Enabling Enduring Space Safety by Managing Orbital Debris

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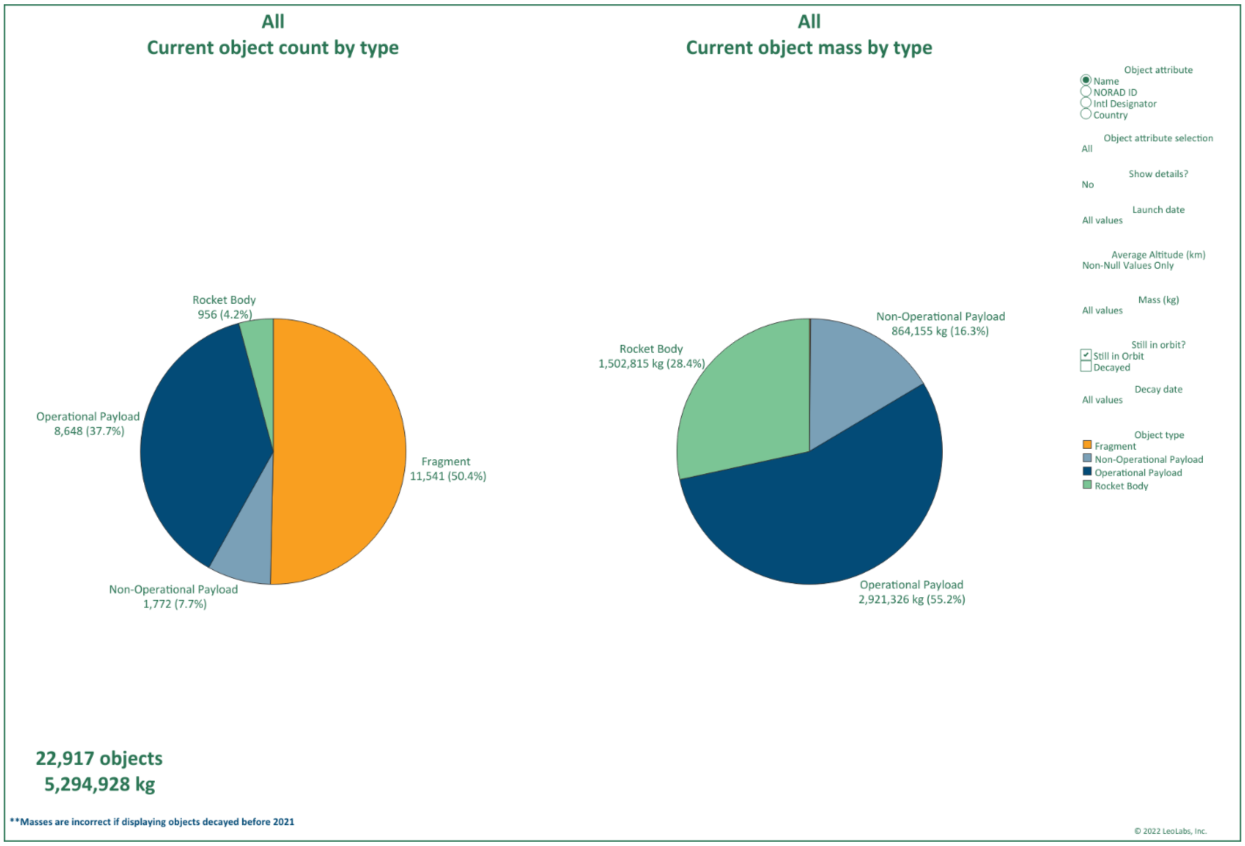
Orbital debris is any manmade object in Earth orbit that performs no useful purpose. This may include abandoned rocket bodies, non-operational spacecraft, and remnants from the fragmentation of space hardware. Unfortunately, any orbit where humans have operated has been sullied by orbital rubbish being left behind; even the Moon (LEO) has been littered by manned spaceflight and robotic missions. However, in Earth orbit the altitudes below 2,000 km, called low Earth orbit (LEO), has had the most amount of activity and thus the greatest number of orbital debris left behind.

LEO is a dynamic environment; in 2023 alone the number of objects in LEO increased by ~3,800 (i.e., ~19%) to ~22,690 with the majority from a ~2,800 net increase in operational payloads. While operational payloads are certainly an important component of the LEO population, even with a plethora of launches, over ~60% of objects in the LEO population are comprised of space debris (i.e., derelict intact hardware, such as rocket bodies and nonoperational payloads, combined with fragments from hundreds of satellite fragmentations). This orbital debris also comprises ~45% of the total mass in LEO.

In summary, the LEO population consists of clusters (of massive derelicts), clouds (of fragments), and constellations (of operational payloads); each exhibit different and interesting collision risk patterns. Figure 1 shows the distribution in number and mass in LEO as of 15 February 2024.



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

Object attribute selection
All

Show details?
No

Launch date
All values

Average Altitude (km)
Non-Null Values Only

Mass (kg)
All values

Still in orbit?
☑ Still in Orbit
☐ Decayed

Decay date
All values

Figure 1. About half of the LEO population is comprised of fragments from satellite breakups.

Before examining the three major constituents of the space object population in LEO, the “life” of a single massive derelict is examined to introduce some useful terms and equations.

The Life of a Rocket Body

The collision risk in low Earth orbit (LEO) can be a confusing mix of terms and equations. In order to better understand the importance of collision risk for the short-term safety of operational constellations and long-term sustainability of LEO, we will follow an individual space object through a sequence of risk calculations. This process will clarify and highlight the need for continuous monitoring and characterizing of all components of the LEO space population to catalyze actions to control the growth of debris.

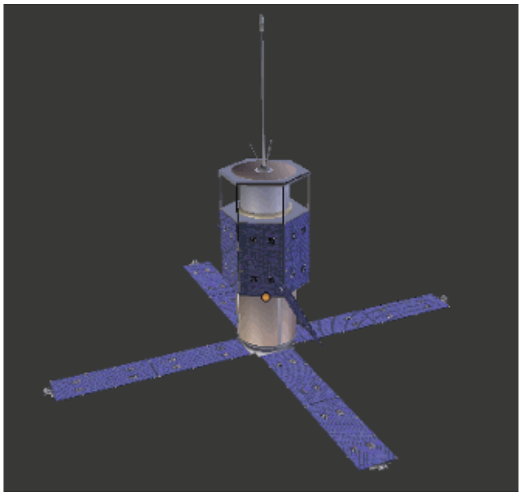


Figure 2. Tselina-2 from [Tselina-2 | 3D Resources (nasa.gov)]

Key Characters in Our Story

On May 22, 1990, the Soviet Union launched Cosmos 2082, Tselina-2, an Electronics Intelligence (ELINT) satellite with a mass of 3,250 kg, into an 840 km circular orbit. The Zenit-2 launch vehicle (also called SL-16) deployed this satellite and the upper stage from this launch vehicle was left in a similar orbit to Cosmos 2082. Cosmos 2082 is also denoted as 1990-46A (i.e., the primary object of the 46th launch of 1990) and Satellite Number 20624 (i.e., the 20,624th object cataloged by the now 18th Space Defense Squadron of the now United States Space Force). The SL-16 rocket body (R/B) has a mass of 9,000 kg, is roughly 11 m in length, and has a diameter of 4 m. The SL-16 R/B is designated 1990-46B and Satellite Number 20625.

The practice of leaving a R/B along with a deployed payload was used by many space operators in the 1980s and 1990s. Both of these objects have now been in orbit about the Earth for over 32 years,

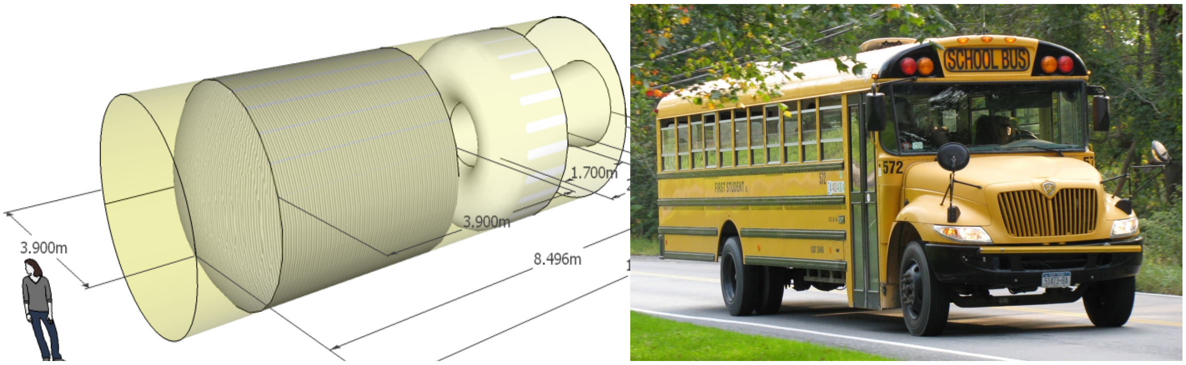
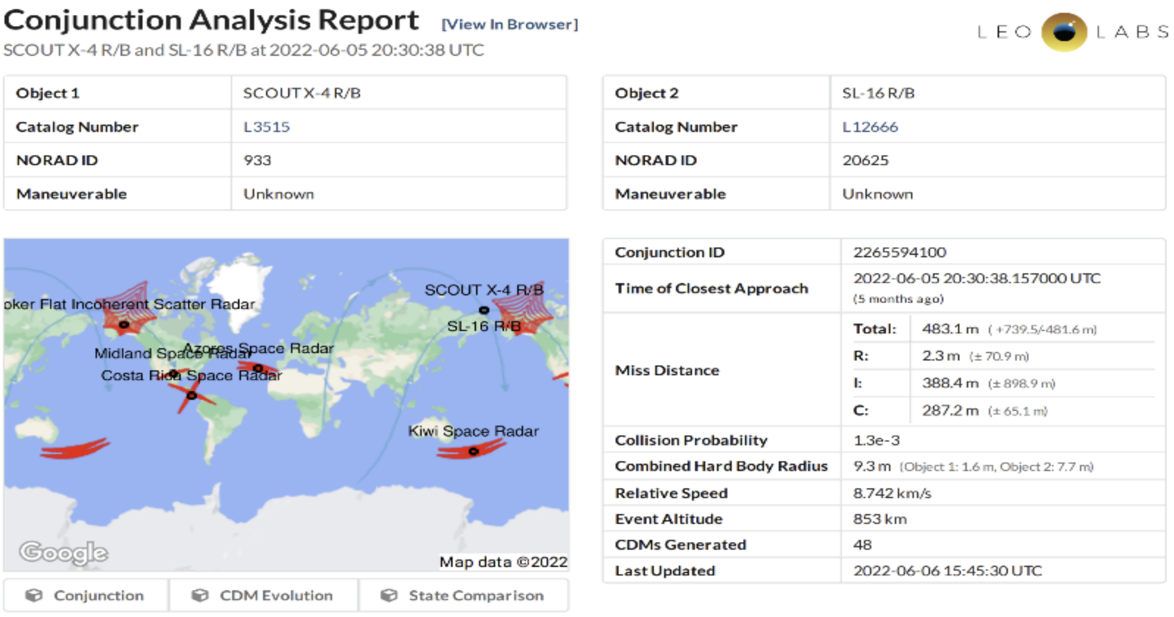


Figure 3. The SL-16 rocket body is similar mass and dimensions to a big yellow school bus except it is going 7.5 km/s, has no brakes, and no steering wheel.

circling the globe over 165,000 times. The distance these two objects have traveled is just under eight billion km; this is equivalent to a round trip from the Sun to Pluto and back!

On 5 June 2022, the S-16 R/B 20625 was involved in a close approach with another derelict rocket body, the 37 kg Scout X-4 upper stage, deposited in LEO in 1964 by the United States to deploy Explorer 25 (INJUN-4). The Conjunction Analysis Report, provided by LeoLabs, details this conjunction of 483 m miss distance with a relative velocity of 8.7 km/s (i.e., ~17,000 mph) with a probability of collision (PC) of 1.3E-3 (i.e., ~1/800 chance). While this may seem like a low probability, typically an operational spacecraft in LEO will take evasive actions if an encounter has a PC greater than 1E-5 (i.e., a hundred times less likely than the close approach that occurred). In 2023, there were over 37,000 close approaches in LEO where the PC exceeded 1E-5. The Conjunction Analysis Report summarizes what is included in a Conjunction Data Message (CDM).



Conjunction Analysis Report

SCOUT X-4 R/B and SL-16 R/B at 2022-06-05 20:30:38 UTC

Object 1	SCOUT X-4 R/B
Catalog Number	L3515
NORAD ID	933
Maneuverable	Unknown

Object 2	SL-16 R/B
Catalog Number	L12666
NORAD ID	20625
Maneuverable	Unknown

Conjunction ID	2265594100	
Time of Closest Approach	2022-06-05 20:30:38.157000 UTC (5 months ago)	
Miss Distance	**Total:**	483.1 m (+739.5/-481.6 m)
	R:	2.3 m (± 70.9 m)
	I:	388.4 m (± 898.9 m)
	C:	287.2 m (± 65.1 m)
Collision Probability	1.3e-3	
Combined Hard Body Radius	9.3 m (Object 1: 1.6 m, Object 2: 7.7 m)	
Relative Speed	8.742 km/s	
Event Altitude	853 km	
CDMs Generated	48	
Last Updated	2022-06-06 15:45:30 UTC	

Figure 4. The Conjunction Analysis Report for a conjunction summarizes the salient features of the close approach between two space objects.

The figure below depicts how the CDM provides the PC between two distinct objects for one specific encounter.

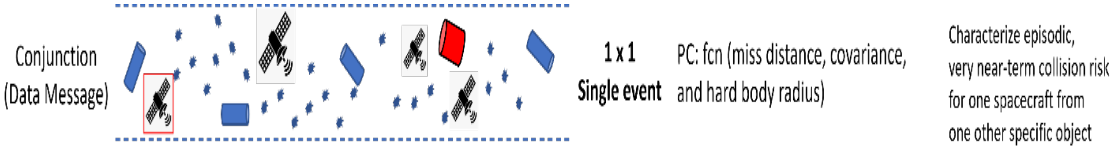
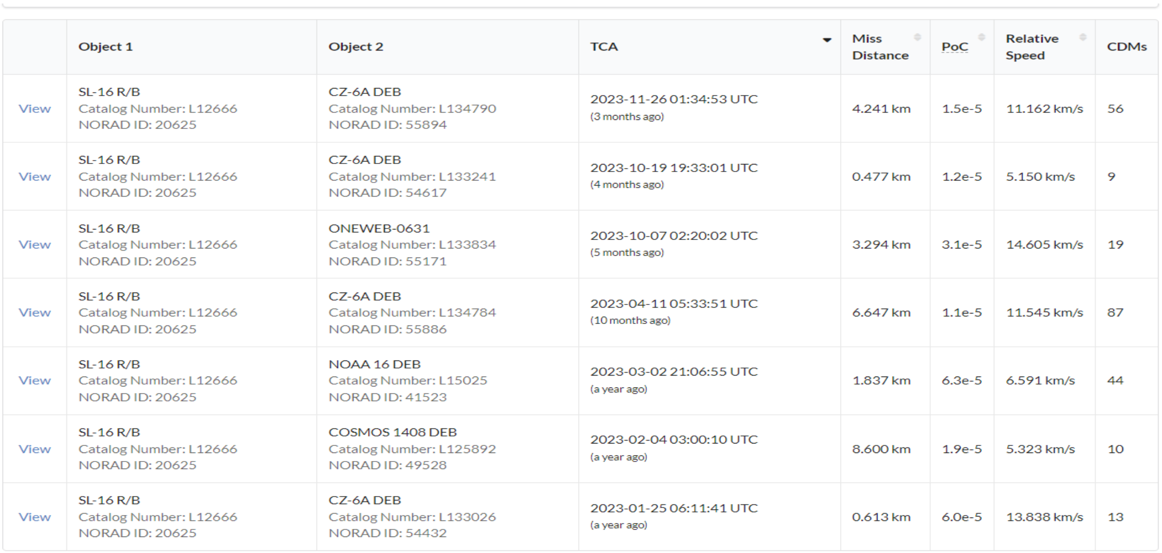


Figure 5. Probability of collision between two objects for a single close approach is given in a CDM.

In 2023, object 20625 had seven conjunction events with a PC over 1E-5, shown in the figure below.



	Object 1	Object 2	TCA	Miss Distance	PoC	Relative Speed	CDMs
View	SL-16 R/B Catalog Number: L12666 NORAD ID: 20625	CZ-6A DEB Catalog Number: L134790 NORAD ID: 55894	2023-11-26 01:34:53 UTC (3 months ago)	4.241 km	1.5e-5	11.162 km/s	56
View	SL-16 R/B Catalog Number: L12666 NORAD ID: 20625	CZ-6A DEB Catalog Number: L133241 NORAD ID: 54617	2023-10-19 19:33:01 UTC (4 months ago)	0.477 km	1.2e-5	5.150 km/s	9
View	SL-16 R/B Catalog Number: L12666 NORAD ID: 20625	ONEWEB-0631 Catalog Number: L133834 NORAD ID: 55171	2023-10-07 02:20:02 UTC (5 months ago)	3.294 km	3.1e-5	14.605 km/s	19
View	SL-16 R/B Catalog Number: L12666 NORAD ID: 20625	CZ-6A DEB Catalog Number: L134784 NORAD ID: 55886	2023-04-11 05:33:51 UTC (10 months ago)	6.647 km	1.1e-5	11.545 km/s	87
View	SL-16 R/B Catalog Number: L12666 NORAD ID: 20625	NOAA 16 DEB Catalog Number: L15025 NORAD ID: 41523	2023-03-02 21:06:55 UTC (a year ago)	1.837 km	6.3e-5	6.591 km/s	44
View	SL-16 R/B Catalog Number: L12666 NORAD ID: 20625	COSMOS 1408 DEB Catalog Number: L125892 NORAD ID: 49528	2023-02-04 03:00:10 UTC (a year ago)	8.600 km	1.9e-5	5.323 km/s	10
View	SL-16 R/B Catalog Number: L12666 NORAD ID: 20625	CZ-6A DEB Catalog Number: L133026 NORAD ID: 54432	2023-01-25 06:11:41 UTC (a year ago)	0.613 km	6.0e-5	13.838 km/s	13

Figure 6. Satellite 20625 was involved in seven conjunctions in 2023 with the PC exceeding 1E-5.

That large number of high-PC conjunctions involving 20625 in 2023 is only the tip of the iceberg. In 2023, there were 58 conjunctions with PC greater than 1E-6 for this specific SL-16 R/B. The distribution of the objects 20625 encountered in orbit from 1 January 2022 to 15 February 2024 is shown in the figure below produced by the LeoLabs' LeoMap tool.

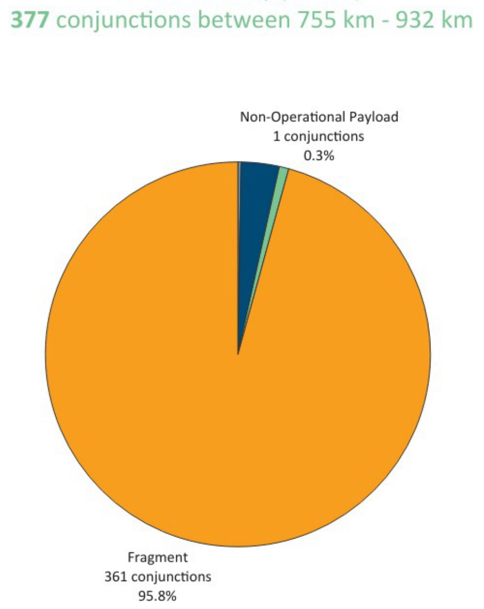


Figure 7. Depiction of all encounters with 20625 over two years shows that fragments are the most likely conjuncting object.

While ~96% of the encounters are with fragments there were 12 events with operational payloads and three with other R/Bs. This examination hints at the larger perspective of all objects in the vicinity of our SL-16 R/B 20625 posing a collision risk to this massive derelict.

Statistical Probability of Collision (PC)

The statistical PC for a single object from all of the resident space objects that might cross the object's orbit is determined using an equation that considers the object's size (i.e., collision cross-section) times the spatial density of other objects (i.e., number of objects per cubic kilometer) times the relative velocity between these objects (~12 km/s in LEO).[1]

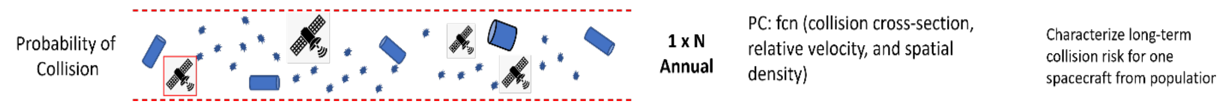
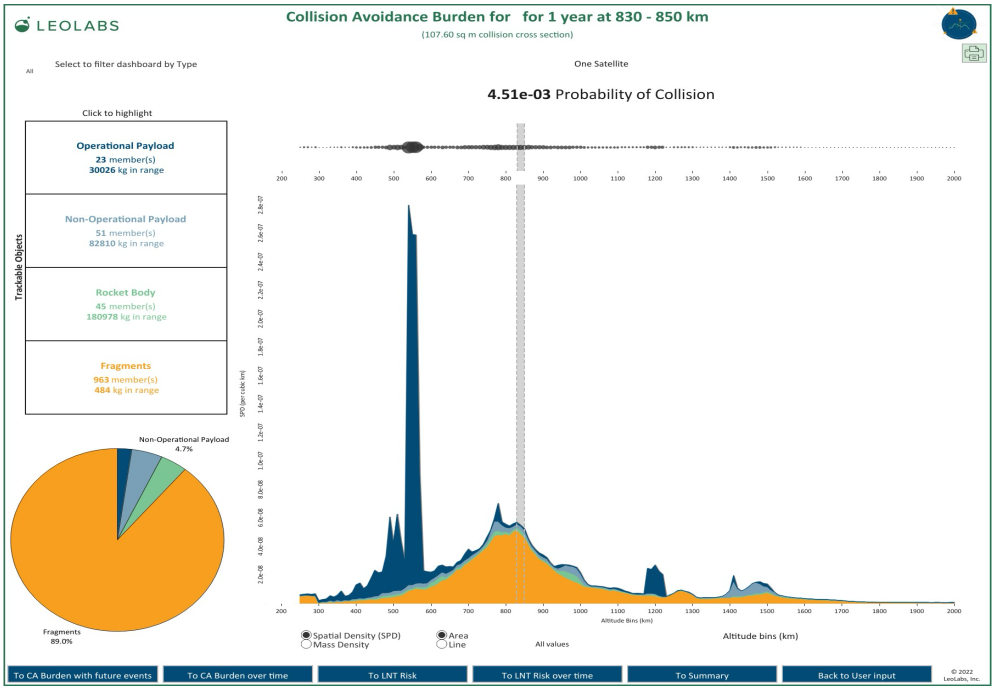


Figure 8. Probability of collision for one year provides a statistical measure of collision likelihood.

The LeoLabs LeoRisk tool provides a way to determine the statistical annual PC levels and what objects contribute to the collisional hazard for any object in LEO. As shown in the figure below, the types of objects 20625 encounters throughout the course of a year to reach a PC of 4.51E-3 (i.e., ~1/220) is within a factor of eight of the summation of CDMs issued during 2023. Note, the summation of the CDM PC values will not necessarily be equal to the statistical PC level over a short period such as a year; it may take a decade or more for these values to line up, if at all.



Collision Avoidance Burden for   for 1 year at 830 - 850 km

(107.60 sq m collision cross section)

One Satellite

4.51e-03 Probability of Collision

Operational Payload
23 member(s)
30026 kg in range

Non-Operational Payload
51 member(s)
82810 kg in range

Rocket Body
45 member(s)
180978 kg in range

Fragments
963 member(s)
484 kg in range

Non-Operational Payload 4.7%

Fragments 89.0%

● Spatial Density (SPD)
○ Mass Density

● Area
○ Line

All values

Figure 9. The statistical PC over a year for 20625 is 4.51E-3 (i.e., ~1/220).

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[1] PC = 1-e$^{\lambda t}$ where λ = collision cross-section (km^2)*relative velocity (km/s)*spatial density (#/km^3) and t is time (s).

The consequence of these events with 20625 may range from minor to very consequential. For example, a fragment impacting 20625 may create hundreds of pieces of debris while a collision between 20625 and the Tselina-2 satellite (20624) that it deployed would likely create over 15,000 cataloged fragments and many more lethal nontrackable debris. Now, let’s examine how likely it is for these most massive objects (i.e., SL-16 R/Bs and non-operational Tselina-2 satellites) to collide in LEO.

Cluster 840 as a Hotspot in LEO

The original characters in this risk story, 20624 and 20625, were part of a larger deployment by the Soviets/Russians. In total, from 1985 to 2007, 18 ELINT satellites and their associated 18 SL-16 upper stages were deposited between 825 and 865 km. While our previous collision hazard calculations examined a single event between two objects against each other (i.e., a CDM) and an annual risk for one object vs all other space objects it could possibly encounter (i.e., statistical PC), a collision rate (CR) can be determined among any subset of objects. In this case, that subset is these 36 massive objects deposited centered around 840 km that we call Cluster 840 (C840). This dynamic is depicted in the figure below.

Figure 10. Collision rate within a subset of the space object population is the summation of PCs of any two objects within the population.

These 36 objects alone amount to 208,000 kg, this is equivalent to over ~800 Starlink V1 satellites or ~1,400 OneWeb satellites (i.e., about double of the eventual constellation deployment plans). CR is a relevant concept[2] when any collision event amongst a population is meaningful. In this case, the catastrophic collision between any two objects in C840 would likely create over 15,000 cataloged fragments, in essence doubling the LEO fragment population in one instance. This debris would likely be spread over many hundreds of kilometers. For example, the debris cloud from the fragmentation of the Chinese Fengyun-1C satellite in 2007 at 860 km have been involved in over 19,000 high-PC conjunctions at altitudes as low as ~330 km and as high as ~1,630 km in 2023 alone. It is also important to note that debris created at these altitudes will linger for many decades, even centuries.

The current annual collision rate within C840 is 1.7E-3 (i.e., a 1/580 chance each year).[3] The importance of C840, however, is amplified when we remember this ensemble of derelict mass has been whizzing past each other for decades (i.e., the Sun to Pluto and back). Taking this into account, the probability that the first collision between these objects may occur by 2025 is ~6%. By 2040, this expectation will increase to ~9% without any intervention such as removing some of these objects. The 18 SL-16 R/Bs in

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[2] CR = $(N^2/2)$*collision cross-section (km^2)*relative velocity (km/s)*relative velocity (km/s)*time (sec)/Volume of altitude expanse of cluster (km^3) where N is the number of objects in the cluster

[3] The CR is for any of the 36 massive derelicts colliding with each other which would result in nearly 15,000 cataloged fragments while the annual PC for 20625 involves any object interacting with 20625; this includes hundreds of fragments.

C840 have been highlighted on numerous occasions as posing a significant debris-generating potential in LEO and have been identified as 18 of the top 50 objects that should be removed from LEO.[4]

Other Clusters of Massive Derelicts

Many of the most massive objects added to the LEO population were abandoned in the last 20 years. The littering of LEO with defunct rocket bodies is a long sad consequential common practice. The seventh space launch ever – deployment of Vanguard 2 in 1959 – left a rocket body that is still in LEO today, more than 64 years later! Since 2004, ~282 more R/Bs were abandoned in LEO (above 500 km average altitude) with an average mass of over 2,000 kg (i.e., over 150 times more massive than a 6U cubesat). These R/Bs were left by launches from seven different countries – including every major spacefaring entity. Nearly 40% (i.e., 132) of these R/Bs were left by China (two within the "bad neighborhood" of 800 to 900 km), while Russia only left ~50 R/Bs in LEO in the last 20 years. It should be noted there were an additional ~30 rocket bodies deposited in higher orbits outside of LEO (i.e., typically much more long-lived than LEO) in 2023. The "bad neighborhood" (which includes C840), noted above and in previous reports by LeoLabs, is where many of the most massive derelicts have been abandoned historically. This region continues to be a hot spot for debris collision risk. In 2023, there were 1,352 conjunctions in LEO with a miss distance of less than 100 m. Over 20% of these most dangerous conjunctions (i.e., 291 instances) occurred between 800 and 900 km. Plotting the mass density of derelict objects in LEO provides a mapping of all the clusters at 840 km, 980 km, 770 km, and 630 km (in decreasing order) . Figure 11 shows the accumulation of mass by altitude.

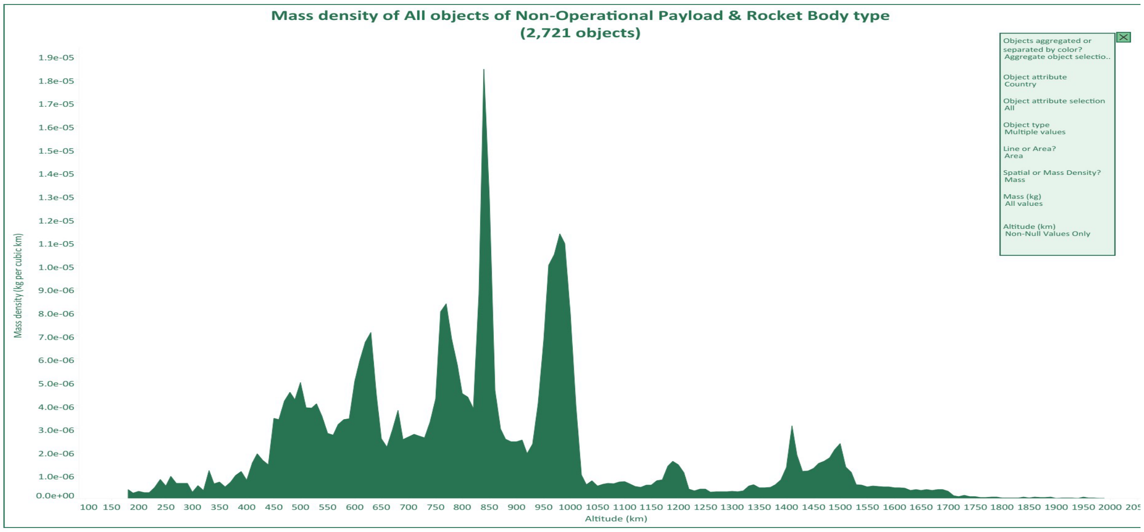

Figure 11. The mass distribution of derelict objects provides a mapping of clusters.

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[4] McKnight, et al, "Identifying the 50 Statistically-Most-Concerning Derelict Objects in LEO," 71st International Astronautical Congress (IAC) – The CyberSpace Edition, Dubai, UAE, October 20 and McKnight, D., Dale, E., Bhatia, R., Kunstadter, C., Stevenson, M., and Patel, M., "A MAP OF THE STATISTICAL COLLISION RISK IN LEO", 73rd International Astronautical Congress, Paris, France, September 2022.

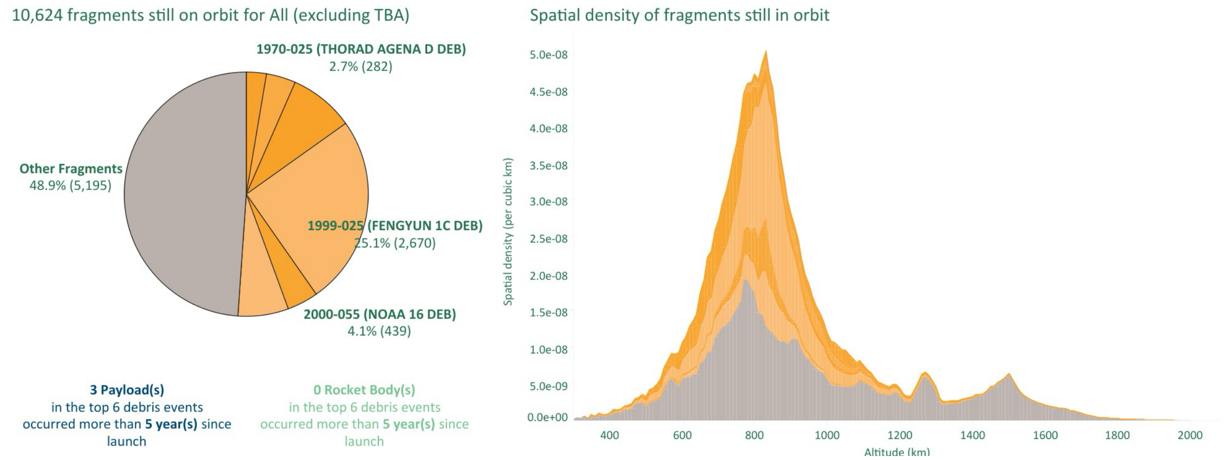
Clouds of Fragments

The second major constituent of LEO, after clusters of massive derelict objects, are clouds of fragments.

As shown earlier, ~50% of the current LEO satellite catalog is comprised of fragments (i.e., ~11,541 out of ~22,917 as of 15 February 2024). While most fragments are the majority by number, the mass that they represent is almost trivial in comparison to the ~11,000 intact objects in LEO. Fragments are usually much smaller than a meter in size with typical "fragments" being on the order of 10 to 50 cm.

The term "debris" is used by the 18th Space Defense Squadron (SDS) whenever there is an object related to a launch that is neither a payload nor a rocket body. This "debris" may include a small number of mission-related items such as payload adapters, lens covers, retaining clamps, etc. There have been ~310 launches that have only one piece of debris associated with it and another ~130 with only two pieces associated with the launch. Summing up all the debris that include single digit numbers associated for a given launch amounts to ~1,400 objects (i.e., 12 %) of the ~11,500 "fragment" population.

At the other end of the spectrum, major breakup events have liberated hundreds, even thousands, of fragments from a single mission. More specifically, the top six breakup events, in terms of the remaining debris on orbit, contribute 50% (i.e., ~5,200 fragments) of the current fragment population in LEO. Further, the top 24 breakup events encompass a full 75% of the total fragment population in LEO. The fragment population peaks at ~840 km but has two smaller peaks at ~1,250 km and ~1,500 km; at these altitudes, this debris will not reenter for centuries. The source of these fragments is primarily rocket bodies, however, four out of the top six most dominant clouds have payloads as their parent.


10,624 fragments still on orbit for All (excluding TBA)

Spatial density of fragments still in orbit

3 Payload(s) in the top 6 debris events occurred more than **5 year(s)** since launch

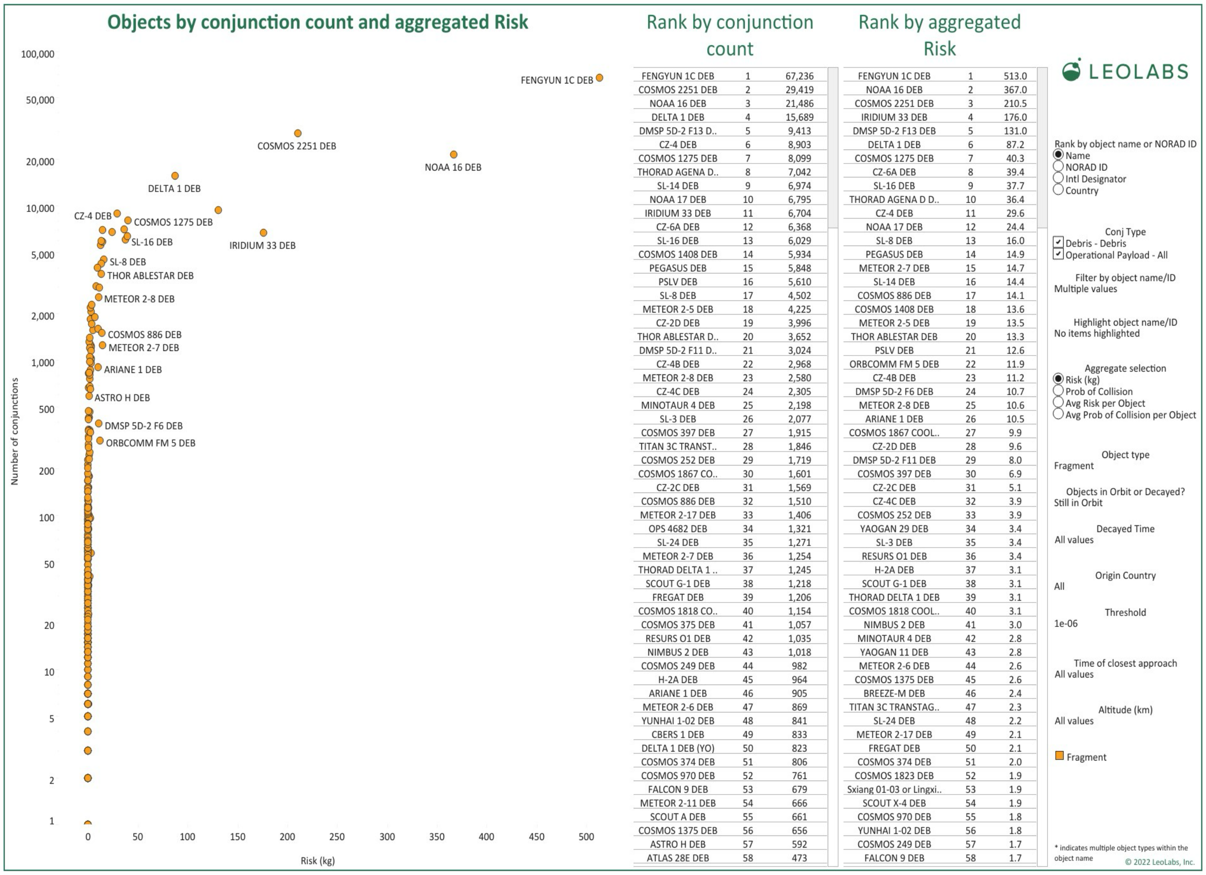
0 Rocket Body(s) in the top 6 debris events occurred more than **5 year(s)** since launch

Intl Designator Group	*Cause*	*Event Parent Type*	*Breakup year*	*Years since launch*	*Breakup altitude (km)*	*Max Pieces*	*Distinct count of Still in Orbit Debris*	*Percent still in orbit*
1999-025 (FENGYUN 1C DEB)	Deliberate Collision	Payload	2007	8	855	3,519	2,670	75.9%
1993-036 (COSMOS 2251 DEB)	Accidental Collision	Payload	2009	16	775	1,711	914	53.4%
2022-151 (CZ-6A DEB)	Accidental Explosion	Rocket Body	2022	0	840	793	710	89.5%
1981-053 (COSMOS 1275 DEB)	Accidental Explosion	Payload	1981	0	980	475	414	87.2%
2000-055 (NOAA 16 DEB)	Accidental Explosion	Payload	2015	15	850	458	439	95.9%
1970-025 (THORAD AGENA D DEB)	Unknown	Rocket Body	1970	0	1075	437	282	64.5%

Figure 12. Half of all fragments on orbit in LEO came from just six breakup events.

It is very important to note that the three major space powers each have two of the top six most prolific breakup events. Accidental explosion is the most frequent cause for these breakup sources; amongst the top six events three of them were accidental explosion and the Thor Agena D R/B event is listed as unknown but is likely also an accidental explosion. These fragments pose a significant collision risk across LEO: from 1 January 2022 to 15 February 2024, there were ~808,000 conjunctions in LEO where the probability of collision (PC) exceeded one in a million (i.e., 1E-6). Of these events, ~385,000 (i.e., 48%) involved at least one fragment.

Looking more closely at the risk posed by fragment clouds, where risk is defined by PC times the mass involved in each conjunction, a different aspect of the collision hazard is exposed. Figure 13 plots the aggregate risk (i.e., debris-generating potential) from each cloud on the x-axis and the total number of conjunctions in which it was involved on the y-axis. The NOAA 16 fragment cloud surpassed the Cosmos 2251 cloud in aggregate risk, despite having fewer fragments on orbit, due to its proximity to the most massive, abandoned derelicts in LEO in the cluster centered around 840 km.



Rank by conjunction count

FENGYUN 1C DEB	1	67,236
COSMOS 2251 DEB	2	29,419
NOAA 16 DEB	3	21,486
DELTA 1 DEB	4	15,689
DMSP 5D-2 F13 D..	5	9,413
CZ-4 DEB	6	8,903
COSMOS 1275 DEB	7	8,099
THORAD AGENA D..	8	7,042
SL-14 DEB	9	6,974
NOAA 17 DEB	10	6,795
IRIDIUM 33 DEB	11	6,704
CZ-6A DEB	12	6,368
SL-16 DEB	13	6,029
COSMOS 1408 DEB	14	5,934
PEGASUS DEB	15	5,848
PSLV DEB	16	5,610
SL-8 DEB	17	4,502
METEOR 2-5 DEB	18	4,225
CZ-2D DEB	19	3,996
THOR ABLESTAR D..	20	3,652
DMSP 5D-2 F11 D..	21	3,024
CZ-4B DEB	22	2,968
METEOR 2-8 DEB	23	2,580
CZ-4C DEB	24	2,305
MINOTAUR 4 DEB	25	2,198
SL-3 DEB	26	2,077
COSMOS 397 DEB	27	1,915
TITAN 3C TRANST..	28	1,846
COSMOS 252 DEB	29	1,719
COSMOS 1867 CO..	30	1,601
CZ-2C DEB	31	1,569
COSMOS 886 DEB	32	1,510
METEOR 2-17 DEB	33	1,406
OPS 4682 DEB	34	1,321
SL-24 DEB	35	1,271
METEOR 2-7 DEB	36	1,254
THORAD DELTA 1 ..	37	1,245
SCOUT G-1 DEB	38	1,218
FREGAT DEB	39	1,206
COSMOS 1818 CO..	40	1,154
COSMOS 375 DEB	41	1,057
RESURS O1 DEB	42	1,035
NIMBUS 2 DEB	43	1,018
COSMOS 249 DEB	44	982
H-2A DEB	45	964
ARIANE 1 DEB	46	905
METEOR 2-6 DEB	47	869
YUNHAI 1-02 DEB	48	841
CBERS 1 DEB	49	833
DELTA 1 DEB (YO)	50	823
COSMOS 374 DEB	51	806
COSMOS 970 DEB	52	761
FALCON 9 DEB	53	679
METEOR 2-11 DEB	54	666
SCOUT A DEB	55	661
COSMOS 1375 DEB	56	656
ASTRO H DEB	57	592
ATLAS 28E DEB	58	473

Rank by aggregated Risk

FENGYUN 1C DEB	1	513.0
NOAA 16 DEB	2	367.0
COSMOS 2251 DEB	3	210.5
IRIDIUM 33 DEB	4	176.0
DMSP 5D-2 F13 DEB	5	131.0
DELTA 1 DEB	6	87.2
COSMOS 1275 DEB	7	40.3
CZ-6A DEB	8	39.4
SL-16 DEB	9	37.7
THORAD AGENA D D..	10	36.4
CZ-4 DEB	11	29.6
NOAA 17 DEB	12	24.4
SL-8 DEB	13	16.0
PEGASUS DEB	14	14.9
METEOR 2-7 DEB	15	14.7
SL-14 DEB	16	14.4
COSMOS 886 DEB	17	14.1
COSMOS 1408 DEB	18	13.6
METEOR 2-5 DEB	19	13.5
THOR ABLESTAR DEB	20	13.3
PSLV DEB	21	12.6
ORBCOMM FM 5 DEB	22	11.9
CZ-4B DEB	23	11.2
DMSP 5D-2 F6 DEB	24	10.7
METEOR 2-8 DEB	25	10.6
ARIANE 1 DEB	26	10.5
COSMOS 1867 COOL..	27	9.9
CZ-2D DEB	28	9.6
DMSP 5D-2 F11 DEB	29	8.0
COSMOS 397 DEB	30	6.9
CZ-2C DEB	31	5.1
CZ-4C DEB	32	3.9
COSMOS 252 DEB	33	3.9
YAOGAN 29 DEB	34	3.4
SL-3 DEB	35	3.4
RESURS O1 DEB	36	3.4
H-2A DEB	37	3.1
SCOUT G-1 DEB	38	3.1
THORAD DELTA 1 DEB	39	3.1
COSMOS 1818 COOL..	40	3.1
NIMBUS 2 DEB	41	3.0
MINOTAUR 4 DEB	42	2.8
YAOGAN 11 DEB	43	2.8
METEOR 2-6 DEB	44	2.6
COSMOS 1375 DEB	45	2.6
BREEZE-M DEB	46	2.4
TITAN 3C TRANSTAG..	47	2.3
SL-24 DEB	48	2.2
METEOR 2-17 DEB	49	2.1
FREGAT DEB	50	2.1
COSMOS 374 DEB	51	2.0
COSMOS 1823 DEB	52	1.9
Sxiang 01-03 or Lingxi..	53	1.9
SCOUT X-4 DEB	54	1.9
COSMOS 970 DEB	55	1.8
YUNHAI 1-02 DEB	56	1.8
COSMOS 249 DEB	57	1.7
FALCON 9 DEB	58	1.7

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

Conj Type
☑ Debris - Debris
☑ Operational Payload - All

Filter by object name/ID
Multiple values

Highlight object name/ID
No items highlighted

Aggregate selection
● Risk (kg)
○ Prob of Collision
○ Avg Risk per Object
○ Avg Prob of Collision per Object

Object type
Fragment

Objects in Orbit or Decayed?
Still in Orbit

Decayed Time
All values

Origin Country
All

Threshold
1e-06

Time of closest approach
All values

Altitude (km)
All values

🟧 Fragment

* indicates multiple object types within the object name

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Figure 13. Examining the aggregate risk (i.e., summing up PC times mass involved in each conjunction) posed by each debris cloud shows that NOAA 16 rises above Cosmos 2251 due to the NOAA 16 fragment cloud being centered within C840 which has many of the most massive derelicts in all of LEO.

It is also important to note that 12 of the top 24 major fragmentation events occurred more than five years after deployment. This means that if the new 5-year post mission disposal (PMD) guideline had been applied a significant amount of the current fragment burden in LEO could have been avoided. Whereas, only three events occurred more than 25 years after the parent object was launched into space. This means that even if the old 25-year PMD rule had been adhered to, it would not have prevented much of the current fragment population from being generated. This reminds us all that the sooner derelict objects can be removed from orbit, the less likelihood that significant long-lived, debris-generating events will litter the LEO environment. While only one of these 24 events involved an object launched in the last 20 years, the frequency of breakup events over time has stayed fairly constant at about two to four per year. The altitude of these major events is typically over ~750 km since atmospheric drag will act quickly on fragments below this altitude; there have been many more breakup events that have occurred below ~750 km but they have not had persistent effects on the LEO population.

It is noted that the most long-lived debris clouds are the ones involving payloads versus rocket bodies. This is partially due to the more compact construction of payloads. Rocket body debris may contain a significant amount of thin-walled structure representing the roughly cylindrical shape of rocket bodies while payloads will contain dense components such as batteries, structural members, and payload hardware (e.g., transmitters, cameras, etc.).

In examining the contributions by country to the population of fragments in LEO, ~90% of the population originated from the US, China, and Russia. The peak of the Chinese contribution is clearly from the Fengyun-1C ASAT Test conducted in 2007 while the contribution from Russia (peaking at ~750

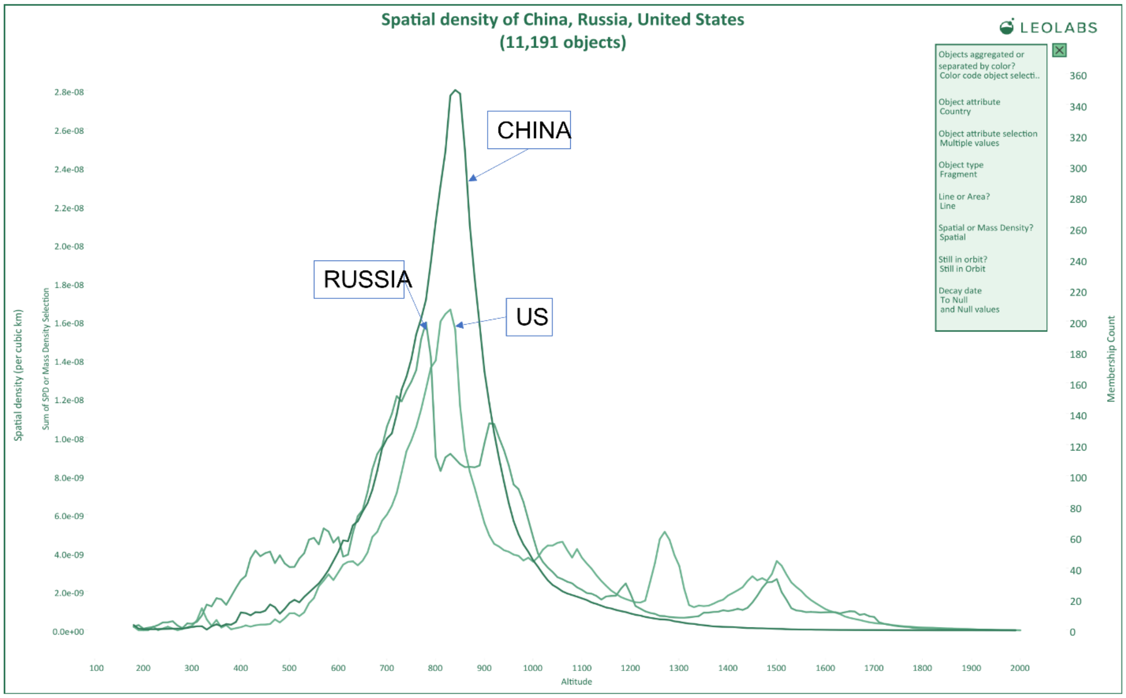


Figure 14. The three major space powers have contributed significantly to the on-orbit fragment population.

km) is largely from the remnants of Cosmos 2251 that collided with the American Iridium-33 satellite in 2009. However, the US contribution peaks just above ~800 km from a number of DMSP/NOAA spacecraft "minor" fragmentation events that add up to a significant contribution to the fragment collision hazard in LEO.

The beginning of 2022 saw the quick rise of cataloged fragments from the purposeful destructive on-orbit antisatellite (ASAT) test by Russia of their Cosmos 1408 (C1408) payload. The fragmentation event eventually consisted of over ~1,800 fragments cataloged but never more than ~1,200 fragments in the catalog at any one time. The ~1,200 fragment peak occurred in March 2022 has dwindled to ~65 by 15 February 2024.

Interestingly, despite the rapid decline of the number of C1408 fragments in the catalog, the number of Conjunction Data Messages (CDMs) issued involving a fragment from the C1408 breakup did not follow the same steep drop-off. This was partially due to the increased number of operational satellites deployed in 2022 that were characteristically challenged by C1408 fragments in the 400 km to 600 km altitude range.

However, just as the C1408 fragment cloud was being cleansed from LEO, the explosion of a Chinese CZ-6A rocket body in the middle of C840 (but, of course!) on 12 November 2022, partially reversed this trend of a shrinking fragment count. One day after the CZ-6A rocket body deployed the Yunhai 3 weather satellite into an 854/856 km orbit, the rocket body exploded. The total number of cataloged fragments from this event is 793 of which 710 (i.e., ~90%) are still in orbit.

While this event occurred in the most densely populated region in LEO, since it occurred so soon after deployment, it was likely triggered by something related to the propulsion system and is likely not a collision-induced fragmentation. It may have been triggered (1) by attempted venting of remaining propellants, (2) if an orbit-lowering burn was attempted, or (3) the rocket stage simply failed to shut down smoothly.

The potential of it being propulsion-related is reinforced by reporting of Cees Bassa that "observations from two consecutive passes over the US in the hours after launch show fuel leaking from the rocket" as filmed by Dan Bush of Missouri Skies. Satellite Fuel Dump ??? Possibly Chinese CZ-6A launch - YouTube Other energy sources on the rocket body also likely include batteries and pressurized vessels related to the propulsion system.

A fragment cloud can be represented in two ways: a Gabbard diagram and a spike plot. The Gabbard diagram for the CZ-6A rocket body shows the distribution of objects in LEO from as low as ~320 km and to as high as ~1,500 km.

The LeoLabs' LeoBreakup tool has assessed the CZ-6A R/B event as a high intensity explosion largely because (1) some of the objects with the greatest impulse imparted to them (i.e., moved to the highest orbits) were some of the largest objects, (2) the number of cataloged objects is small in comparison to the mass of the rocket body (i.e., many fewer cataloged fragments than the mass of the rocket body in kilograms), and (3) it occurred so soon after payload deployment.

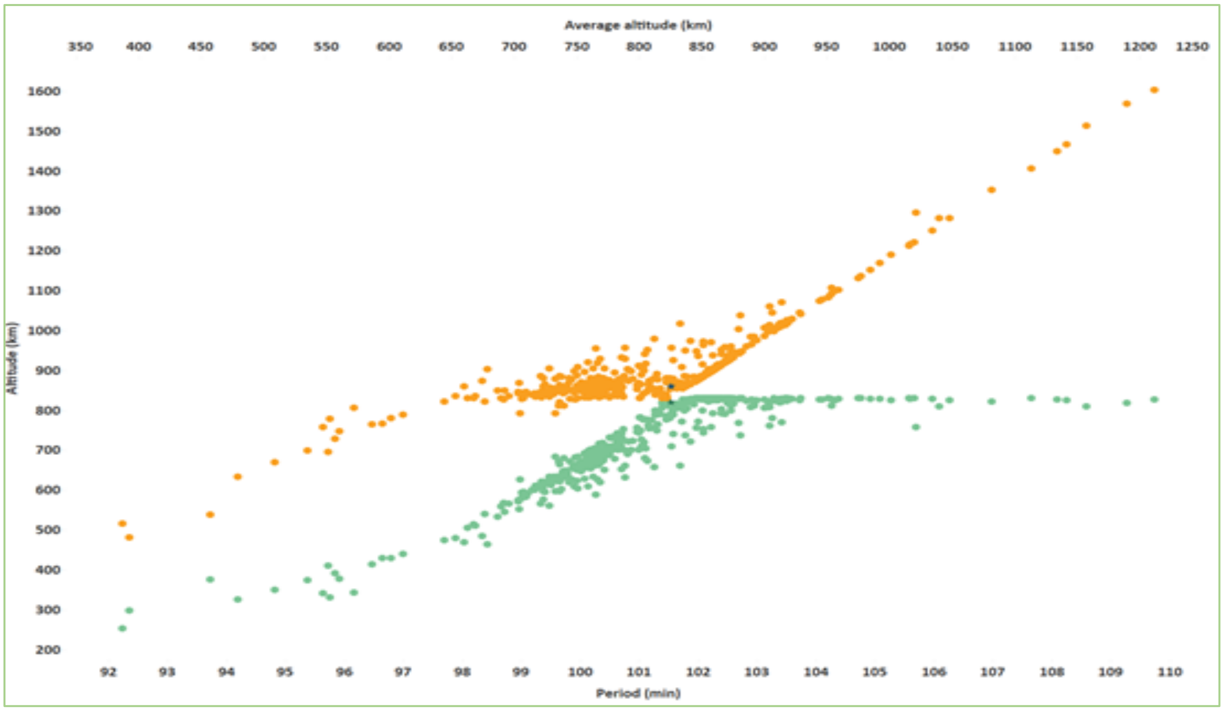


Figure 15. A fragment cloud is often represented with a Gabbard diagram showing the distribution of fragments by orbital period (x-axis) and altitude extremes (y-axis).

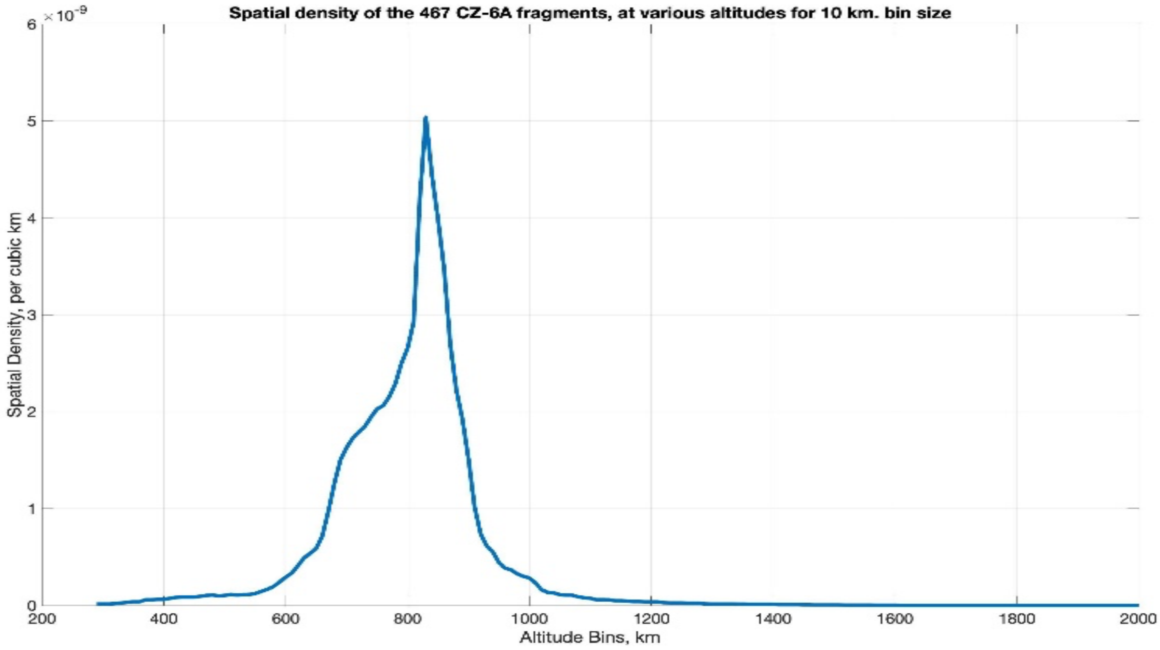
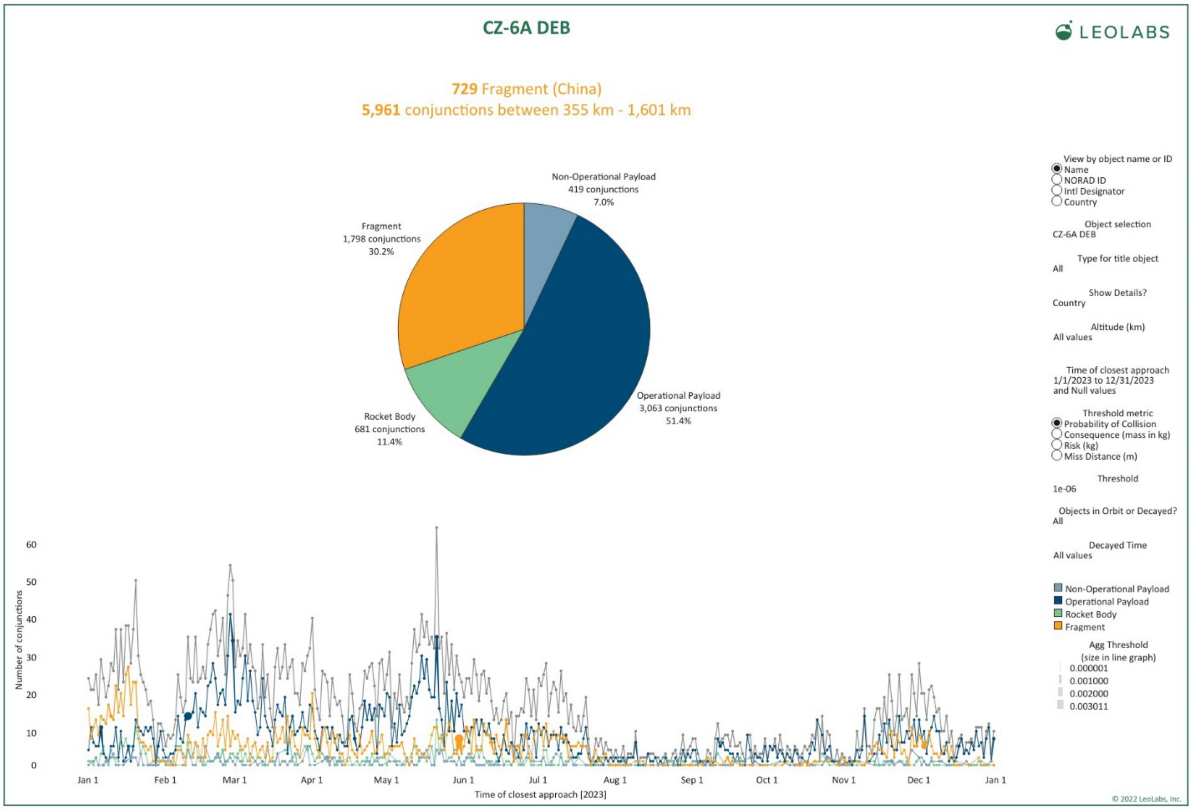


Figure 16. A spike plot, created by LeoLabs for measuring effects of a fragment cloud on the on-orbit population, plots the spatial density (i.e., # of objects per cubic kilometer) against altitude.

The spike plot provides an immediate measure of the collision risk posed to other resident space objects from a breakup event by plotting the spatial density of the fragment cloud as a function of altitude. The peak and average spatial density values can be compared to the existing background population levels at these altitudes. The spatial density at 830 km before the event was 5.6E-8, where the fragment cloud from the CZ-6A rocket body peaks at 5.0E-9. As a result, the collision probability at 830 km has risen ~9% as the result of this breakup. This percentage increase drops off rapidly to under 2% below 700 km and above 900 km.

In 2023, there were nearly 6,000 conjunctions with a PC greater than 1E-6 involving a fragment from this event. These events occurred between 355 km to 1,601 km in altitude, as shown in the figure below. Further, the number of conjunctions with a PC greater than 1E-5 and 1E-4 were 666 and 84, respectively. The figure from LeoLabs' LeoMap tool shows the distribution of conjunction events as a function of time and type of object with which the CZ-6 fragments are conjuncting; over half of the events involved an operational payload and ~11% were with rocket bodies. Of the ~700 events involving rocket bodies, 158 were with the massive SL-16 rocket bodies, proposed as the most important derelict objects to remove from LEO.



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

Object selection
CZ-6A DEB

Type for title object
All

Show Details?
Country

Altitude (km)
All values

Time of closest approach
1/1/2023 to 12/31/2023
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

Figure 17. The fragment cloud from the recent CZ-6A R/B explosion has contributed significantly to the collision risk in LEO over the last 15 months.

Constellations of Operational Payloads

While Starlink has captured the imagination and the high-level statistics regarding the absolute number of payloads added to their constellation (~1,600 in 2022 and ~1,950 in 2023), taking a closer look shows several other constellations also grew significantly since 2021: OneWeb, Planet, SpaceBee, and Spire Global all had double digit percentage growth rates of their constellations over this time.

As the number of operational payloads continues to increase, the importance of space traffic coordination grows. This is reflected in the changing proportion of high probability conjunctions (i.e., PC > 1E-6), with an increase in what we call "space traffic management (STM)" conjunctions relative to "space debris management (SDM)" conjunctions. A STM conjunction is any close approach that includes at least one operational payload while a SDM event is a conjunction between two debris objects (i.e., neither object is an operational payload). Since 2021, the balance of high-PC conjunction events involving an operational payload has gone from being 40% of the events to being 95% of events by the beginning of 2024.

Examining the filings for satellite constellations in the US and news reports abroad it is seen that over 95% of operational satellites in LEO by 2030 will be from six constellations: SpaceX V1 & V2, Guowang, Kuiper, G60, and OneWeb. Figure 18 depicts the likely trend in operational satellites from these six constellations alone through 2030.

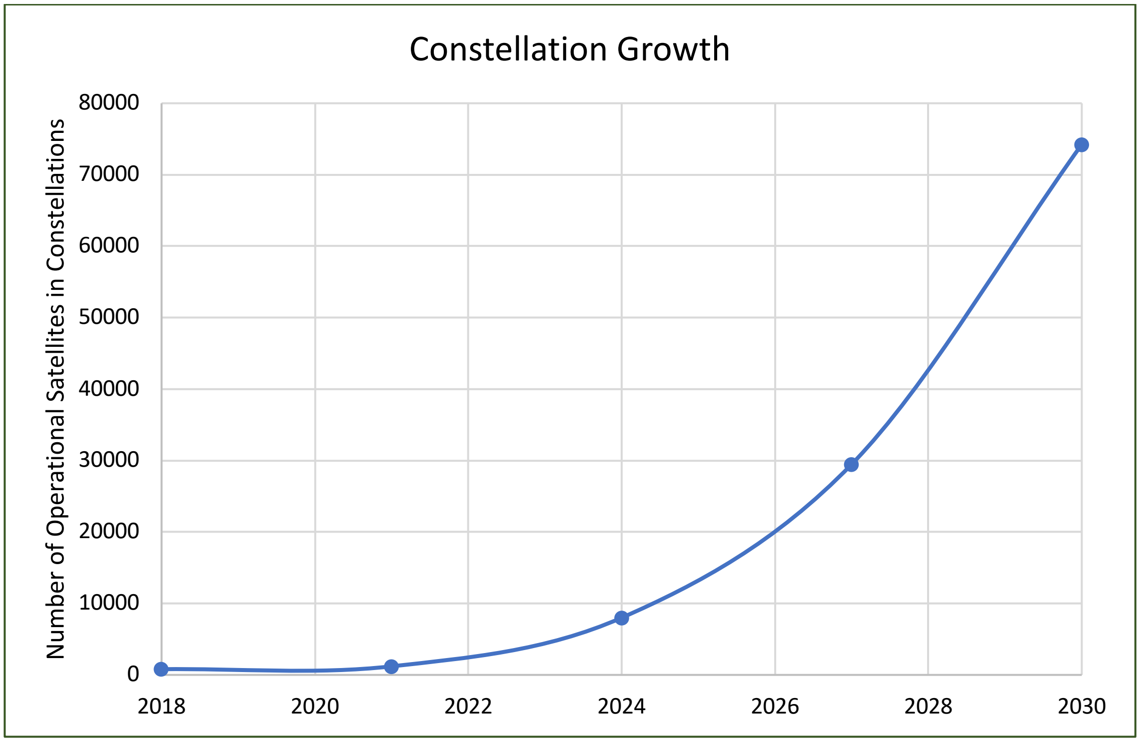


Figure 18. The growth of satellites to be part of major constellations will continue to rise exponentially through 2030 challenging space situational awareness and space traffic coordination resources and processes.

While this growth will require significant care by spacecraft operators, current constellations have shown the capability to operate thousands of satellites in close proximity very safely and reliably. Of course, we cannot ignore the space safety risk from the “other” 2,000 to 6,000 operational satellites (i.e., not in large constellations). Some satellite operators have less robust risk reduction processes so in aggregate tens or hundreds of satellites may pose a greater collision risk than thousands of responsibly-operated satellites. Further, the continued generation of thousands of fragments and abandonment of hundreds of massive derelicts will continue to present an operational collision risk to even the most responsible satellite operators.

It should be noted that the catalog population only represents about 10% of the lethal debris population in LEO. There is an estimated 250,000 fragments between 1 cm and 10 cm that are not currently being tracked by any entity to provide sufficient information to enable risk reduction maneuvers (RRMs) to avoid all of the lethal collision hazard. This hazard increases exponentially as altitude increases since the atmospheric drag at lower altitudes accelerates the reentry of the all objects but especially fragments, as they have characteristically higher area-to-mass ratios.

Three Ways to Manage the Orbital Debris Environment

The characteristics of the three major constituents highlight how much of LEO is accumulating numbers and mass of debris that are mathematically a ticking time bomb that the global aerospace community must cooperatively work to manage.

The three primary means to control the debris collision risk and support space sustainability are:

- Conjunction Data Messages (CDMs) are the currency for timely and effective **space traffic management**. Massive derelicts (i.e., rocket bodies and non-operational payloads) and fragments cannot execute risk reduction maneuvers but most of the over ~8,400 operational payloads in LEO can act on these warnings.
- Statistical probability of collision highlights the need to stop adding debris to LEO (i.e., **debris mitigation**).
- The collision rate between clusters of massive derelicts amplifies the need for **debris remediation** (i.e., active debris removal).

It is hoped that the continual discussion of these facts and figures will help motivate policymakers, regulators, space operators, and international military services to act responsibly to preserve the space environment for the generations to come. As a member of the next generation – Tamara from Williamston High School in Michigan – stated so eloquently in a recent letter to LeoLabs: “The longer that the government waits to help solve this problem, the more debris there will be in orbit.”

The persistence of the massive derelicts in the clusters centered around 840 km and 980 km bodes poorly when considering the multi-decade length of these objects interacting. As a matter of fact, at these two altitudes the probability that there will be a collision between the massive derelicts by 2025 are ~6% and ~18%, respectively.

While constellations with literally thousands of members are getting the lion’s share of the attention it is critical for all satellite operators to maintain high standards of space safety practices to include robust/responsive propulsion system, consistent/transparent PC thresholds for maneuver/abatement, sharing propagated ephemeris, and open communications.

Massive derelicts continue to be abandoned in long-lived (i.e., ≥ 25 yr) orbits, since 2004 over ~300,000 kg in ~140 R/Bs have been abandoned in LEO. This adds to the already significant debris-generating potential brewing at high altitudes within LEO with little hope for immediate removal missions over the next few years. Some good news is that fragmentation events have been abating slightly in number and severity over the last 10 years as is evidenced that only one of “top six” breakups occurred in the last decade. However, the rapid increase in operational satellites coupled with the increasing debris-generating potential of the massive derelicts and dispersed fragment clouds lingering in LEO paints a concerning picture as the global space economy is rumbling forward at a rapid pace.

Parting Comments

All the action “in” LEO of the last few years has not been in orbit; three major policy advancements of note have matured space safety principles and provided some positive trends to watch carefully to offset the ever-increasing space safety and space sustainability issues.

First, the U.S. Federal Communications Commission (FCC) implemented a reduction of the 25-yr rule (i.e., require licensees to show that their payloads will be removed from orbit within 25 years after the end of their mission lifetime) to a 5-yr rule. This forward-leaning change is indicative of national and international entities understanding the importance of leaving less debris in orbit from operational missions is important moving forward for enhancing enduring space safety (i.e., space sustainability).

Second, the United States spearheaded, through the United Nations, a call for a global moratorium on destructive on-orbit anti-satellite (ASAT) testing. This initiative is reflective of the enormous contribution of the last two on-orbit ASAT tests has had on collision risk in LEO; ~10% of all high-risk conjunctions in LEO since 1 January 2022 involved a fragment from one of these two events.

Third, Senator Hickenlooper’s (Democratic Senator from Colorado) staff rallied a bipartisan initiative that culminated in the Senate unanimously passing the Orbital Sustainability Act of 2022 (i.e., ORBITS Act). The ORBITS Act is focused on operationalizing active debris removal on massive derelict objects that have been left in orbit by previous U.S. Government space missions. It is exciting to see the U.S. commit to remediate some of the mass that poses such a great debris-generating potential.