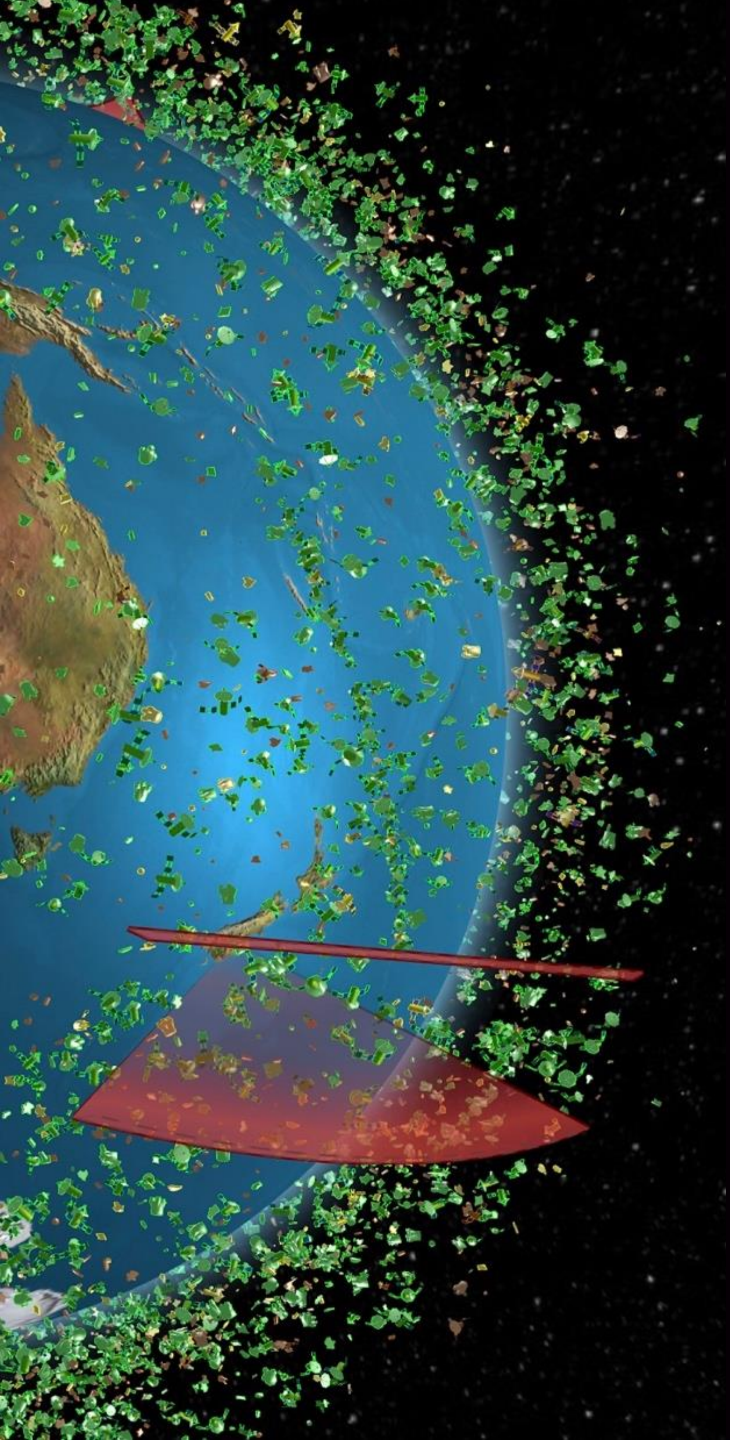


LEO LABS

IAA Space Debris Committee Meeting

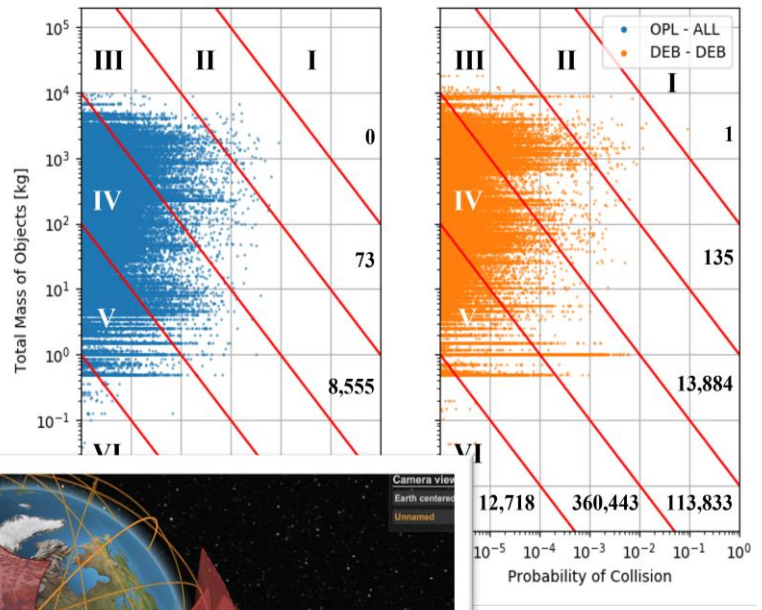
Update on LeoLabs

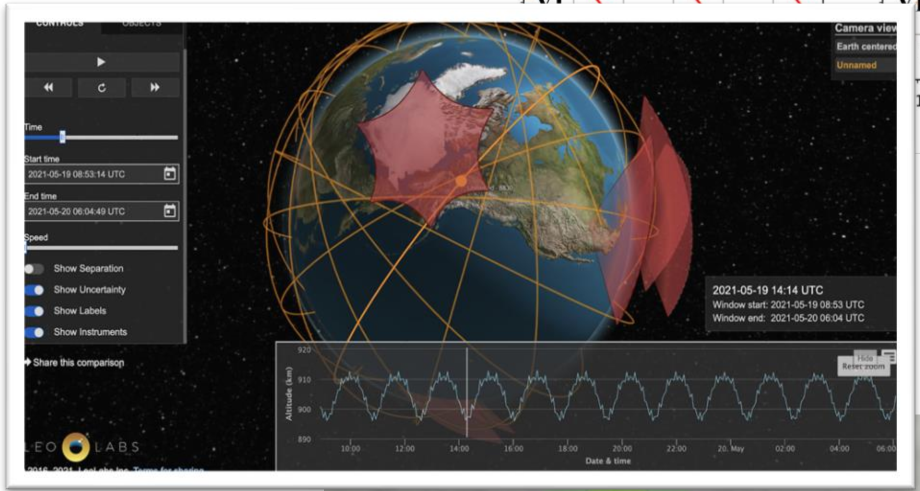
LeoLabs
Dr. Darren McKnight, Senior Technical Fellow

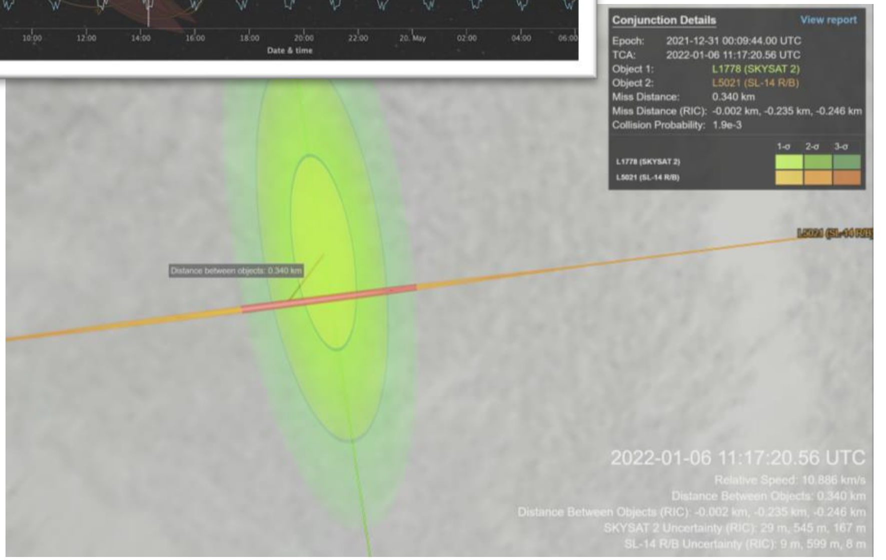
28 March2022

LeoLabs Value Proposition

- Solving tough, relevant space domain awareness (SDA) challenges
  ✓ More frequent, high-quality, and globally-derived radar observations provide foundation for enhanced…
    - Launch and early operations awareness and support
    - Responsive space traffic management
      - Timely, accurate collision risk assessments
    - Patterns of life analysis
      - Change of state (orbit and stability) awareness
    - Statistical risk and hazard evolution
      - Space incident investigations
    - Start to catalog sub-10 cm debris in 2022
- LeoLabs capabilities trajectory is steep…







LeoLabs Capabilities Trajectory

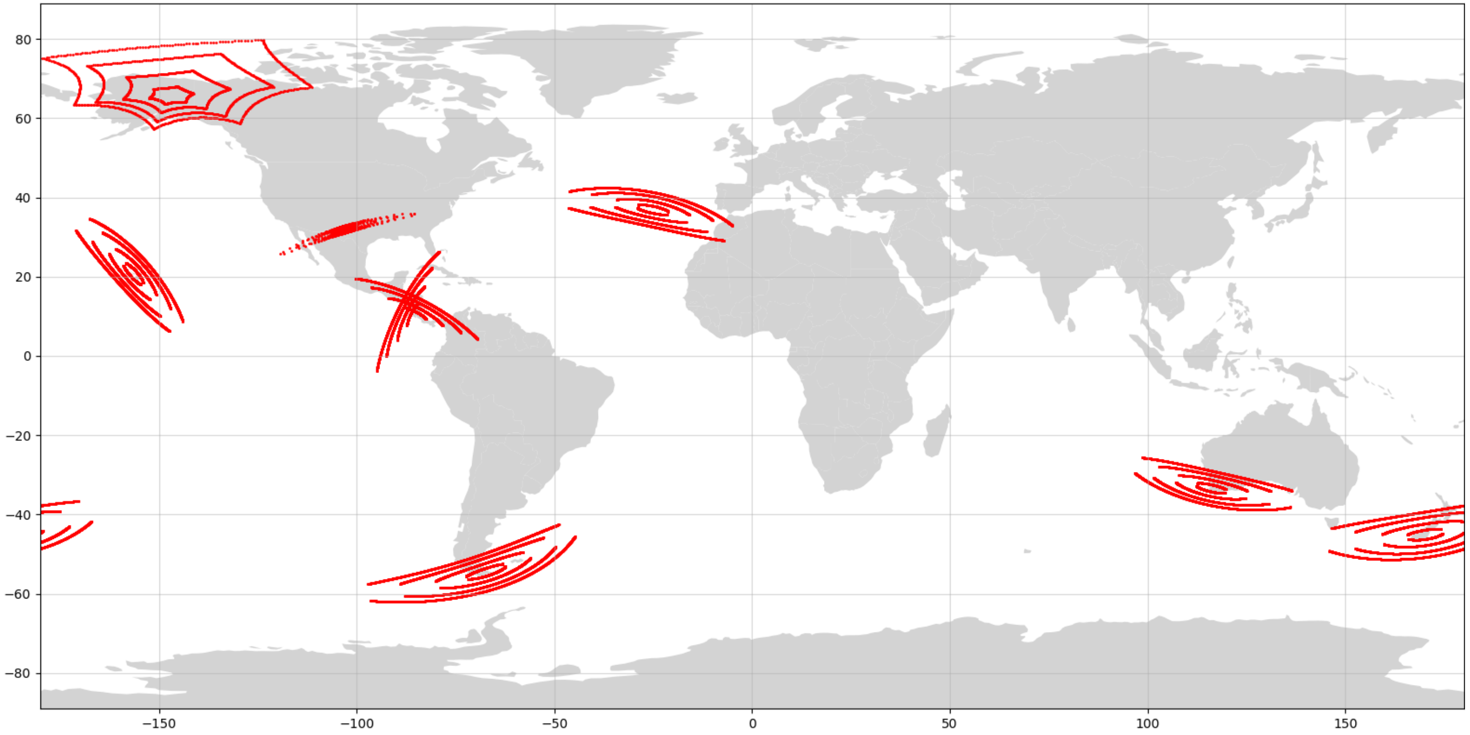
Costa Rica Space Radars (S-Band), Costa Rica – Active

Kiwi Space Radars (S-Band), Central Otago, New Zealand - Active

Midland Space Radar (UHF), Midland Texas - Active

Poker Flat Incoherent Scatter Radar (UHF), Fairbanks Alaska - Active

- Operating 6 radars in 4 locations – incl. *Southern Hemisphere*
  - ✓ Will add 6-8 more radars by the end of 2022
    - ○ Drastically improve accuracy and timeliness
    - ○ Goal to develop ability to update every object every orbit
  - ✓ Start cataloging sub-10 cm debris
- Used operationally by SpaceX, OneWeb,NOAA, Maxar, and others
  - ✓ Over 60% of operational satellites in LEO



Azores framework → Operational by June

LeoLabs System Metrics

Full transparency on LeoLabs system speed, accuracy, and quantity of data

Key Performance Indicators

12/3/2021 - 1/2/2022

LATENCY TIME - RADAR PASS TO STATE VECTOR 6 MIN	ACCURACY VS TRUTH DATA DIFFERENCE BETWEEN LEOLABS & TRUTH DATA 55 METERS	PRECISION OF STATE VECTORS RMS UNCERTAINTY 60 METERS
RADAR PASSES 742,176	MEASUREMENTS 13,438,024 ~450,000/day	OBJECTS 18,064
STATE VECTORS 586,963	CONJUNCTION DATA MESSAGES 321,357,772 ~11M/day	OPERATIONAL EPHEMERIS SCREENINGS 226,950

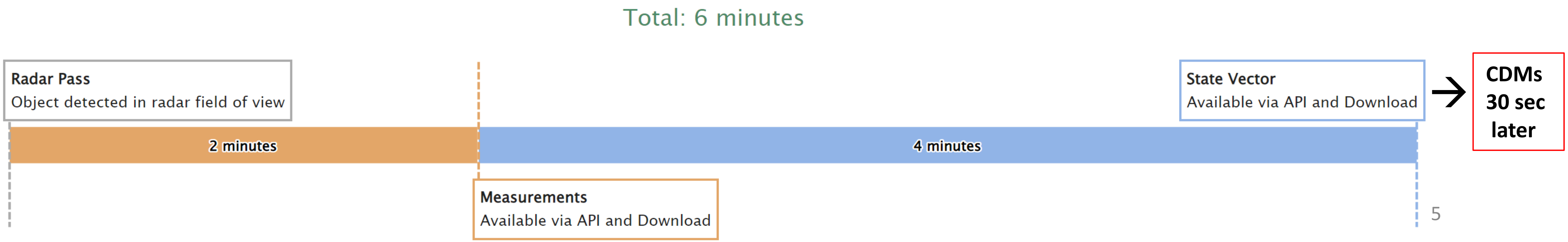
Livestream Counter

All time

MEASUREMENTS	622,543,666
STATE VECTORS	16,634,858
CONJUNCTION DATA MESSAGES	6,048,283,414

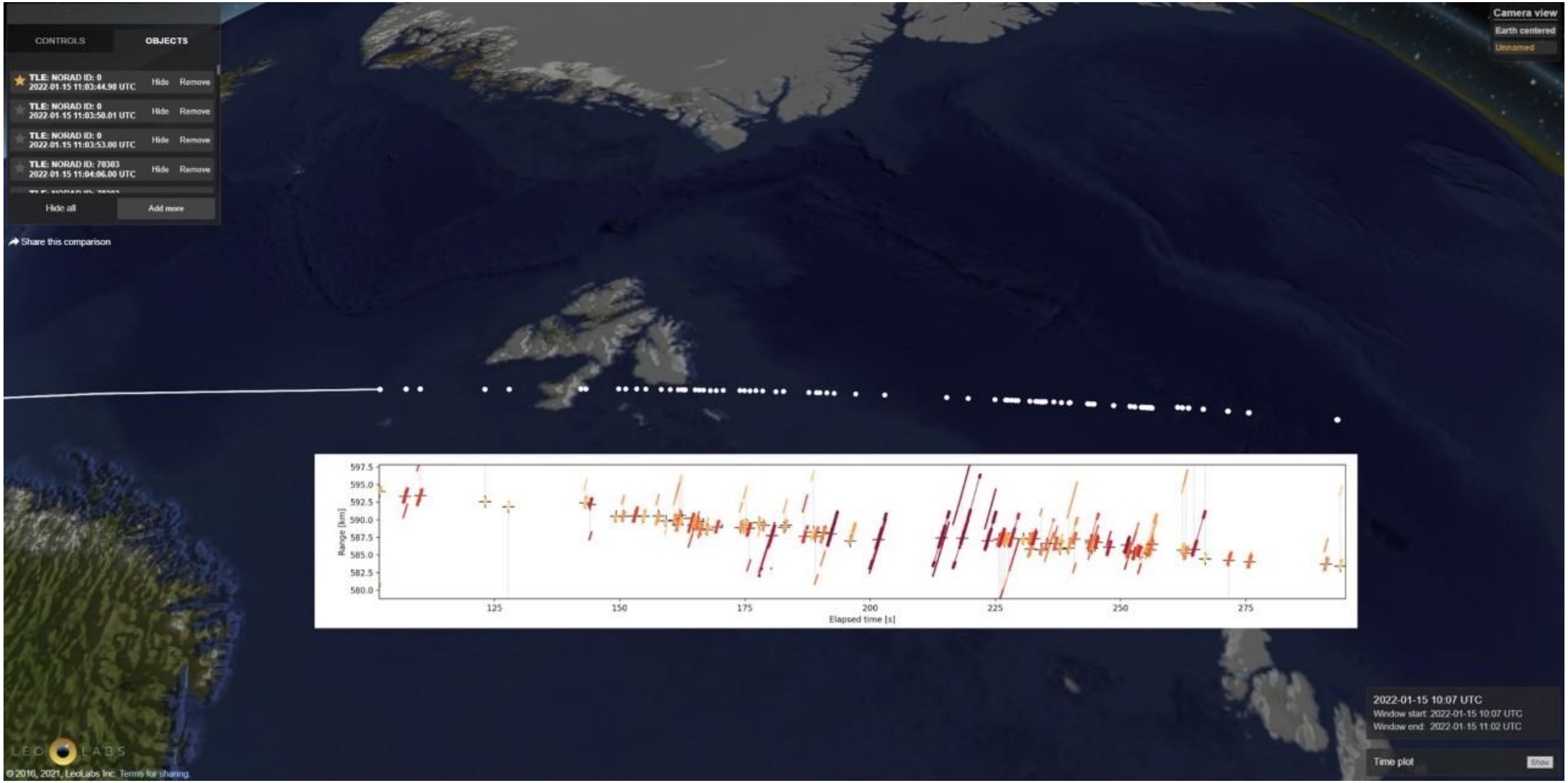
Latency

Time from when an object passes over a LeoLabs radar to when its state vector is available on the platform. Median value taken from the past 30 days.

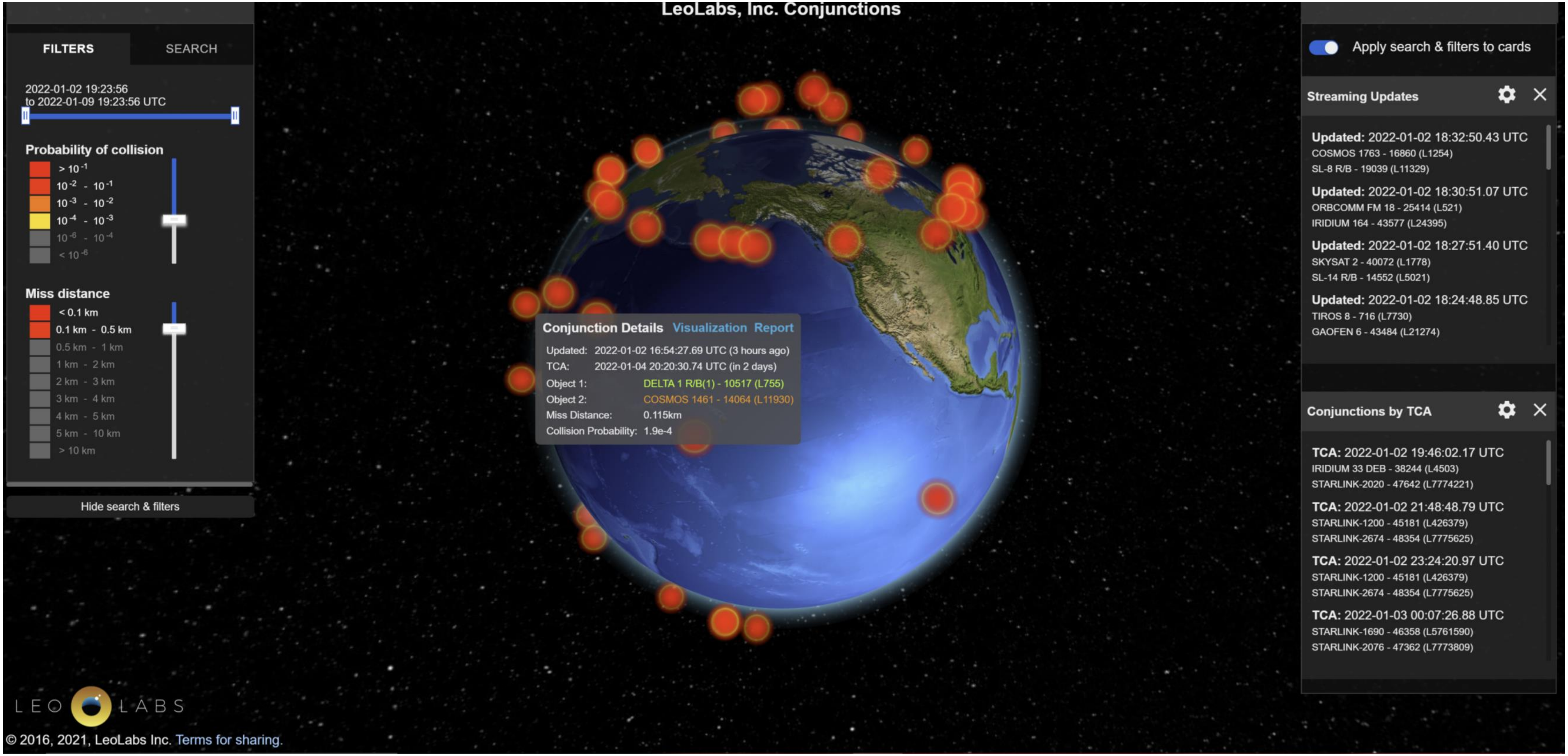


Launch and Early Orbit Operations (LEOP)

Provided object track and characterization for 32 SpaceX launches → +1750 satellites

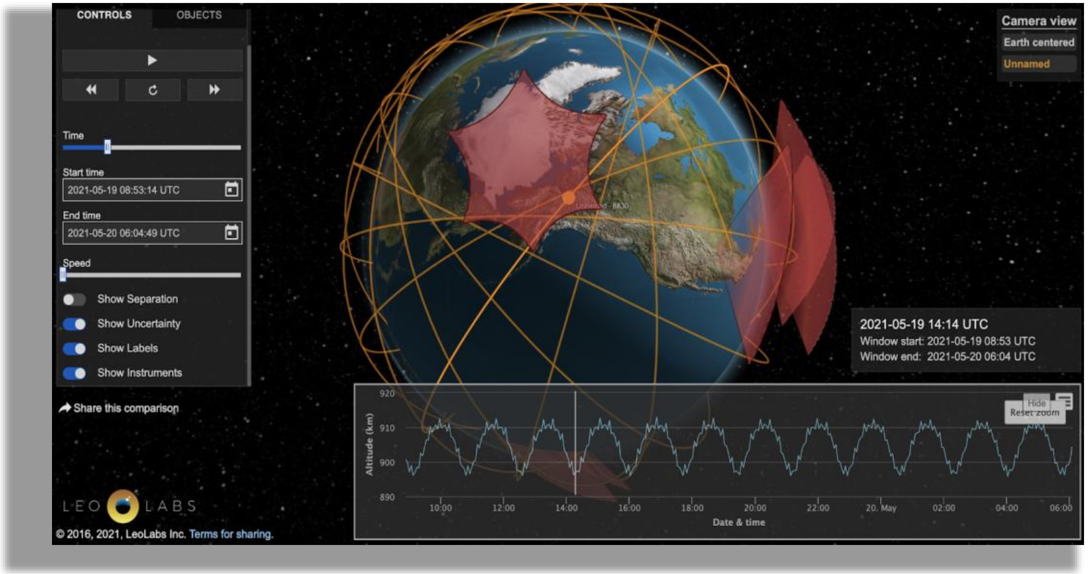


Conjunctions – 30DEC2021 to 5JAN2022: PC > 10^{-4}

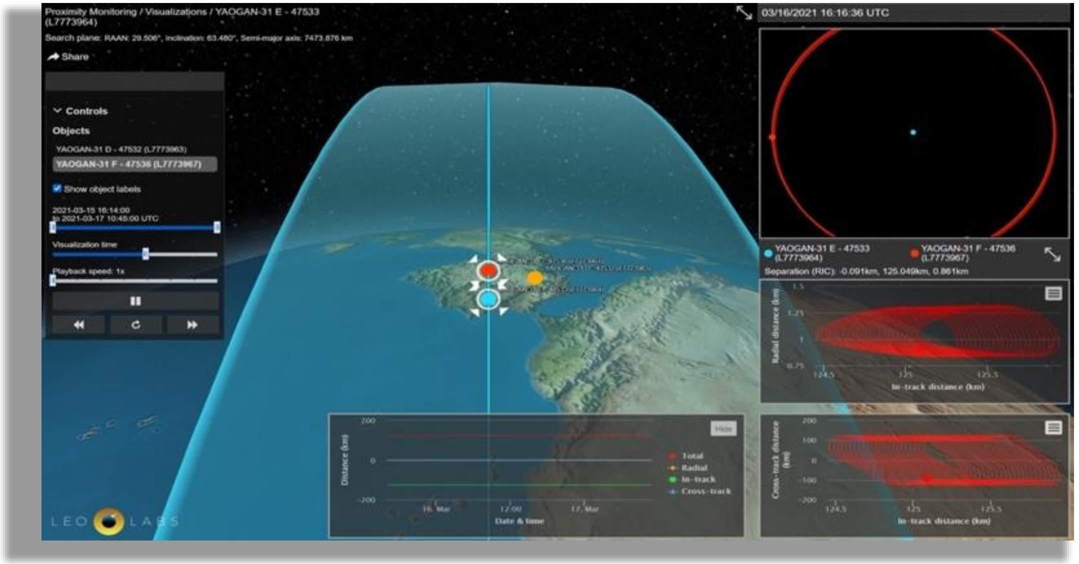


Monitor, Characterize, and Inform

- Threatening/Confusing Behaviors
  - ✓ Release of secondary small spacecraft and objects
  - ✓ Rendezvous and proximity operations (RPO)
  - ✓ Swarm and micro constellation operations
  - ✓ Unwarned maneuvers or perturbations



Haiyang-2D Launch 19 May – first pass – 4 object detection

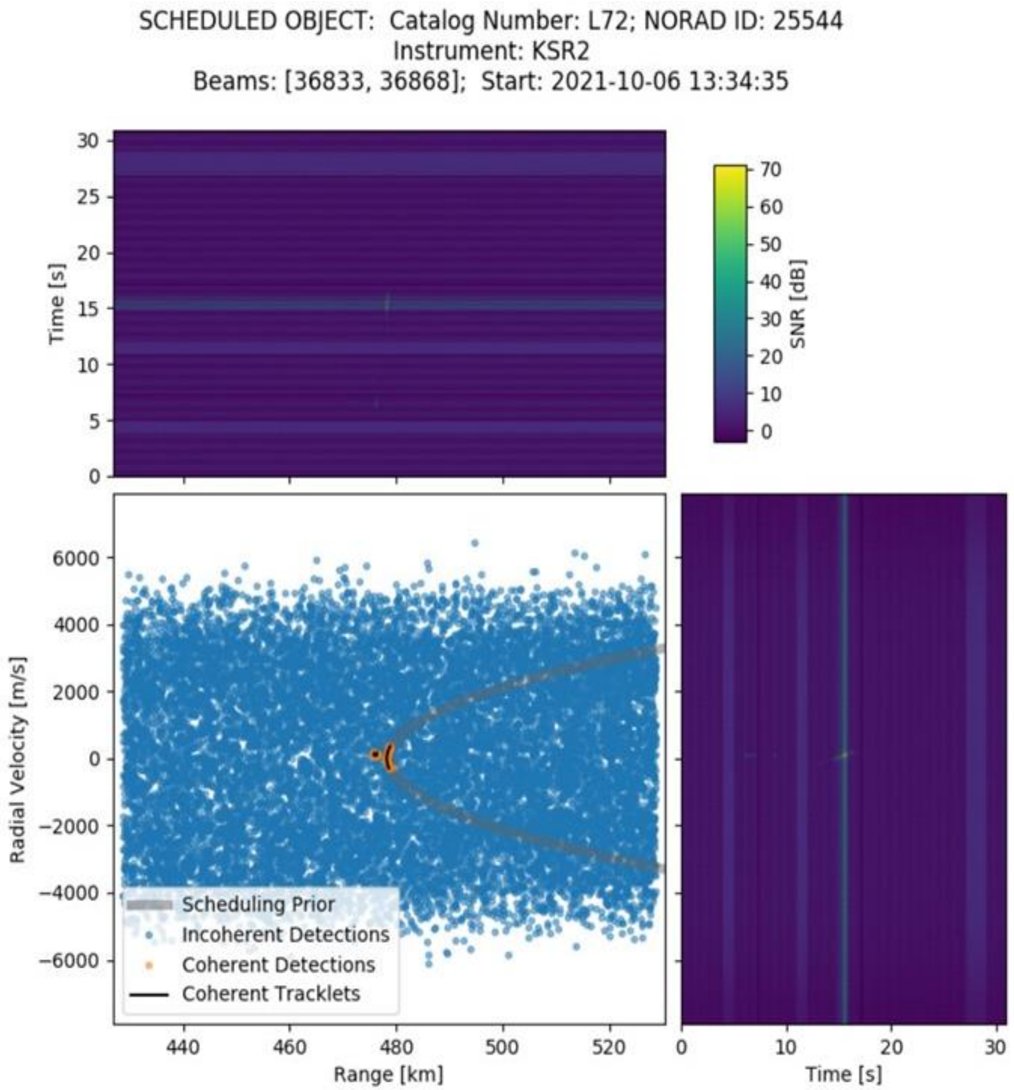


Yaogan-31D/E/F triplets

New Capability

Better Characterize "Spawning"

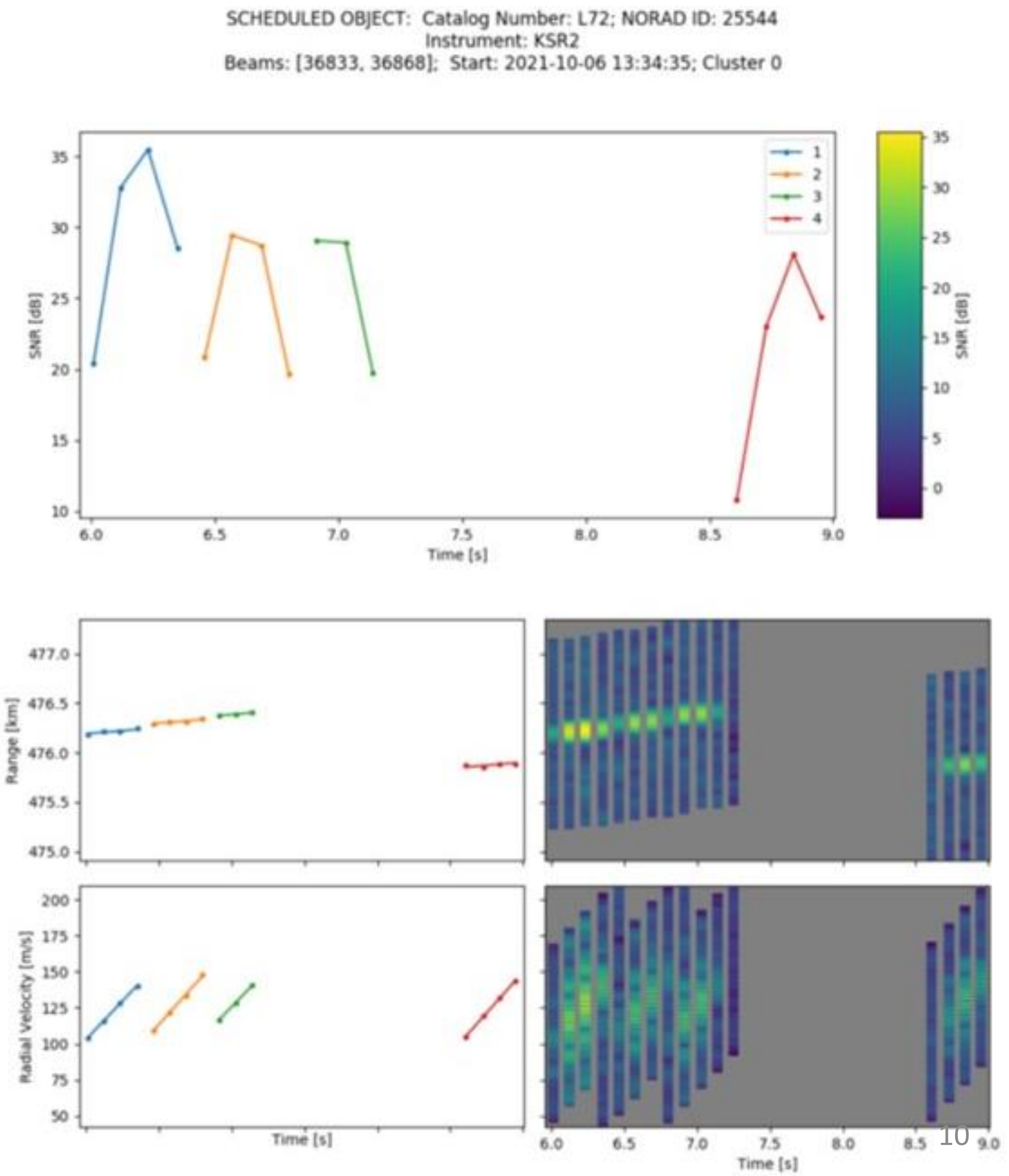
- On 6 October 2021, there was a deployment from the ISS
- LeoLabs' search pipeline at KSR2 picked it up – found after the fact
- Detection plot and the ISS tracklet plot shown to the right
- Can see that there are some detections at a slightly lower orbit than the ISS



KSR2 = 2nd radar at New Zealand site (Kiwi Space Radar)

Identified Four Objects

- Doppler measurements were key to distinguishing the three closely-spaced tracklets from each other
  - ✓ High fidelity doppler is part of our “secret sauce”
  - ✓ Most SSA radars do not acquire doppler explicitly or accurately
    - Some do not even know how to use…
  - ✓ The Space Fence’s doppler is not as good as LeoLabs’ (as per third party assessment – Omitron)
- Three 1U cubesats deployed followed later by fourth object
  - ✓ Without high quality doppler, the first three objects would not have been resolved so quickly

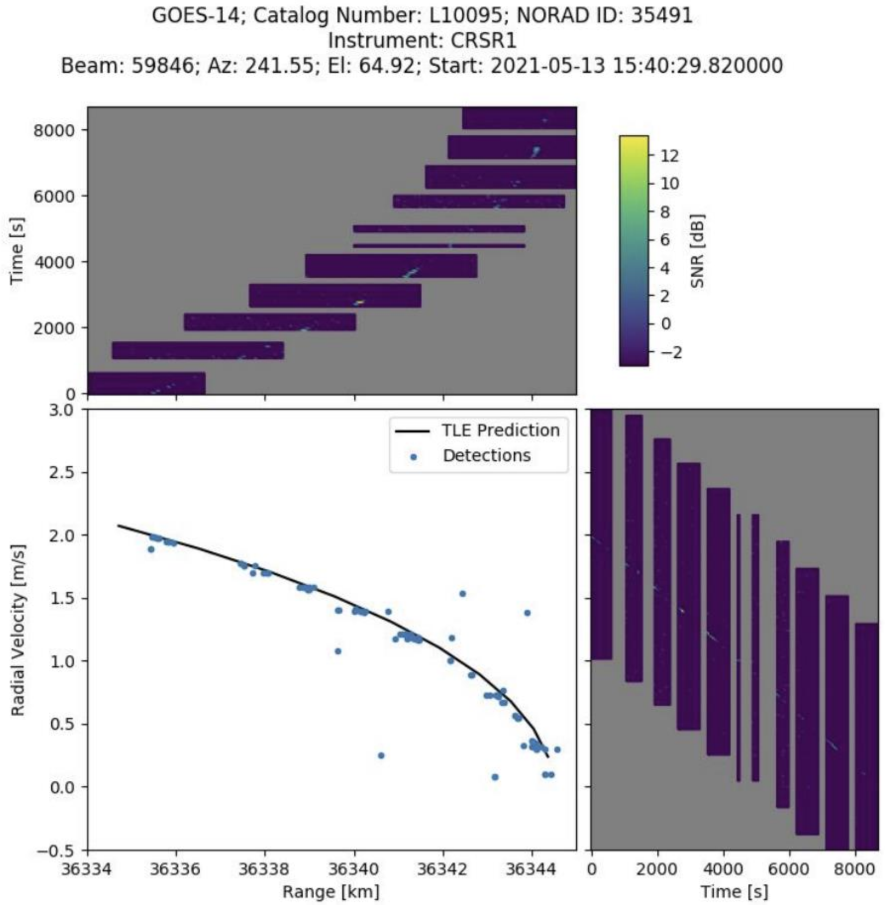


LeoLabs Going Beyond LEO…

Geosynchronous Object Tracking Proof of Concept Demo

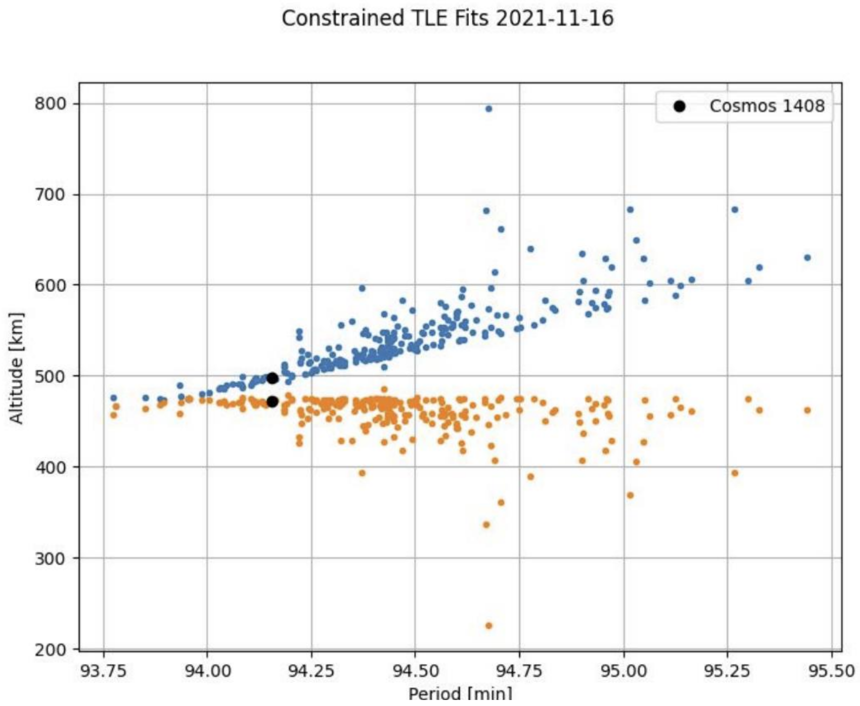
Demonstrates Viability of LeoLabs Approach to 2-D Modular Phased Array

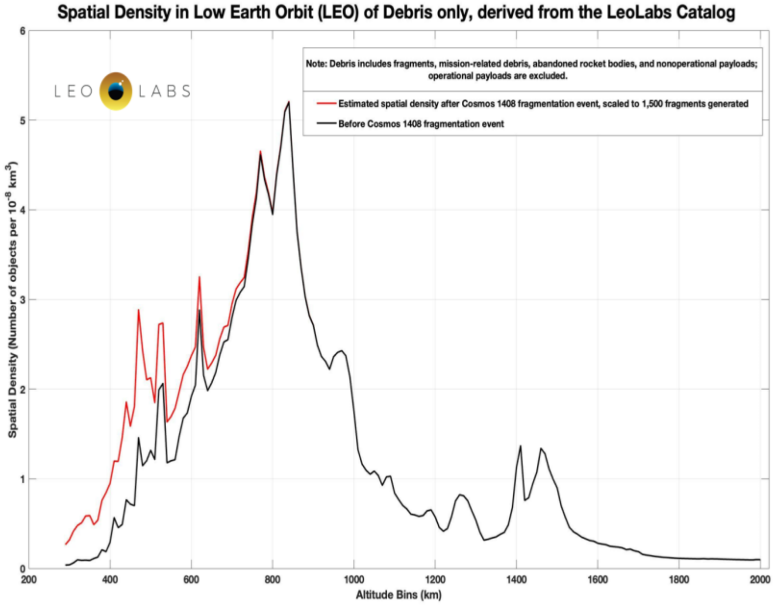
- **Using LeoLabs Costa Rica 1-D radar, we successfully tracked GOES-14 using 1 minute coherent integrations**.
- Confirmation of link budget for long integrations
- Demonstration of phase stability and control needed for long duration coherent integration

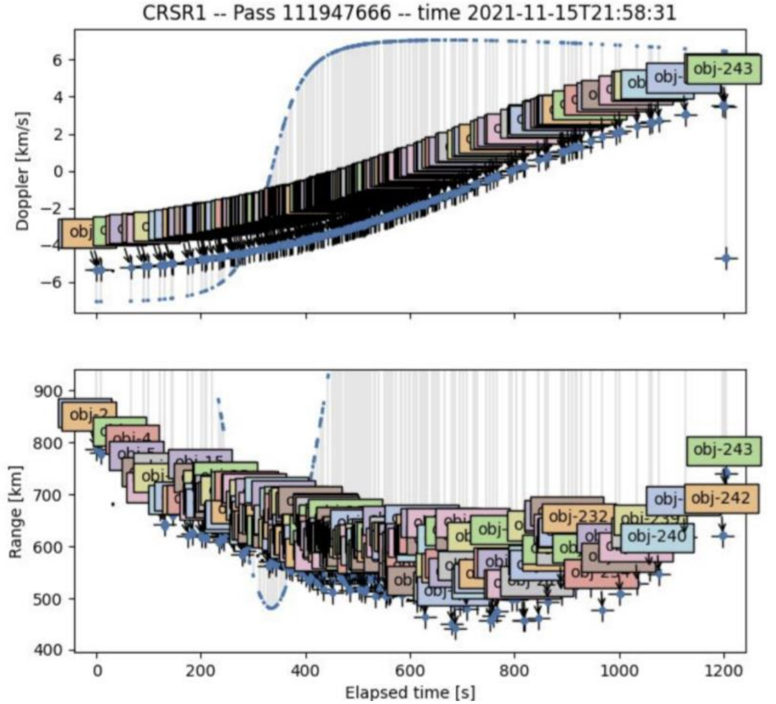


Cosmos 1408 Response

- First Gabbard within 24 hours →
- Used LEOP mode initially →
  - ✓Transitioned to new observation mode
- Value-added analysis
  - ✓Content and context!
  - ✓Double PC in most of LEO
  - ✓Physics is great equalizer
  - ✓Apply breakup models
  - ✓RCS to mass conversions



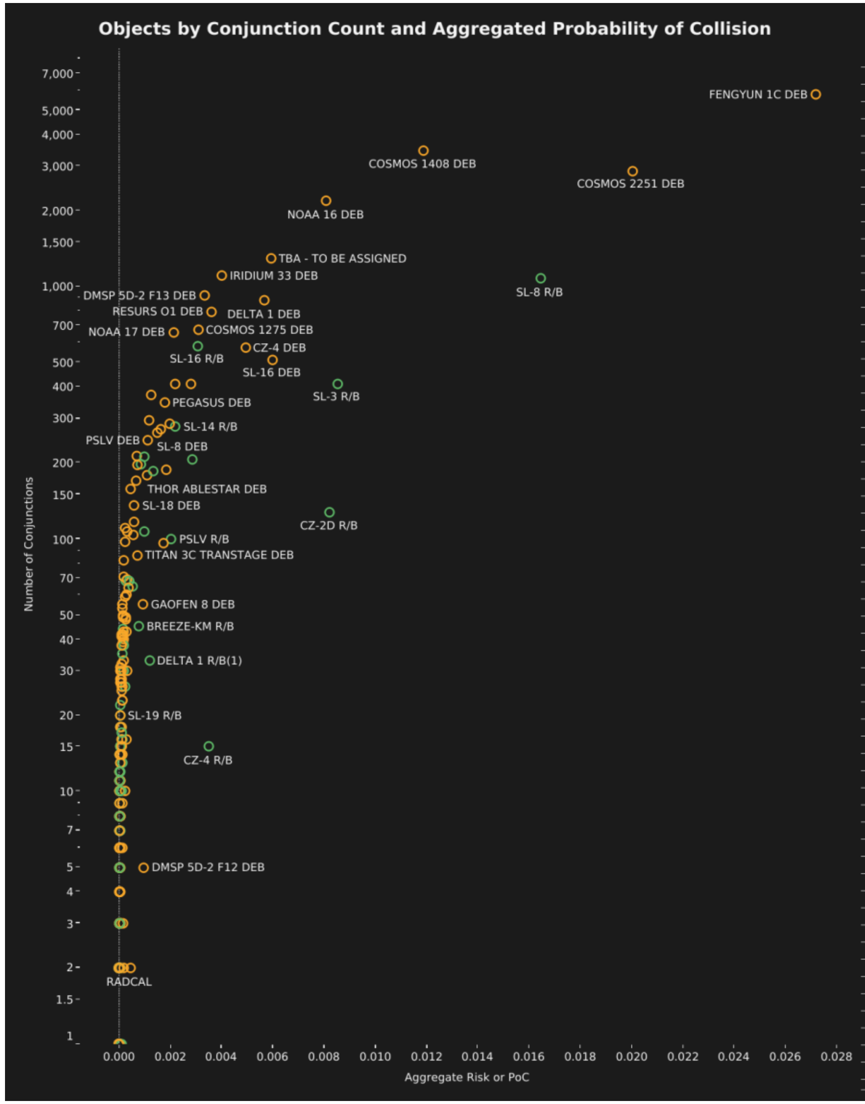




C1408 Debris Cloud Already in Top Three!!!

(January 2022)

- Fengyun 1C
  - ✓~#2800
- Cosmos 1408
  - ✓~#1,500
- Cosmos 2251
  - ✓~#1,100
- Altitude and mechanism of breakup both matter…



Rank by Conjunction Count

FENGYUN 1C DEB	1	5,745
COSMOS 1408 DEB	2	3,461
COSMOS 2251 DEB	3	2,880
NOAA 16 DEB	4	2,183
TBA - TO BE ASSIGNE..	5	1,296
IRIDIUM 33 DEB	6	1,103
SL-8 R/B	7	1,076
DMSP 5D-2 F13 DEB	8	926
DELTA 1 DEB	9	881
RESURS O1 DEB	10	793
COSMOS 1275 DEB	11	677
NOAA 17 DEB	12	661
SL-16 R/B	13	584
CZ-4 DEB	14	572
SL-16 DEB	15	515
SL-3 R/B	16	414
CZ-2D DEB	17	412
THORAD AGENA D D..	18	411
METEOR 2-5 DEB	19	373
PEGASUS DEB	20	348
DMSP 5D-2 F11 DEB	21	294
SL-14 DEB	22	285
SL-14 R/B	23	279
CZ-4B DEB	24	272
SL-8 DEB	25	264
PSLV DEB	26	246
YUNHAI 1-02 DEB	27	214
CZ-4B R/B	28	212
CZ-4C R/B	29	207
CZ-2C R/B	30	197
CBERS 1 DEB	31	196
COSMOS 1867 COOL..	32	189
H-2A R/B	33	186
THOR ABLESTAR DEB	34	178
CZ-4C DEB	35	171
SL-3 DEB	36	158
SL-18 DEB	37	136
CZ-2D R/B	38	128
WORLDVIEW 2 DEB	39	117
MINOTAUR 4 DEB	40	111
METEOR 2-8 DEB	41	107
ARIANE 40 R/B	41	107
METEOR 2-7 DEB	43	104
PSLV R/B	44	100
FREGAT DEB	45	98
COSMOS 252 DEB	46	96
TITAN 3C TRANSTAG..	47	86
METEOR 2-11 DEB	48	82
METEOR 2-17 DEB	49	71
H-2A DEB	50	69
PEGASUS R/B	51	68
DELTA 1 R/B	51	68
DELTA 2 R/B(1)	53	65
CZ-2C DEB	54	64
ARIANE 1 DEB	55	60
SL-8 DEB *	56	59
GAOFEN 8 DEB	57	55
DMSP 5D-2 F6 DEB	57	55
THORAD DELTA 1 DEB	59	53
OPS 4682 DEB	60	50

Rank by Aggregated Probability of Collision

FENGYUN 1C DEB	1	0.02717
COSMOS 2251 DEB	2	0.02001
SL-8 R/B	3	0.01645
COSMOS 1408 DEB	4	0.01188
SL-3 R/B	5	0.00852
CZ-2D R/B	6	0.00821
NOAA 16 DEB	7	0.00809
SL-16 DEB	8	0.00597
TBA - TO BE ASSIGNE..	9	0.00593
DELTA 1 DEB	10	0.00568
CZ-4 DEB	11	0.00493
IRIDIUM 33 DEB	12	0.00400
RESURS O1 DEB	13	0.00360
CZ-4 R/B	14	0.00350
DMSP 5D-2 F13 DEB	15	0.00332
COSMOS 1275 DEB	16	0.00309
SL-16 R/B	17	0.00305
CZ-4C R/B	18	0.00287
THORAD AGENA D D..	19	0.00278
SL-14 R/B	20	0.00220
CZ-2D DEB	21	0.00219
NOAA 17 DEB	22	0.00212
PSLV R/B	23	0.00203
SL-14 DEB	24	0.00197
COSMOS 1867 COOL..	25	0.00183
PEGASUS DEB	26	0.00178
COSMOS 252 DEB	27	0.00173
CZ-4B DEB	28	0.00161
SL-8 DEB	29	0.00149
H-2A R/B	30	0.00131
METEOR 2-5 DEB	31	0.00124
DELTA 1 R/B(1)	32	0.00118
DMSP 5D-2 F11 DEB	33	0.00116
PSLV DEB	34	0.00113
THOR ABLESTAR DEB	35	0.00110
CZ-4B R/B	36	0.00099
ARIANE 40 R/B	37	0.00099
DMSP 5D-2 F12 DEB	38	0.00097
GAOFEN 8 DEB	39	0.00093
CZ-2C R/B	40	0.00087
BREEZE-KM R/B	41	0.00077
CBERS 1 DEB	42	0.00073
TITAN 3C TRANSTAG..	43	0.00071
YUNHAI 1-02 DEB	44	0.00068
CZ-4C DEB	45	0.00067
WORLDVIEW 2 DEB	46	0.00060
SL-18 DEB	47	0.00059
METEOR 2-7 DEB	48	0.00057
DELTA 2 R/B(1)	49	0.00051
RADCAL	50	0.00045
SL-3 DEB	51	0.00044
DELTA 1 R/B	52	0.00037
CZ-2C DEB	53	0.00037
H-2A DEB	54	0.00033
METEOR 2-8 DEB	55	0.00033
METEOR 2-6 DEB	56	0.00032
COSMOS 249 DEB *	57	0.00030
ASTRO H DEB	58	0.00029
ARIANE 1 DEB	59	0.00028
COSMOS 886 DEB	60	0.00027

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Rank by Object Name or NORAD ID
Name
NORAD ID

Filter by Object Name/ID
All

Highlight Object Name/ID
No items highlighted

Aggregate Selection
Risk (kg)
Prob of Collision

Type
Fragment
Non-Operational Payload
Operational Payload
Rocket Body

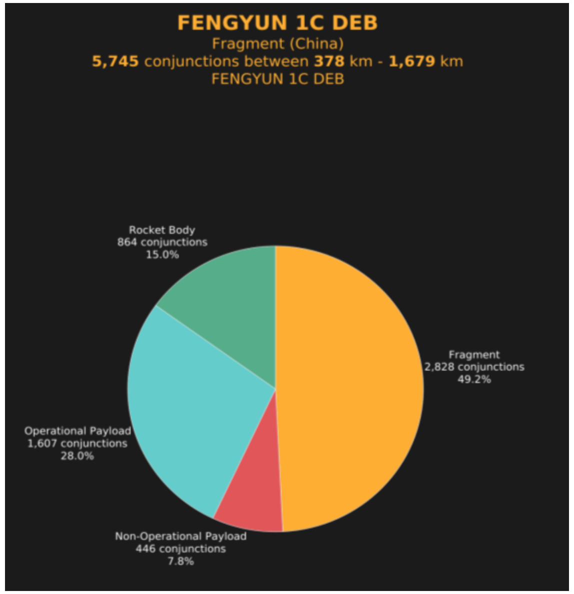
Altitude (km)
All values

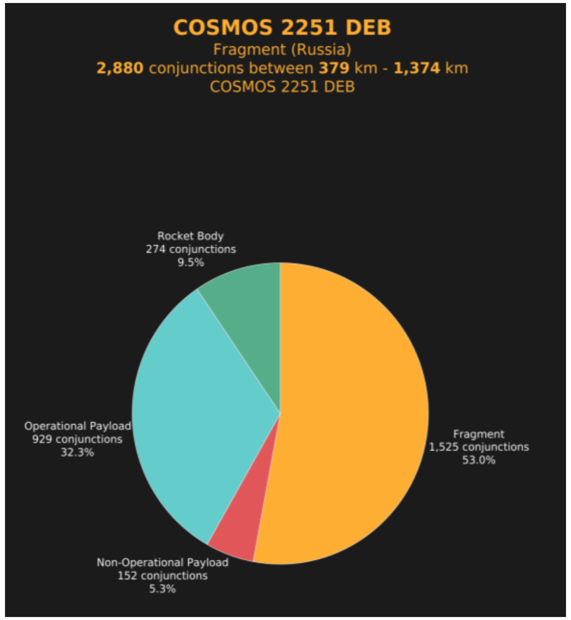
Time of Closest Approach
January 1, 2022 to January 31, 2...

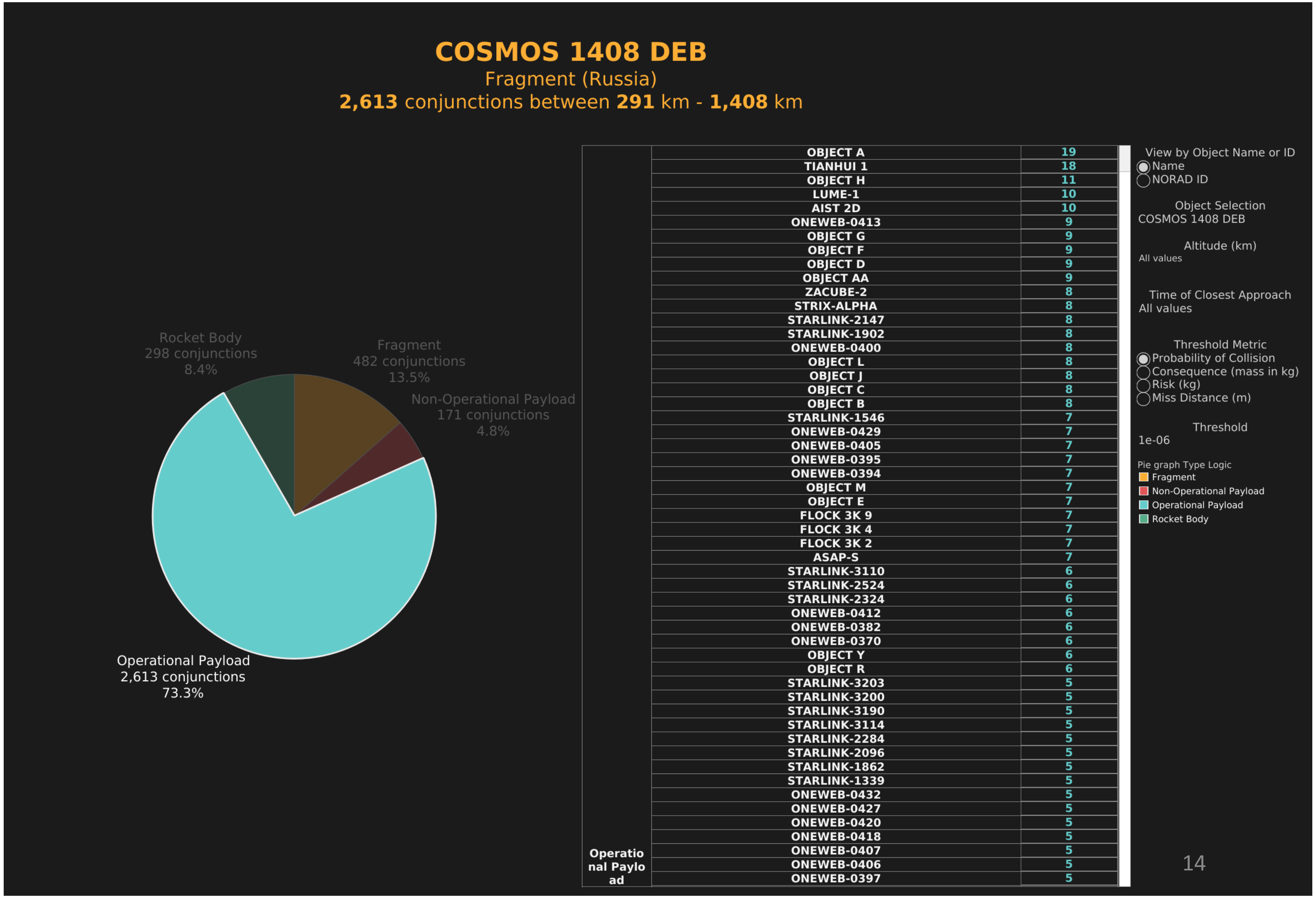
Fragment
Rocket Body

* indicates multiple object types within the object name

Cosmos 1408: Lower and Fewer Fragments/Mass…







Operational Payload	OBJECT A	19
	TIANHUI 1	18
	OBJECT H	11
	LUME-1	10
	AIST 2D	10
	ONEWEB-0413	9
	OBJECT G	9
	OBJECT F	9
	OBJECT D	9
	OBJECT AA	9
	ZACUBE-2	8
	STRIX-ALPHA	8
	STARLINK-2147	8
	STARLINK-1902	8
	ONEWEB-0400	8
	OBJECT L	8
	OBJECT J	8
	OBJECT C	8
	OBJECT B	8
	STARLINK-1546	7
	ONEWEB-0429	7
	ONEWEB-0405	7
	ONEWEB-0395	7
	ONEWEB-0394	7
	OBJECT M	7
	OBJECT E	7
	FLOCK 3K 9	7
	FLOCK 3K 4	7
	FLOCK 3K 2	7
	ASAP-S	7
	STARLINK-3110	6
	STARLINK-2524	6
	STARLINK-2324	6
	ONEWEB-0412	6
	ONEWEB-0382	6
	ONEWEB-0370	6
	OBJECT Y	6
	OBJECT R	6
	STARLINK-3203	5
	STARLINK-3200	5
	STARLINK-3190	5
	STARLINK-3114	5
	STARLINK-2284	5
	STARLINK-2096	5
	STARLINK-1862	5
	STARLINK-1339	5
	ONEWEB-0432	5
	ONEWEB-0427	5
	ONEWEB-0420	5
	ONEWEB-0418	5
	ONEWEB-0407	5
	ONEWEB-0406	5
	ONEWEB-0397	5

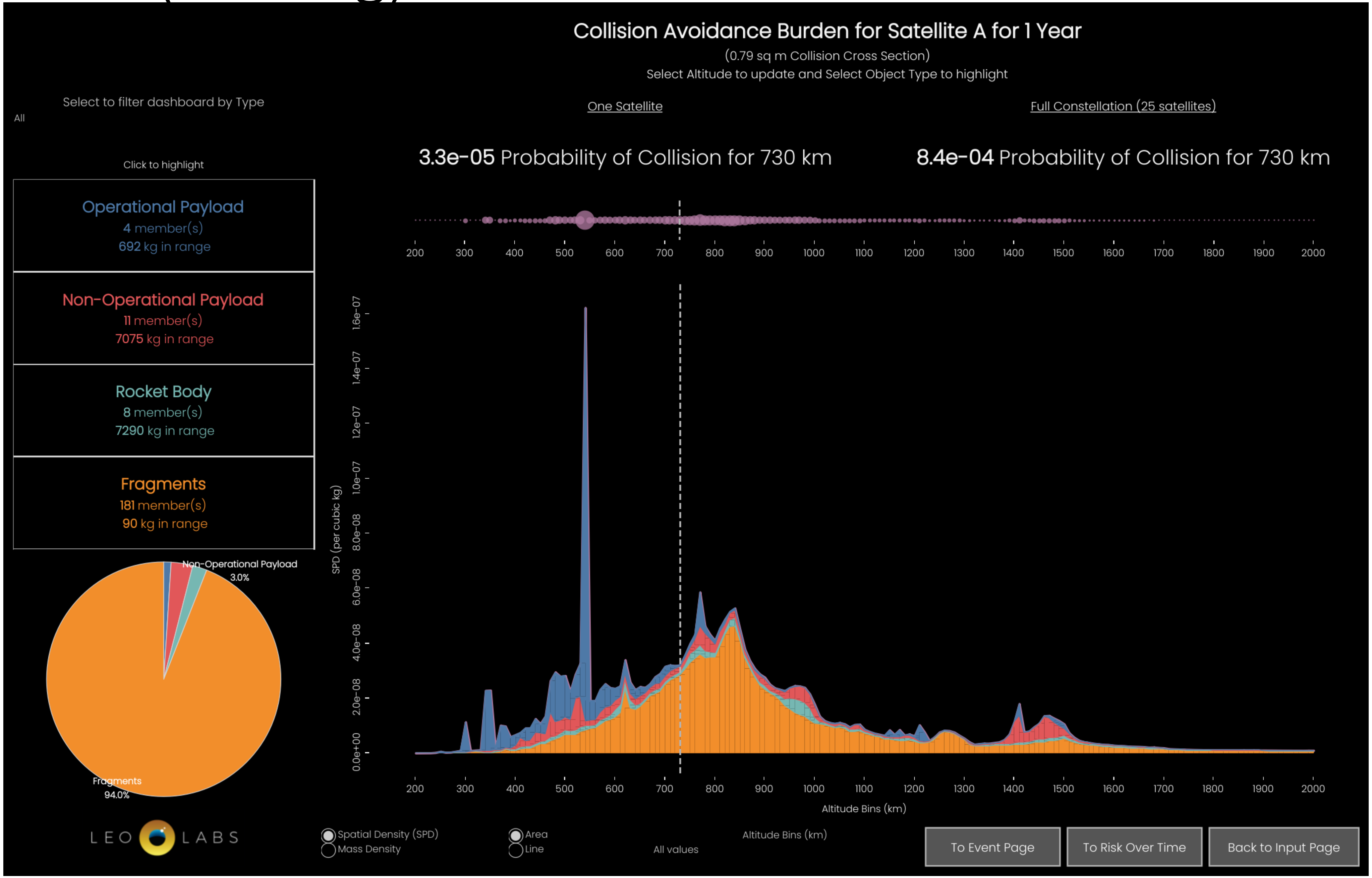
Statistical Risk Assessment

Asking the Right Questions…

- LeoLabs radar and cloud-based computational engine provides data in near-real-time to support current collision risk and understanding of space system behavior at a higher cadence, precision, and accuracy than ever before…
- This also creates a rich data base that powers unique insights into a mapping of low Earth orbit
  - ✓Catalyzing a new industry of "space realtors"…??? Location, location, location!
  - ✓Capturing temporal, spatial, and national trends
  - ✓Realize a deep awareness of the situation – not just an object count…

This is what a real space traffic management system should provide!

PC (Catalog) = Collision Avoidance Burden



Mass is Distributed Non-Uniformly in LEO

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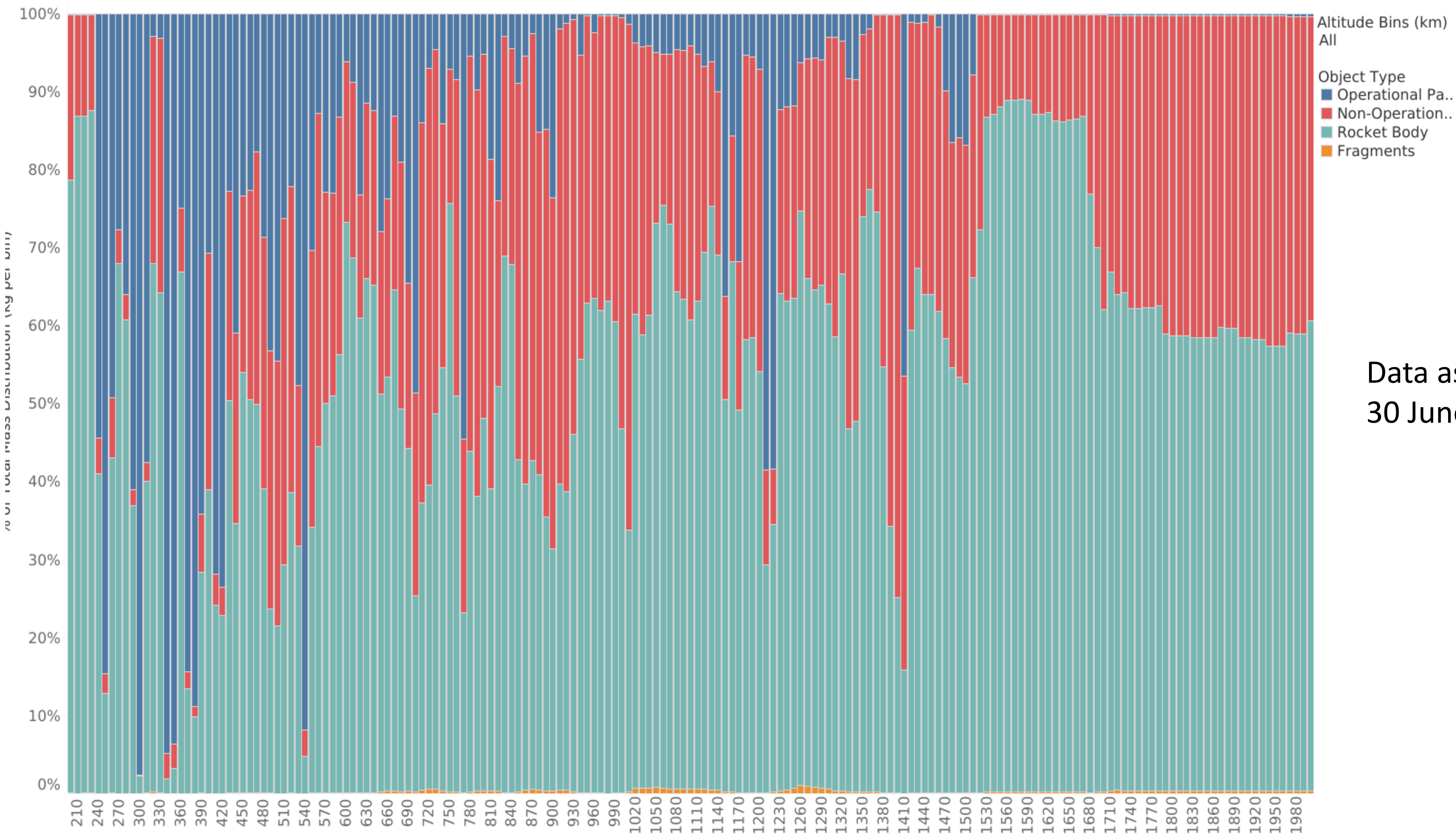


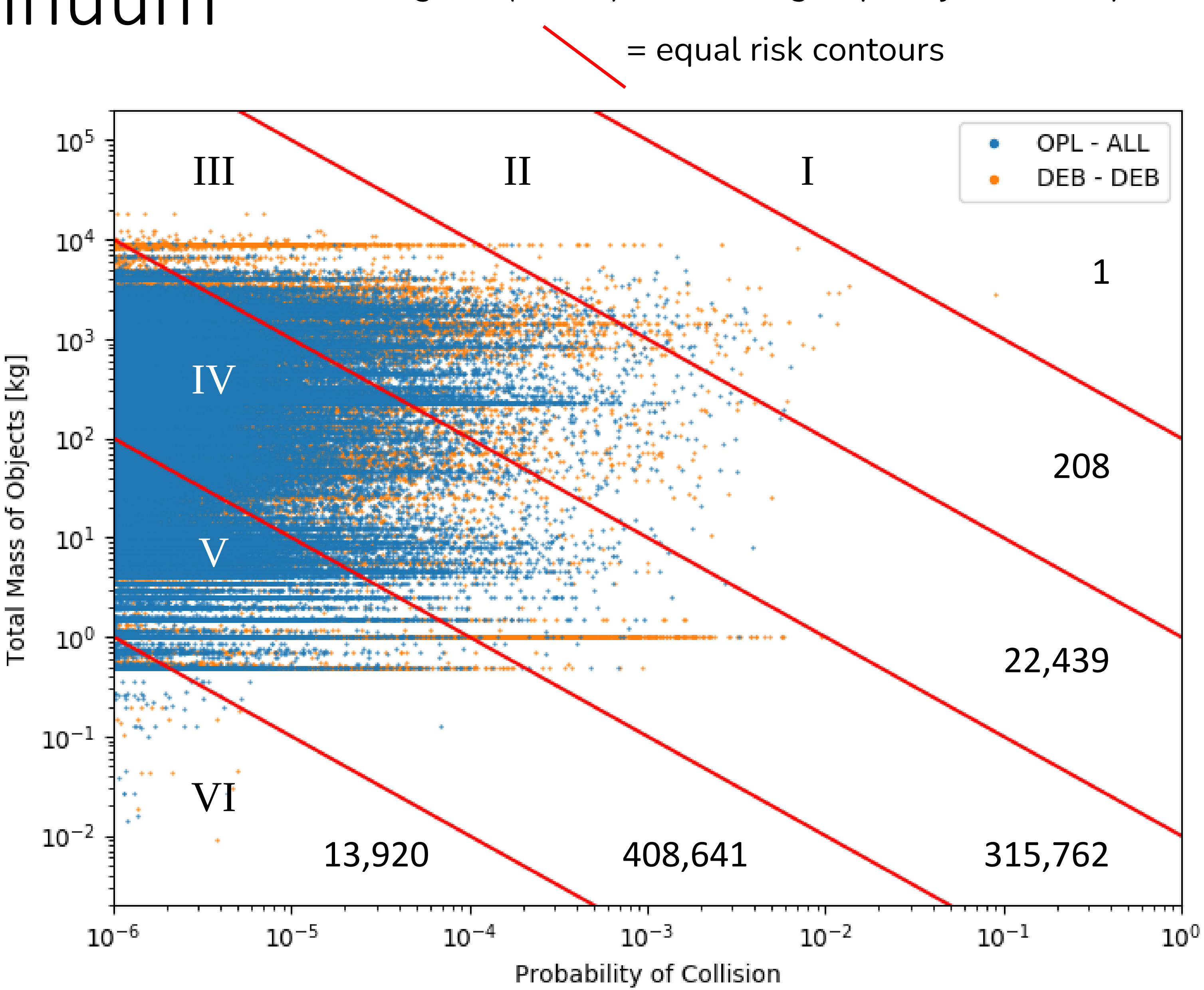
Data as of
30 June 2021

LEO Collision Risk Continuum *(LCRC)*

- ~800k conjunctions with PC > 1E-6 from 1JUL20 – 30 Jun21
  - ✓ OPL-ALL = STM
  - ✓ DEB-DEB = SDM
- Plot probability of collision versus consequence (i.e., debris-generating potential)
- Highlights debris-generating potential reduction by STM & SDM
  - ✓ Look at space via a risk aperture; not driven by Space News headlines about "m^%*-constellations"

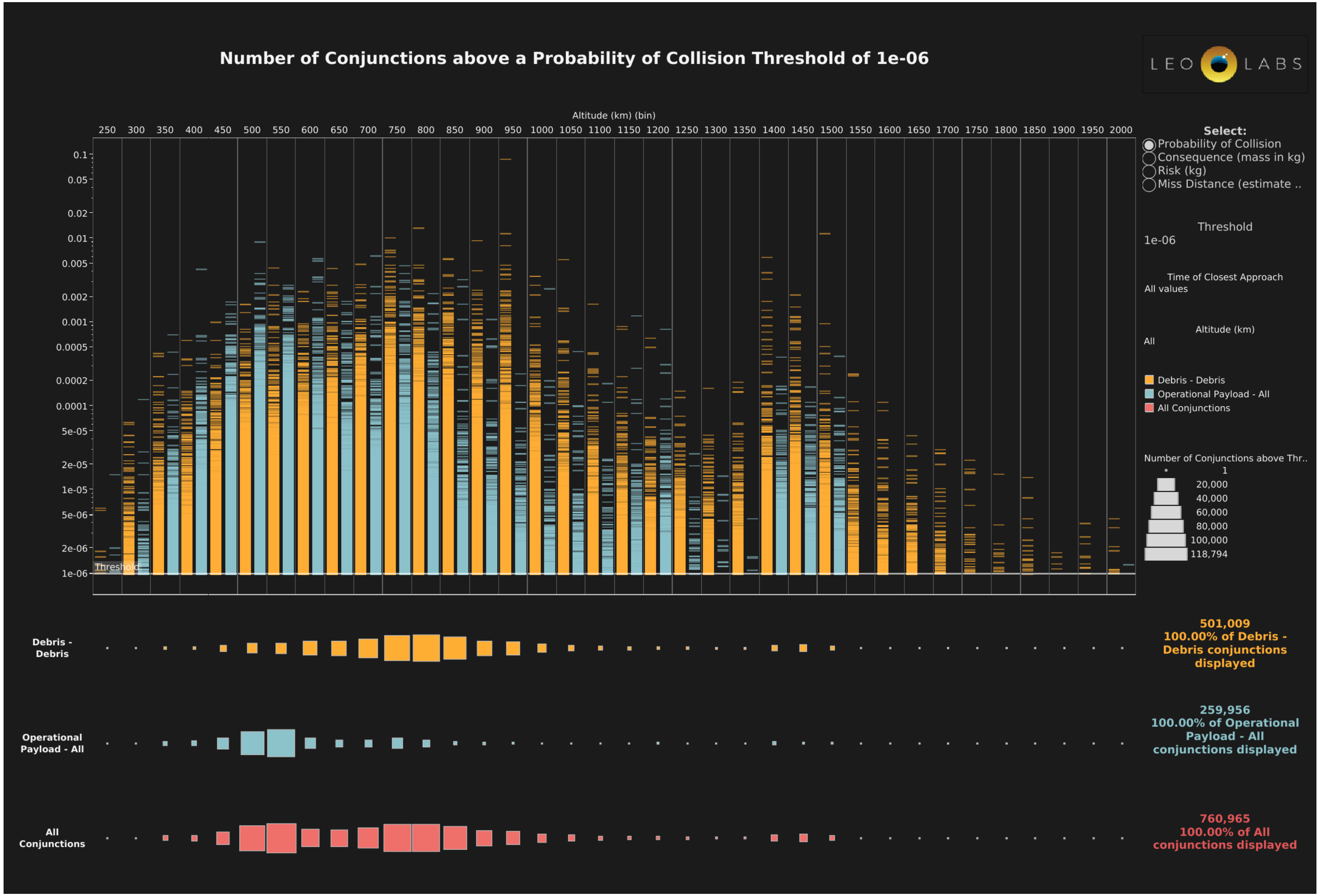
Six regions (I to VI) formed to group conjunctions by risk

= equal risk contours



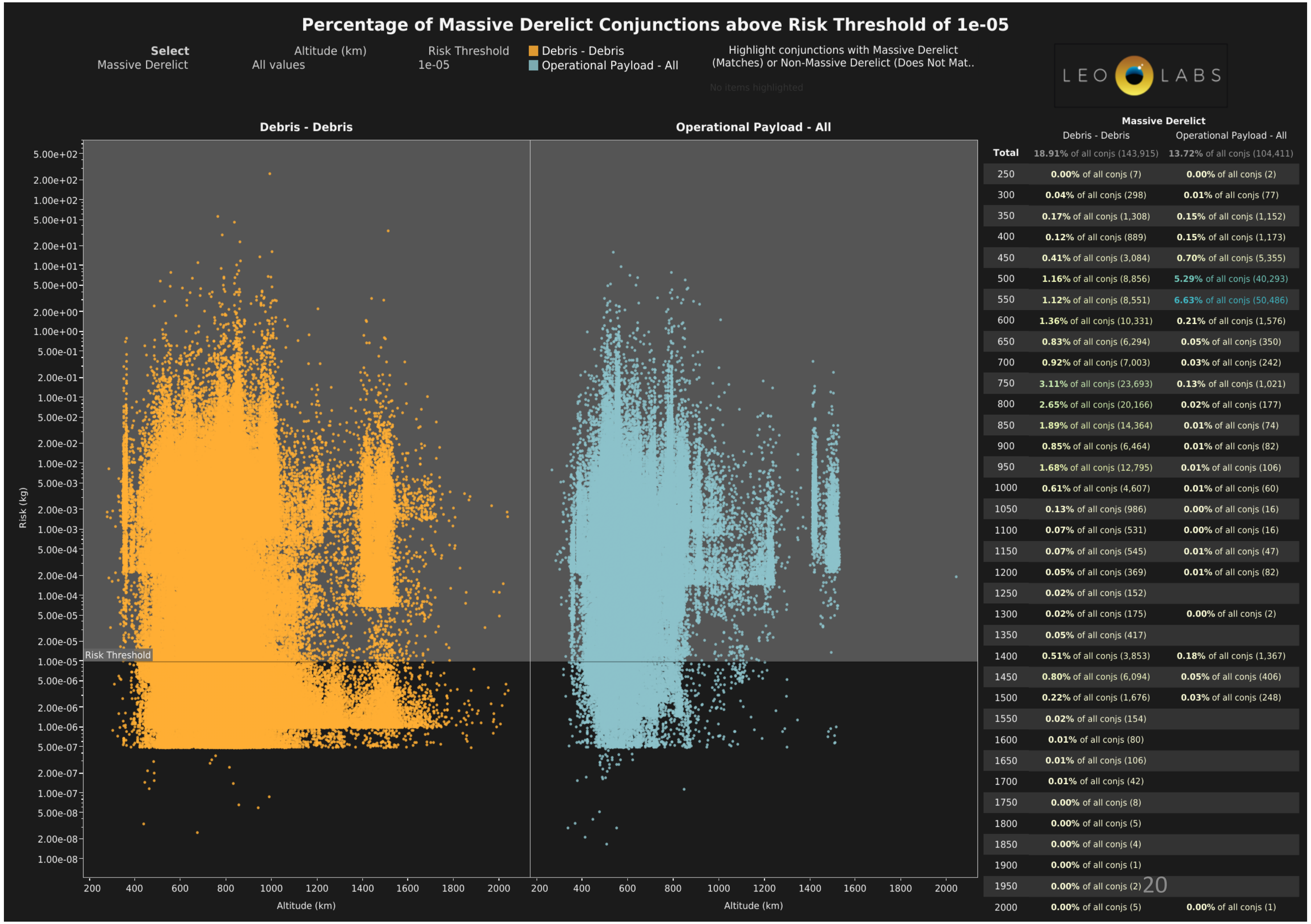
OPL = operational payloads; DEB = debris → fragments and massive derelicts (rocket bodies and dead payloads)

Taking the Heartbeat of LEO…



SDM vs STM…

- Risk = PC x consequence
- Higher risk highlights concerns for future debris generation
  - ✓ Clusters of dead objects > constellations of smallsats
- Lower risk “haze” represents fragment collision risk and hints at associated mission-terminating risk from lethal nontrackable (LNT) debris
  - ✓ LNT likely peaks at ~830km, similar to debris-generating potential peak



Use Millions of “Near Misses” for Future Events

Satellite A Summary Hazards at 730 km through End of Mission Lifetime (0.79 sq m Collision Cross Section)

Select to filter dashboard by Type
Multiple values

Number of Satellites
25

Maximum dimension (m)
1

Minimum dimension (m)
1

Apogee (km)
730

Perigee (km)
730

Add Event(s)
Linearly (starting at year 2 ..

Year of Event
1

Click to highlight graphs (Ctrl + click to multi-highlight)

- Operational Payload
- Non-Operational Payload
- Rocket Body
- Fragments
- 275 Pieces at 580km (SL-3 R/B and FENGYUN 1C DEB)
- 3375 Pieces at 1010km (COSMOS 1709 PL and SL-8 R/B)
- Fragment Model 830 at 950km (CZ-2B DEB and COSMOS 249)
- Fragment Model 4365 at 1510km (COSMOS 1410 and SL-14 R/B)
- Fragment Model 5410 at 630km (SL-14 R/B and CZ-2D R/B)
- Fragment Model 6900 at 840km (COSMOS 1844 and DMSP 5B F5)

Baseline Scenario (no events) with Trackable Objects Only

Year	1	2	3	4	5
One Satellite	3.3e-05	6.7e-05	1.0e-04	1.3e-04	1.7e-04
Full Constellation	8.4e-04	1.7e-03	2.5e-03	3.3e-03	4.2e-03

Selected **Event** Scenario with Trackable Objects Only

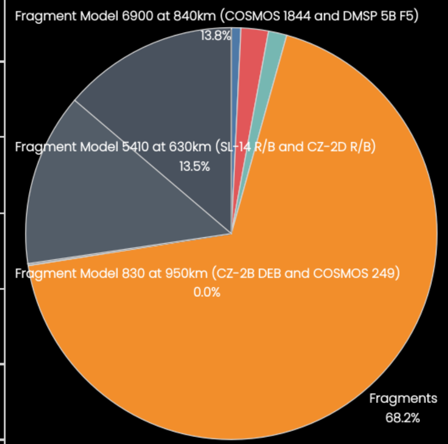
Year	1	2	3	4	5
One Satellite	3.3e-05	7.0e-05	1.1e-04	1.5e-04	2.0e-04
Full Constellation	8.4e-04	1.8e-03	2.7e-03	3.8e-03	5.0e-03

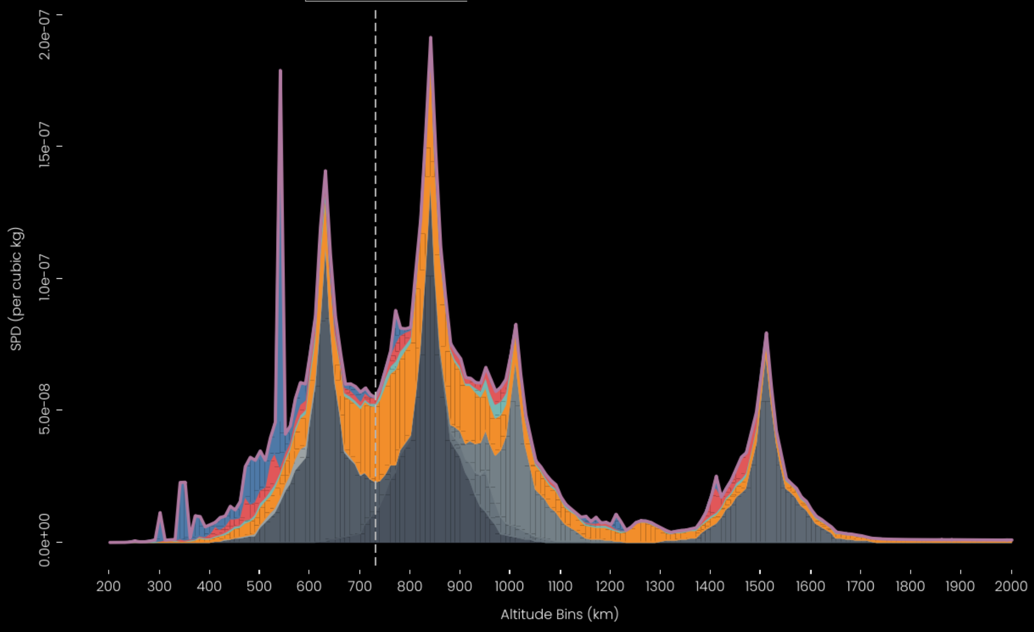
Baseline Scenario (no events) with Lethal Non Trackables

Year	1	2	3	4	5
One Satellite	0.00%	0.01%	0.01%	0.01%	0.02%
Full Constellation	0.08%	0.17%	0.25%	0.33%	0.42%

Selected **Event** Scenario with Lethal Non Trackables

Year	1	2	3	4	5
One Satellite	0.00%	0.01%	0.01%	0.02%	0.02%
Full Constellation	0.08%	0.18%	0.27%	0.38%	0.50%





Spatial Density (SPD)
Mass Density

Area
Line

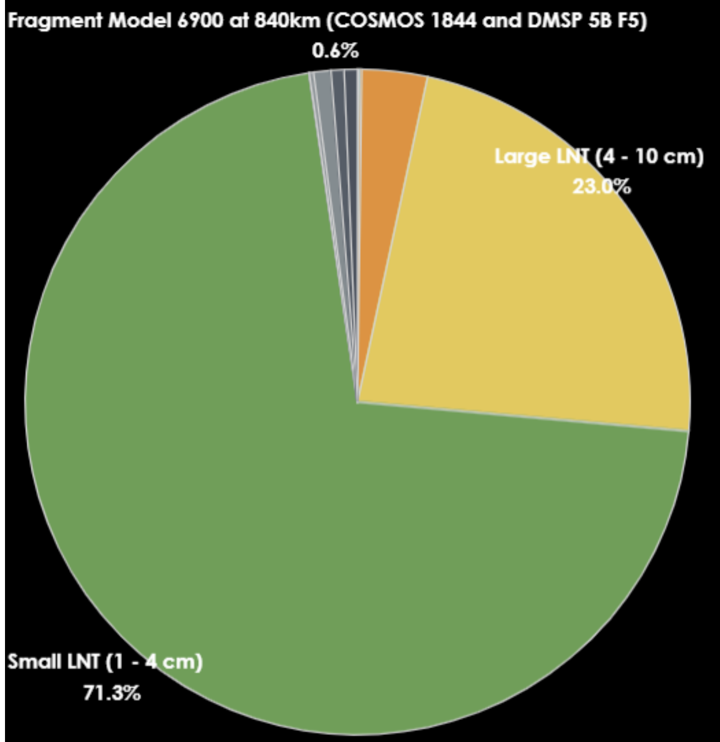
Altitude Bins (km)
All values

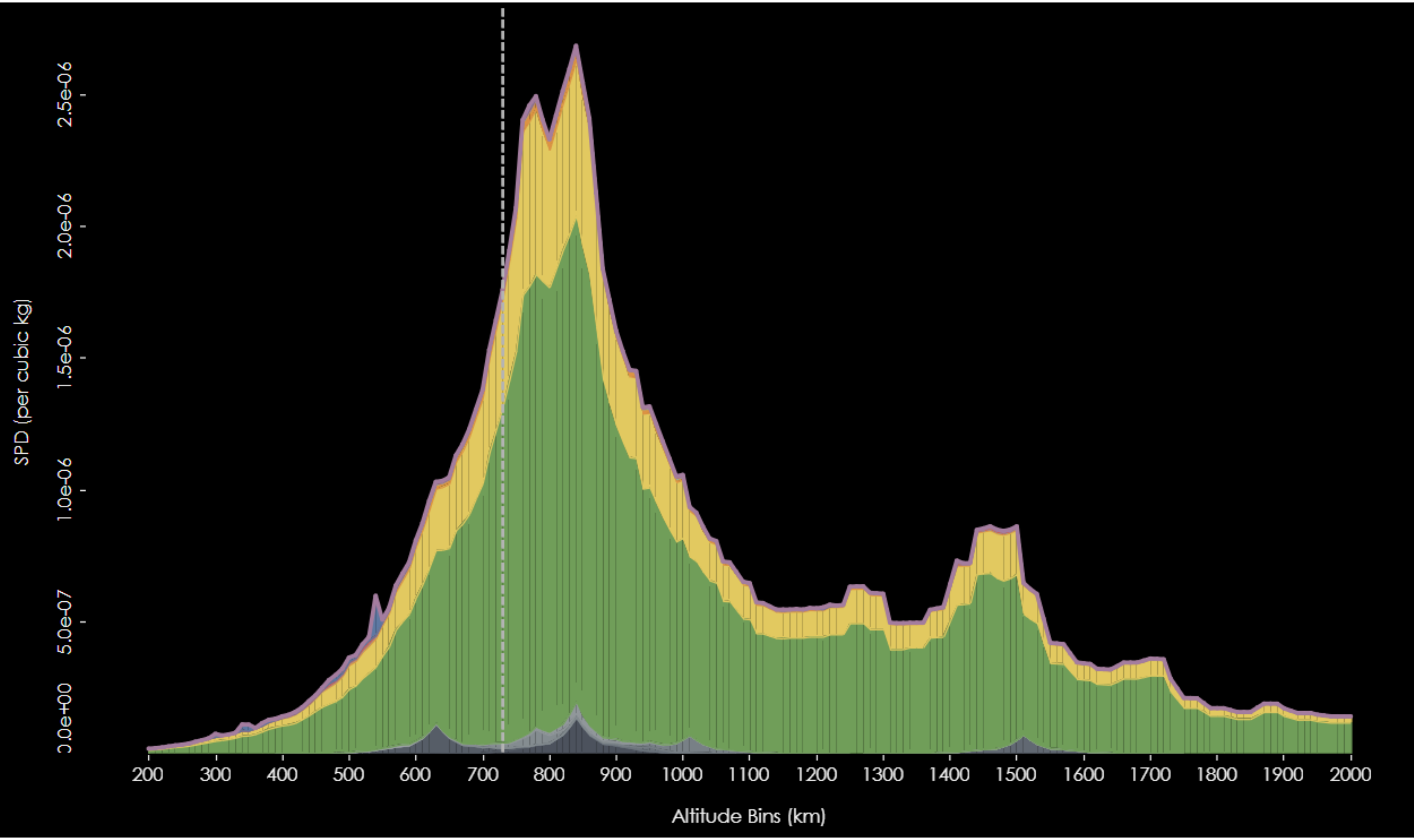
Export as Image

Back to User Input

Now Consider Lethal Nontrackable (LNT) Objects

(LNT numbers derived from MASTER)





LeoLabs is a Full-Service Space Safety Company

LEO Kinetic Space Safety Workshop…

- Co-sponsored by LeoLabs, ClearSpace (Swiss ADR company), AXA XL (French space insurance company), EPFL, and Secure World Foundation
- Three-part activity
    1. Community polling about stakeholder motivations and space safety activities analysis (i.e., rate by cost, benefit, maturity, and resistance)
    2. Hybrid workshop: 4-5 May in Switzerland
    3. Issuance of position paper from 12-person international planning committee on space safety activity prioritization
- Focus is on changing behavior to improve safety of all satellites operating in LEO