)/ **17** kg
TITAN 3C TRANSTAGE DEB	TITAN 3C TRANSTAGE DEB	**32** object(s)/ **16** kg
COSMOS 1579 COOLANT	COSMOS 1579 COOLANT	**30** object(s)/ **15** kg
DELTA 4H DEB	DELTA 4H DEB	**29** object(s)/ **15** kg
SL-3 DEB	SL-3 DEB	**26** object(s)/ **13** kg
COSMOS 2491 DEB	COSMOS 2491 DEB	**26** object(s)/ **13** kg
ARIANE 1 DEB	ARIANE 1 DEB	**26** object(s)/ **13** kg
CBERS 1 DEB	CBERS 1 DEB	**24** object(s)/ **12** kg
USA 40 R/B DEB	USA 40 R/B DEB	**22** object(s)/ **11** kg
SCOUT A DEB	SCOUT A DEB	**21** object(s)/ **11** kg
METEOR 2-11 DEB	METEOR 2-11 DEB	**20** object(s)/ **10** kg
SL-24 DEB	SL-24 DEB	**19** object(s)/ **29** kg
METEOR 2-6 DEB	METEOR 2-6 DEB	**19** object(s)/ **10** kg
MINOTAUR 4 DEB	MINOTAUR 4 DEB	**18** object(s)/ **9** kg
COSMOS 1691 DEB	COSMOS 1691 DEB	**17** object(s)/ **9** kg
COSMOS 1249 COOLANT	COSMOS 1249 COOLANT	**17** object(s)/ **9** kg

Object attribute
● Name
○ NORAD ID
○ Intl Designator
○ Country

Object attribute selection
All

Show details?
Name

Launch date
All values

Average Altitude (km)
All values

Mass (kg)
All values

Still in orbit?
☑ Still in Orbit
☐ Decayed

Decay date
1/1/2022 12:00:00 AM to 7/25/20..
and Null values

Object type
🟧 Fragment
🟦 Non-Operational Payload
🟦 Operational Payload
🟩 Rocket Body

Fig. 10. Of the 12,007 fragments in LEO as of 31 July 2023, only ~130 remained from the ~1,800 liberated in November 2021 from the Cosmos 1408 ASAT test.

The “spike plot” of the remaining fragments from Cosmos 1408 (i.e., spatial density, SPD, as a function of altitude) shows the peak value has dropped in intensity and location since the breakup event; see Fig. 11 (left panel is immediately after the event and right panel is as of 1 August 2023). The current peak SPD of 1.5E-9 at 440 km is down from 2.4E-8 at 480 km immediately after the event (reduced by a factor of 16 and peak 40 km lower in altitude).

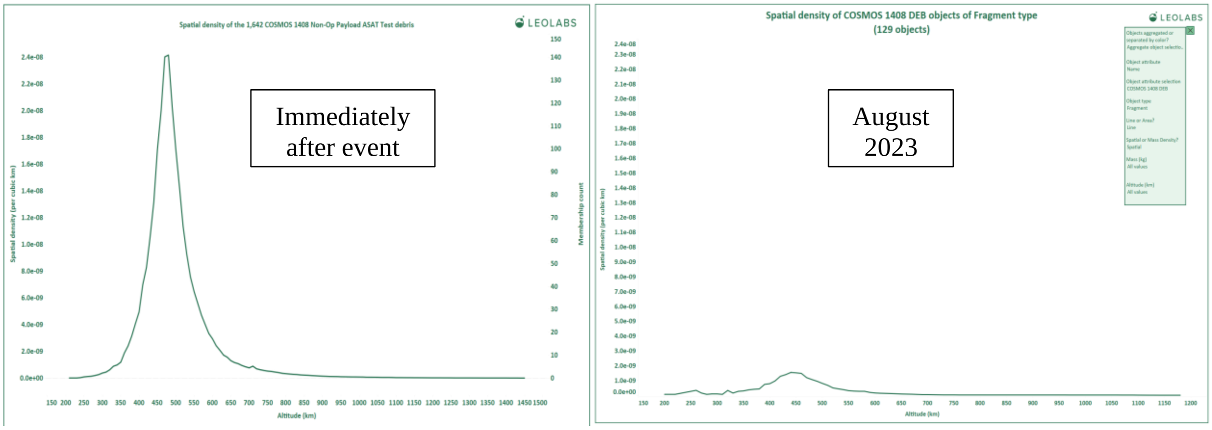
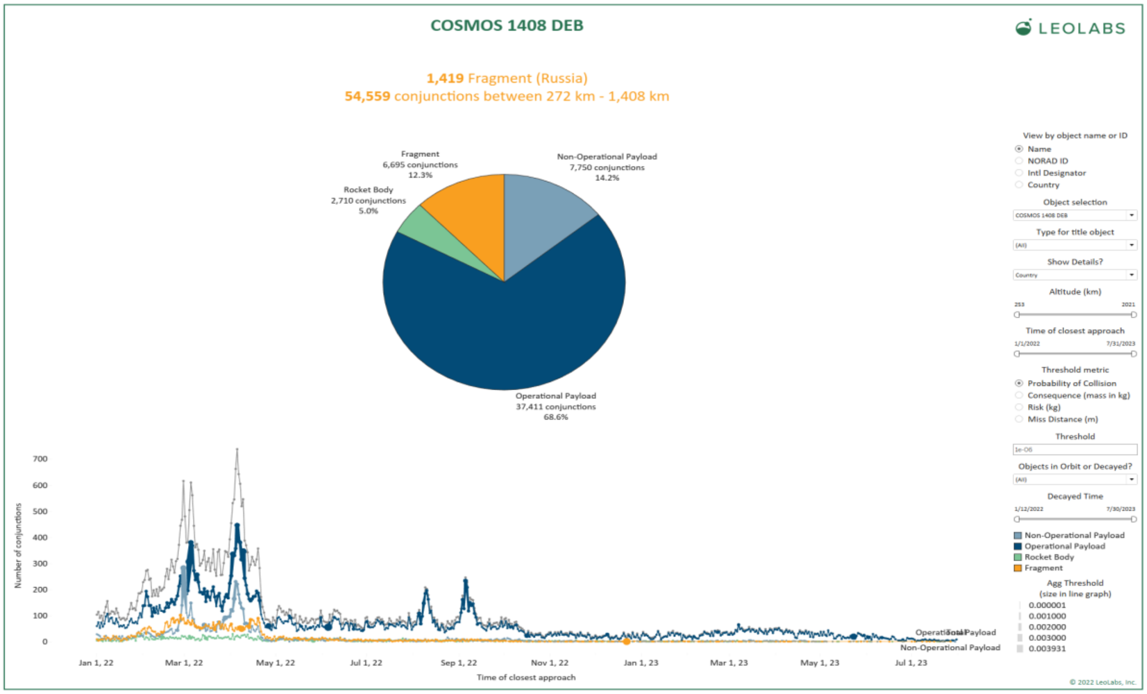


Fig. 11. The current SPD for the Cosmos 1408 debris cloud peaks at 440 km; this is 40 km lower than right after the event a factor of 16 smaller SPD.

LeoMap

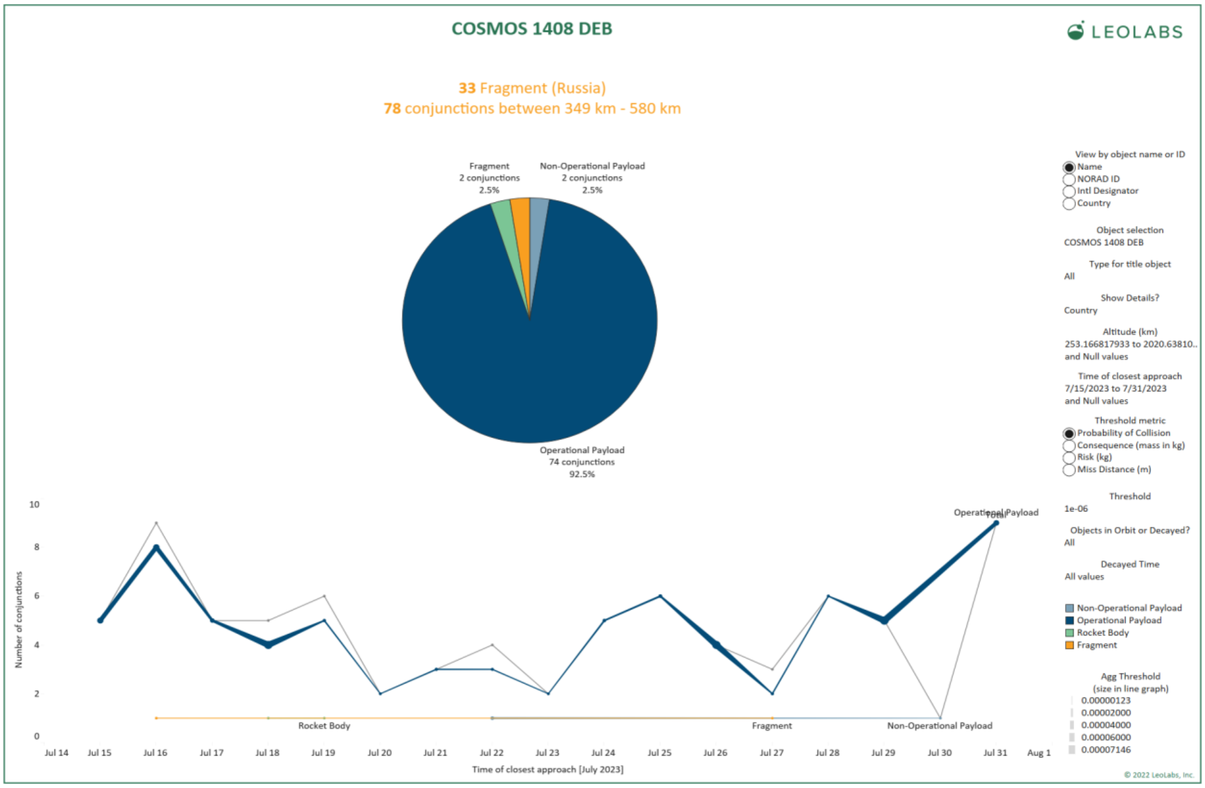
Figure 12 shows that Cosmos 1408 was a significant contributor to space safety concerns in late 2021 and most of 2022 as can be seen by the time sequence of CDMs issued for the Cosmos 1408 fragment cloud. Further, nearly 80% of all of these conjunctions were with operational satellites; Starlink, OneWeb, and Planet were the top three systems put at risk by this purposeful breakup event.



View by object name or ID
● Name
○ NORAD ID
○ Intl Designator
○ Country
Object selection: COSMOS 1408 DEB
Type for title object: (All)
Show Details?: Country
Altitude (km): 253 – 2021
Time of closest approach: 1/1/2022 – 7/31/2023
Threshold metric
● Probability of Collision
○ Consequence (mass in kg)
○ Risk (kg)
○ Miss Distance (m)
Threshold: 1e-06
Objects in Orbit or Decayed?: (All)
Decayed Time: 1/12/2022 – 7/30/2023

Fig. 12. Of the nearly 55,000 conjunctions from COSMOS 1408, only 171 occurred in July 2023.

Over the last two weeks of July 2023, Fig. 13 shows that only 33 fragments from the Cosmos 1408 cloud were involved in 78 events. However, the percentage of these events with operational satellites was over 90%; 69 of those 78 events were with Starlink satellites.



View by object name or ID
● Name
○ NORAD ID
○ Intl Designator
○ Country

Object selection
COSMOS 1408 DEB

Type for title object
All

Show Details?
Country

Altitude (km)
253.166817933 to 2020.63810..
and Null values

Time of closest approach
7/15/2023 to 7/31/2023
and Null values

Threshold metric
● Probability of Collision
○ Consequence (mass in kg)
○ Risk (kg)
○ Miss Distance (m)

Threshold
1e-06

Objects in Orbit or Decayed?
All

Decayed Time
All values

Fig. 13. Even as the size of the Cosmos 1408 fragments cloud has eroded over time, it is still challenging operational payloads and creating collision avoidance burden to operators.

LeoBreakup

LeoBreakup was created to address the need for quick and accurate verification of the cause of a fragmentation. It evolved over decades of testing, analysis, and modeling with some of the algorithms originally derived in the 1986 PhD dissertation by Darren McKnight. Other insights have been drawn gradually over the years of analyzing hypervelocity impact test sequences, hazard assessments from breakups of known cause, and spacecraft anomaly investigations. This process is summarized in the diagram below (Fig.14).

However, the specific tool development has occurred over the last 18 months, catalyzed by discussions with national security counterspace analysts after the breakup of Cosmos 1408 and the "fingerprint" of what some basic physics filters were able to describe about the event scenario.

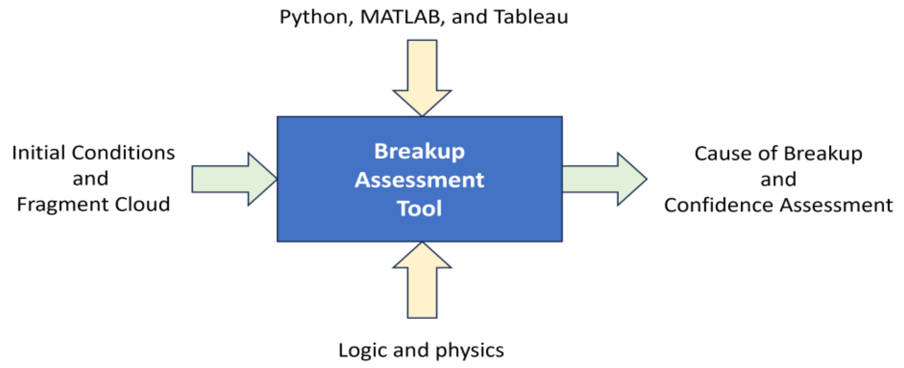


Fig. 14. LeoBreakup leverages logic and physics by applying a number of programming and visualization utilities to discern the cause of a breakup event.

To determine the cause of the event, each diagnostic test (seven total) is assigned a score. The tests cover the logical context (two), fragment size distribution (two), symmetry of the cloud (two), and energetics of the cloud (one). The points of all tests are summed to tally the score and determine the cause. It should be noted that one of the four possible event characterization families (i.e., hypervelocity, catastrophic fragmentation event) is highly unlikely to occur in higher orbits above LEO without some manmade acceleration of the impactor. This makes the tool even more meaningful at those higher orbits. The current instantiation was developed and validated based on known breakup events that have occurred in low Earth orbit (LEO). This provides a much larger set of validation examples without limiting the use of this tool only to LEO since all the algorithms are based solely on the distribution of debris relative to the spacecraft-centered reference frame.

Examining the Cosmos 1408 fragment cloud, LeoBreakup determined it to be a collision with high confidence and a high intensity collision with low confidence. LeoBreakup discriminates between a low intensity explosion and high intensity explosion by the number of cataloged fragments created, the average delta velocity imparted to the fragments, and the symmetry of the debris cloud. The scoring summary is shown in Fig. 15.

Scoring breakdown of all event possibilities for
COSMOS 1408 Non-Op Payload ASAT Test

		Low Intensity Explosion	High Intensity Explosion	Low Intensity Collision	High Intensity Collision
		10	23	69	79
Greater than five years since deployment	Max of 10	5	5	10	10
No known energy source	Max of 20	0	0	20	20
0.75 < Catalog # < 1.25	Max of 20	0	4	20	4
RCS large < medium < small	Max of 10	0	4	4	10
Both med and small RCS inc and SMA symmetrical	Max of 20	0	0	5	20
RCS large Delta V > RCS med Delta V	Max of 10	0	10	0	2
Average Delta V < 200 m/s	Max of 10	5	0	10	10

Fig. 15. The Cosmos 1408 debris cloud had clear characteristics of a collision but leaned slightly more toward high intensity than low intensity.

The weighted Gabbard diagram showed while most of the medium-sized objects were not ejected as far in altitude as the smaller objects, there were several medium-sized objects ejected nearly as far as any of the small fragments, as seen in Fig. 16. This is more indicative of a low intensity collision where there is more momentum transferred to larger fragments. The lack of fragments in the “lower arm” of the Gabbard diagram is likely a combination of the posigrade asymmetry of the fragment cloud, but also because many objects ejected into a retrograde direction (i.e., into the “lower arm”) were likely washed out of orbit quickly due to atmospheric drag. Figure 17 shows that the inclination is distributed symmetrically which is indicative of a high intensity collision.

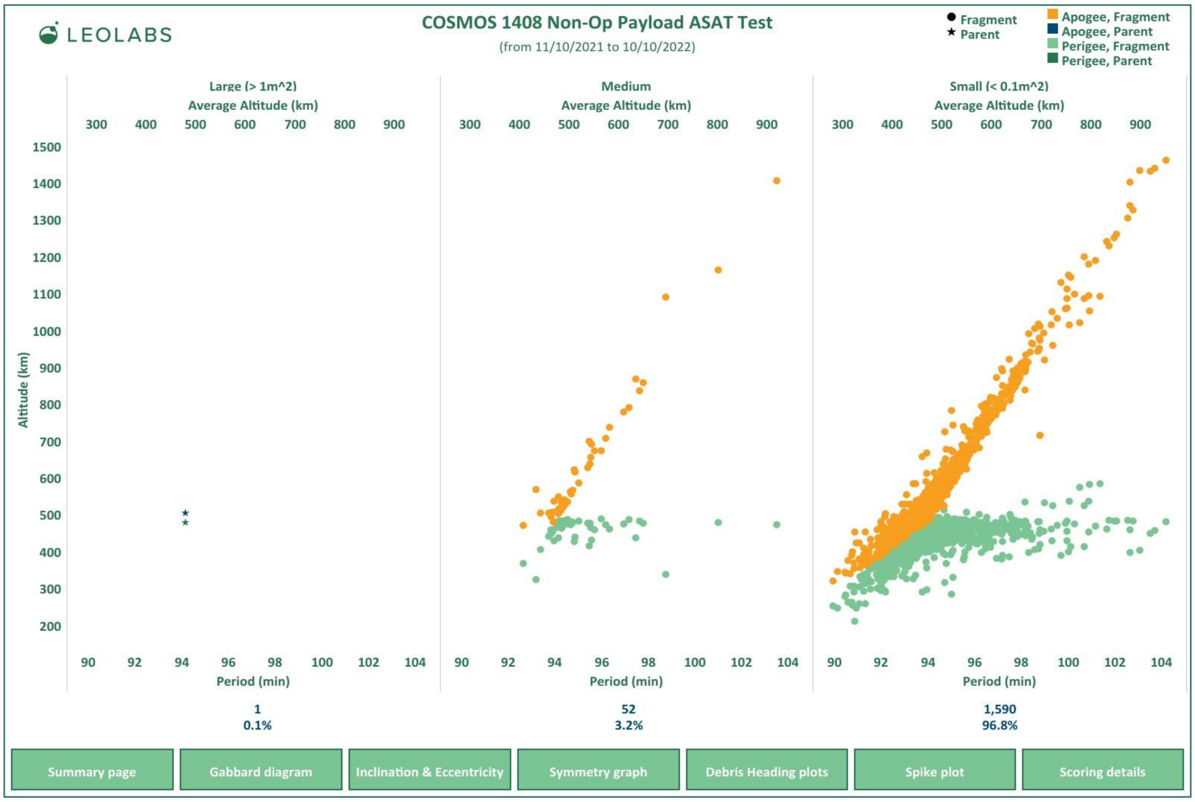


Fig. 16. The large posigrade delta velocity for a few of the larger objects is indicative of a low intensity collision.

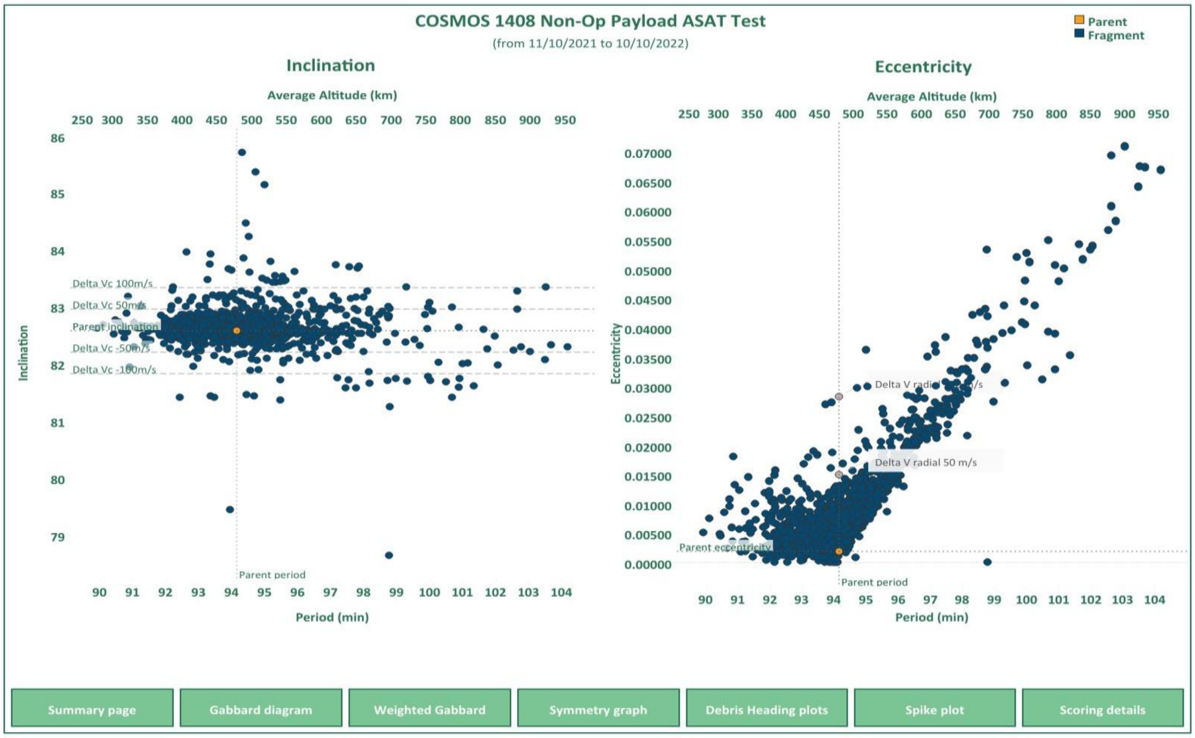


Fig. 17. The more symmetrical distribution in inclination (left panel) is more indicative of a high intensity collision.

In conclusion, all of the indicators point toward a collision, however, the filters were mixed as to high intensity or low intensity collision. This is not surprising as the impact velocity likely did not meet the criteria for a high intensity collision but the energy of the collision relative to the mass of the target may have exceeded the 35 to 45 J/gm catastrophic fragmentation threshold.

Another LeoCat Example

Prior to 2003, Russia and the United States were responsible for 97% of the mass of rocket bodies abandoned in low Earth orbit (LEO). Since 2003, China and the Rest of the World are responsible for 68% of the rocket body mass abandoned in LEO. As a matter of fact, these trends over the last 20 years have resulted in China and the US now having roughly the same amount of rocket body mass in LEO. Russia is still responsible for half of the rocket body mass in LEO, down from ¾ of the total mass in LEO as of 2003. The rate that China is leaving abandoned rocket bodies in orbit reverses the improved behavior of US and Russia and results in a continual accumulation of objects that will be especially prolific in creating fragments if involved in a collision. The total rocket body mass in LEO is currently nearly 1.5M kg; 61% of that mass was abandoned before 2003 (i.e., ~896,000 kg) and 39% (i.e., ~568,000 kg) in the last 20 years. Sadly, the rate of rocket body mass abandonment in LEO has actually increased in the last 20 years relative to the first ~45 years of the space age. These data are summarized in Fig. 18.

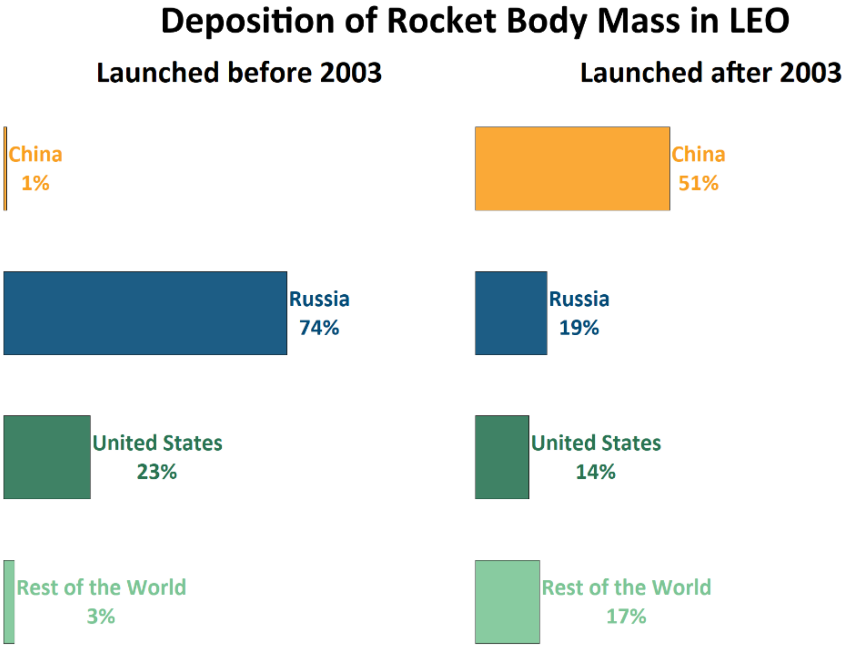


Fig. 18. China has contributed as much mass of abandoned rocket bodies in the last 20 years as Russia, US, and Rest of World combined.

The number and mass of rocket bodies abandoned over the last 20 years shows several very interesting, and surprising, trends:

- Over the last 20 years, China has abandoned nearly four times the rocket body mass in LEO compared to the US.
- The average rocket body mass for China on-orbit in LEO is over 2,700 kg while the US is less than 1,000 kg and Russia is less than 1,800 kg. These larger individual masses pose a greater fragment production level if they are involved in a catastrophic collision.
- Another interesting trend is that over the last 20 years, the Rest of the World has significantly increased its contribution to the derelict rocket body mass in LEO. Its contribution has grown from 3% to 17%, compared to the U.S. contribution of 14% and Russia's contribution of 19%. The Rest of the World's contribution is often overlooked because looking at the data by country the mass and total numbers are small. However, in aggregate, the numbers are becoming significant.

Safe space operations practices and responsible behavior (such as not abandoning derelict objects in long-lived orbits) must be enforced to ensure levels of collision risk remain manageable to the operators in LEO. This is critical for all space operators not just the largest ones. While these numbers are concerning, it is critical to examine the amount of this mass that is likely to not adhere to the 25-yr post-mission disposal (PMD) threshold in order to ascertain just how bad are the common practices relative to existing debris mitigation guidelines. Rocket bodies on-orbit above 615 km will not meet the 25-yr rule because the effects of atmospheric drag for these intact derelicts object will likely take at least 25 yr to reenter. The figure below provides a conservative[6] estimate of rocket body mass that will not comply to the 25-yr rule.

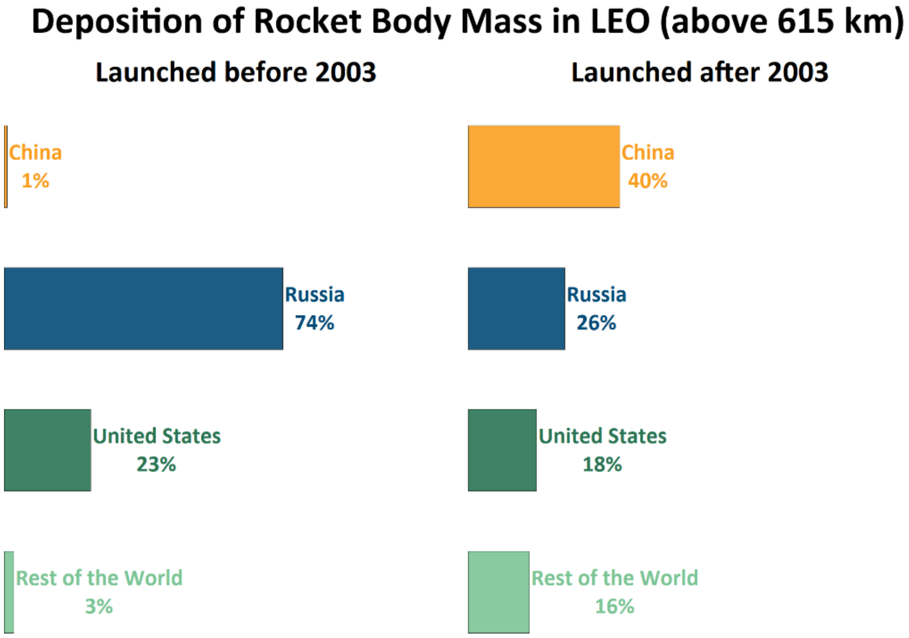


Fig. 19. Russia and China combined to contribute 2/3 of the abandoned rocket body mass in LEO over the last 20 years that will not reenter within the globally-accepted guideline of 25 years.

All of the rocket bodies abandoned more than 20 years ago are still above 500 km (so they are all non-compliant to the 25-yr rule)[7]. While Russia and the US have both improved their "rocket body abandonment behavior" over the last 20 years, the Rest of the World contribution to rocket body mass abandoned in long-lived orbits in LEO has grown by a factor of five and China by 50x.

4. SUMMARY

The large scale of the LeoLabs tracking dataset functions as the foundation for wide scale data evaluation, which may result in deeper insights than what are available simply from an initial observation. Through partnership with novel capabilities in the commercial SDA sector, LeoLabs data can be the cue to identify previously undiscovered operational modes. These efforts extend Space Domain Awareness of on-orbit objects to human operations and behaviors on Earth, allowing for richer understanding of the operational situation. LeoLabs is extending this analytic footing to provide continuous pattern of life monitoring and object characterization at scale.

This object characterization at scale is further extended by LeoCat, LeoMap, and LeoBreakup. The perspective provided by these tools puts current behavior of a single space operator (e.g., Morocco) or a single event (e.g., Cosmos 1408 ASAT test) into context with the community at large in operational, technical, and risk dimensions.

---

[6] Since some of the objects may have already been in orbit for up to 20 years, if they have an average altitude of 615 km now that means that they will have been in orbit for much longer than 25 yr by the time of their demise.

[7] The orbital lifetime of an intact object such as a rocket body at 500 km is about 5 yr.