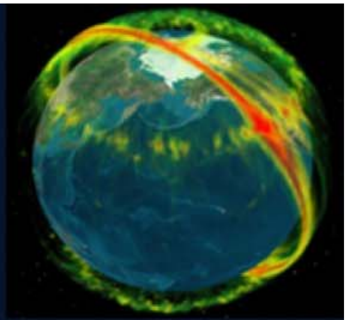

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LEO Collision Risk

Dan Oltrogge (Oltrogge@agi.com)

27 April 2017

CSSI
Center for Space Standards & Innovation

ComSpOC
Commercial Space Operations Center

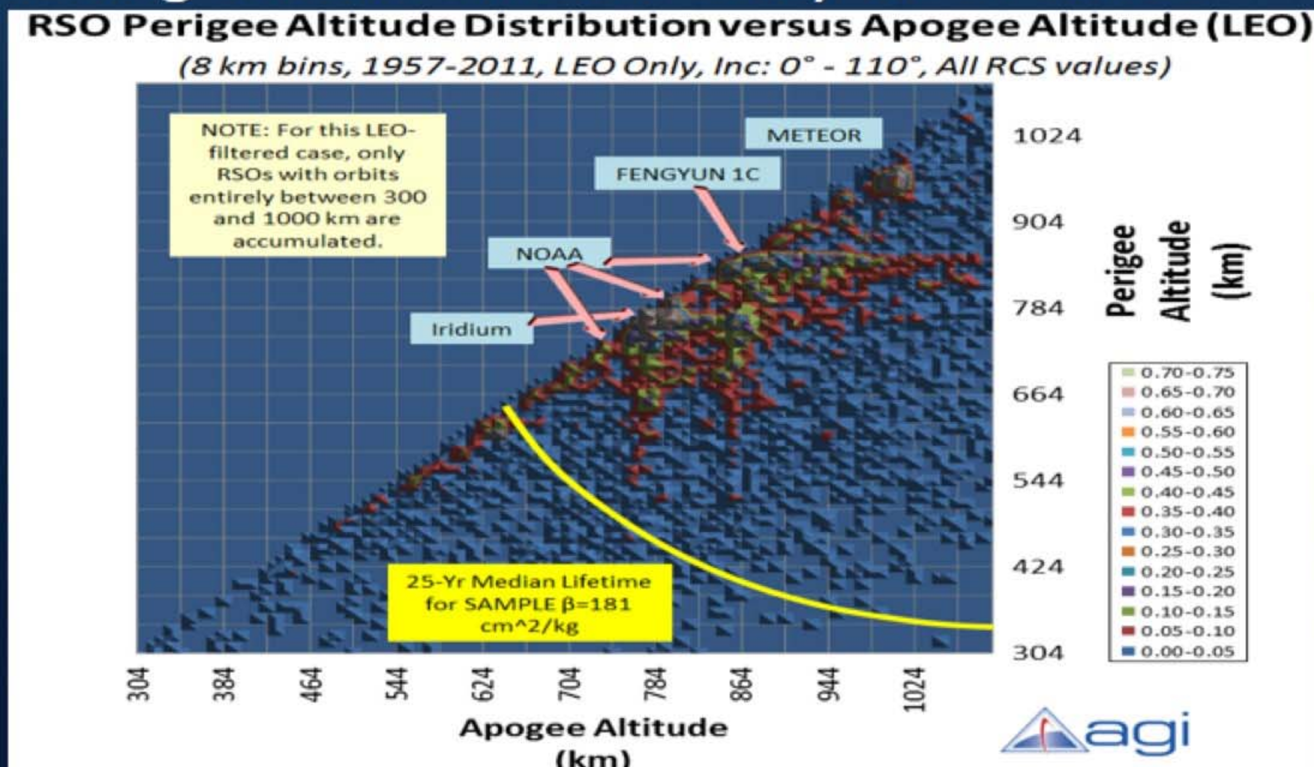
Topics

- Estimated current space population to 1 cm
- Assess average collision/warning rates for active LEO S/C
  - Typical collision probability metrics not relevant
  - Collisions, warnings, avoidance maneuvers
- Portray aftermath of a collision (or explosion)

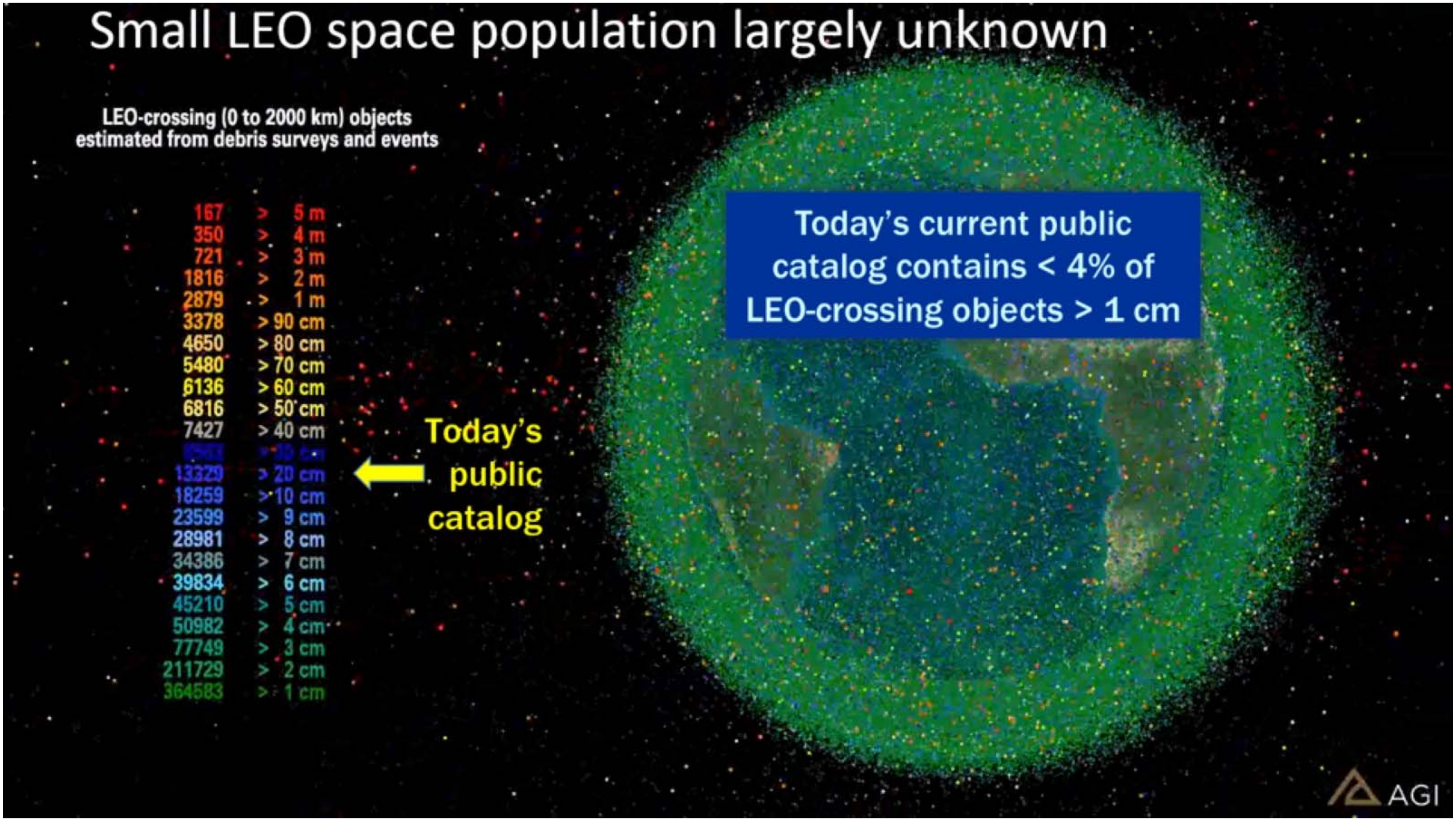
Today's space environment

Distribution of LEO-crossing space population

- Shortening orbit lifetime is a key ODM tenet



Oltrogge and Kelso, "Getting To Know Our Space Population From The Public Catalog, AAS 11-413



Small LEO space population largely unknown
LEO-crossing (0 to 2000 km) objects
estimated from debris surveys and events
167 > 5 m
350 > 4 m
721 > 3 m
1816 > 2 m
2879 > 1 m
3378 > 90 cm
4650 > 80 cm
5480 > 70 cm
6136 > 60 cm
6816 > 50 cm
7427 > 40 cm
13329 > 20 cm
18259 > 10 cm
23599 > 9 cm
28981 > 8 cm
34386 > 7 cm
39834 > 6 cm
45210 > 5 cm
50982 > 4 cm
77749 > 3 cm
211729 > 2 cm
364583 > 1 cm
Today's public catalog
Today's current public catalog contains < 4% of LEO-crossing objects > 1 cm
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Assessing LEO collision risk

LEO collision risk increasing for 3 primary reasons

1. Increased collision risk from past collisions that leave a lasting legacy: "The gift that keeps on giving"
2. More and more satellites being orbited
   - Increasingly cheaper and easier launch access
   - Increasing quantities of satellites produced & flown
   - Planned large ("mega") constellations (e.g., > 500 S/C)
3. Operators still not getting it; ESA 2017 study shows:
   - Only 60% of LEO S/C comply w/25 yr post-mission lifetime
   - Only 20% of LEO S/C above 650 km are compliant

LEO constellations to assess:

- We'll use the existing, planned and hypothetical constellations contained in this table to estimate LEO encounter rates
  - Collisions, warnings (3km miss distance) and avoidance manoeuvres (1km miss distance)
  - Caution: S/C and constellation characteristics from public sources

#	Operator	# S/C	Altitude (km)	Inclination (deg)	S/C Hardbody SIZE (full dimension in m)	Secondary's Hardbody SIZE (full dimension in m)	Combined Hardbody Radius (m)
1a	Boeing V-band	1120	1200	45°	3*	0.1	1.55
1b	Boeing V-band	828	1200	55°	3*	0.1	1.55
1c	Boeing V-band	1008	1000	88°	3*	0.1	1.55
2	CubeSat 380	100	380	98.5°	0.3	0.1	0.2
3	CubeSat 600 (≈Planet)	100	600	[illegible]	[illegible]	0.1	0.2
4	CubeSat 800	100	800	98.5°	0.3	0.1	0.2
5	Globalstar	40	1400	52°	9.7	0.1	4.9
6a	Hawkeye 360	6	650	44°	0.4	0.1	0.25
6b	Hawkeye 360	6	650	63.5°	0.4	0.1	0.25
6c	Hawkeye 360	6	650	97°	0.4	0.1	0.25
7	Iridium	71	780	86.4°	4.27	0.1	2.19
8	LeoSat	140	1400	90°	2	0.1	1.05
9	OneWeb	648	1200	87°	2	0.1	1.05
10	Orbcomm	31	750	45°	10.5	0.1	5.3
11	SpaceX	4000	1100	90°	2	0.1	1.05
12	Spire	100	651	97.95°	0.3	0.1	0.2
13	Terra Bella	28	576	97.76°	1.5	0.1	0.8

Hypothetical...

Assessing LEO collision and close approach risk

- Several ways to assess LEO conjunction "encounter rates" (for both warnings & actual collisions):
  - Method 1: Surveys & anecdotal accounts of suspected collisions
  - Method 2: Generate stats from SDC CA reports
  - Method 3: Generate stats from JSpOC CDMs
  - Method 4: Parametric AdvCAT of all LEO orbits
  - Method 5: Encounter volumetric assessment
    - Patent awarded April 2017, Alfano & Oltrogge
    - Designed for high-density, non-synodic (LEO) regimes
    - Demonstrated that $\# \, encounters \propto R_{encounter}^2$

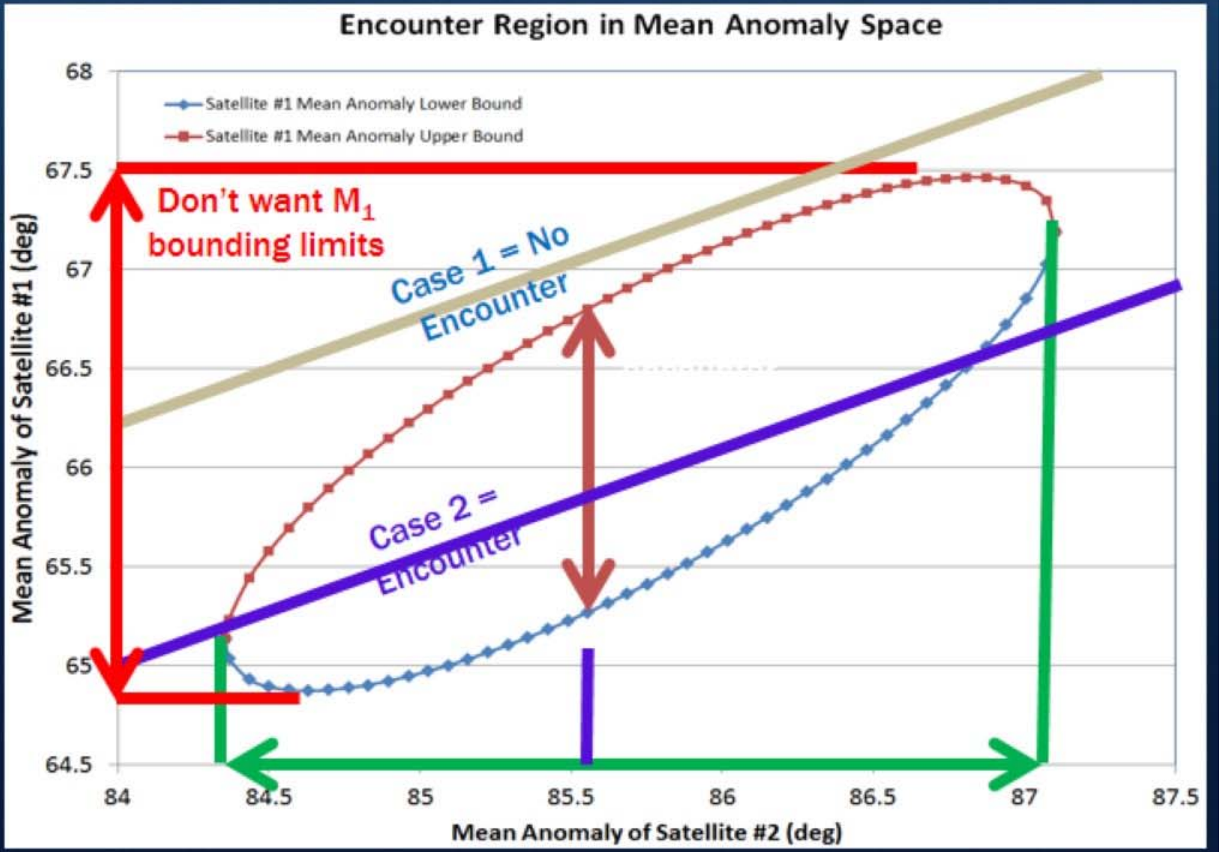
★ **Selected for its suitability, efficiency, generality and accuracy**

How often do space objects encounter each other?

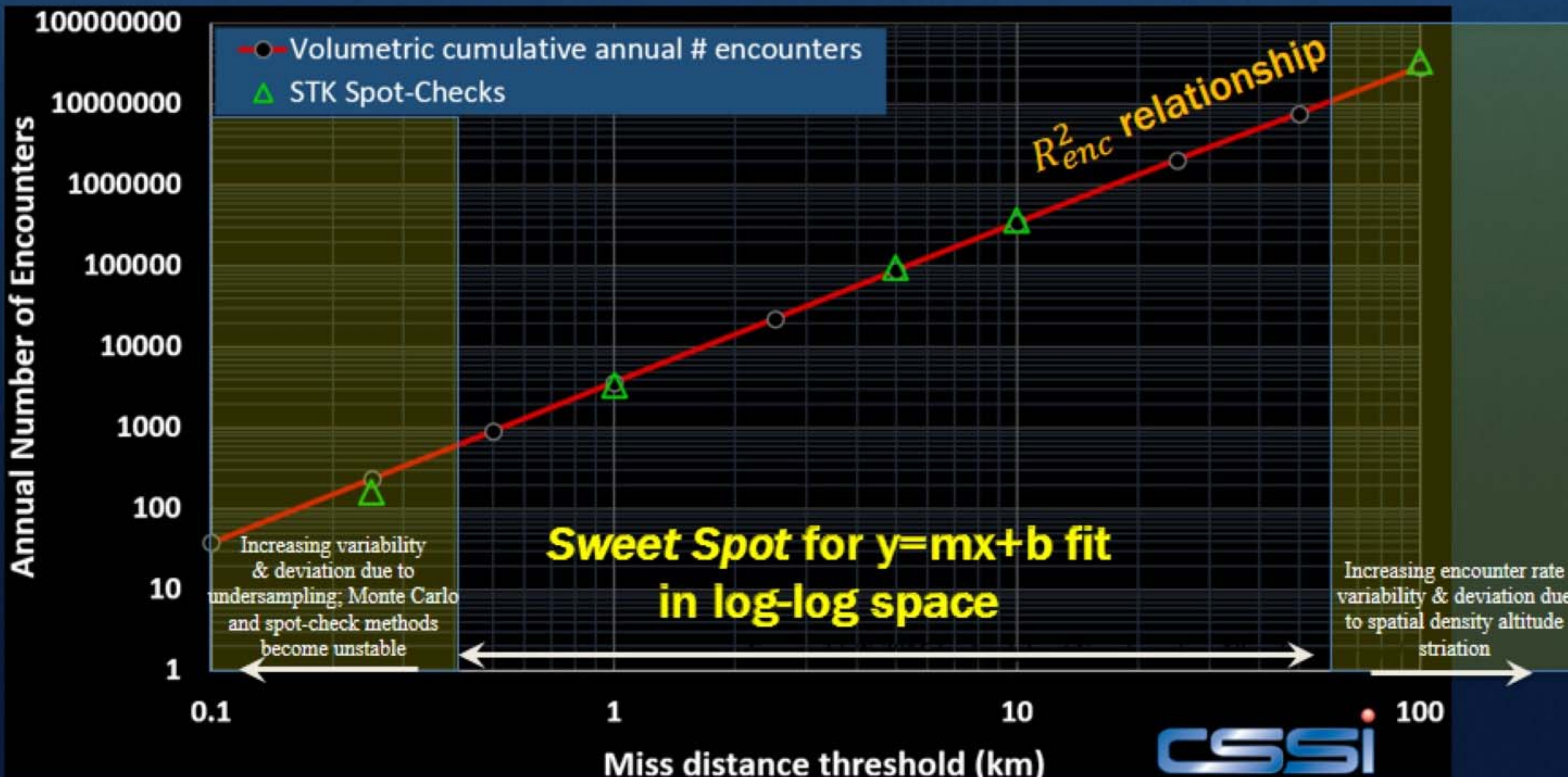
- **Volumetric incursion detection and encounter tool*,**:**
  - Detects if encounter can occur
  - Counts incursions ($N_{ENCOUNTER}$)

*Alfano, S. & Oltrogge, D., "Volumetric Assessment of Encounter Probability," AAS 14-4230, 2014 Astro Specialist Conference, San Diego CA

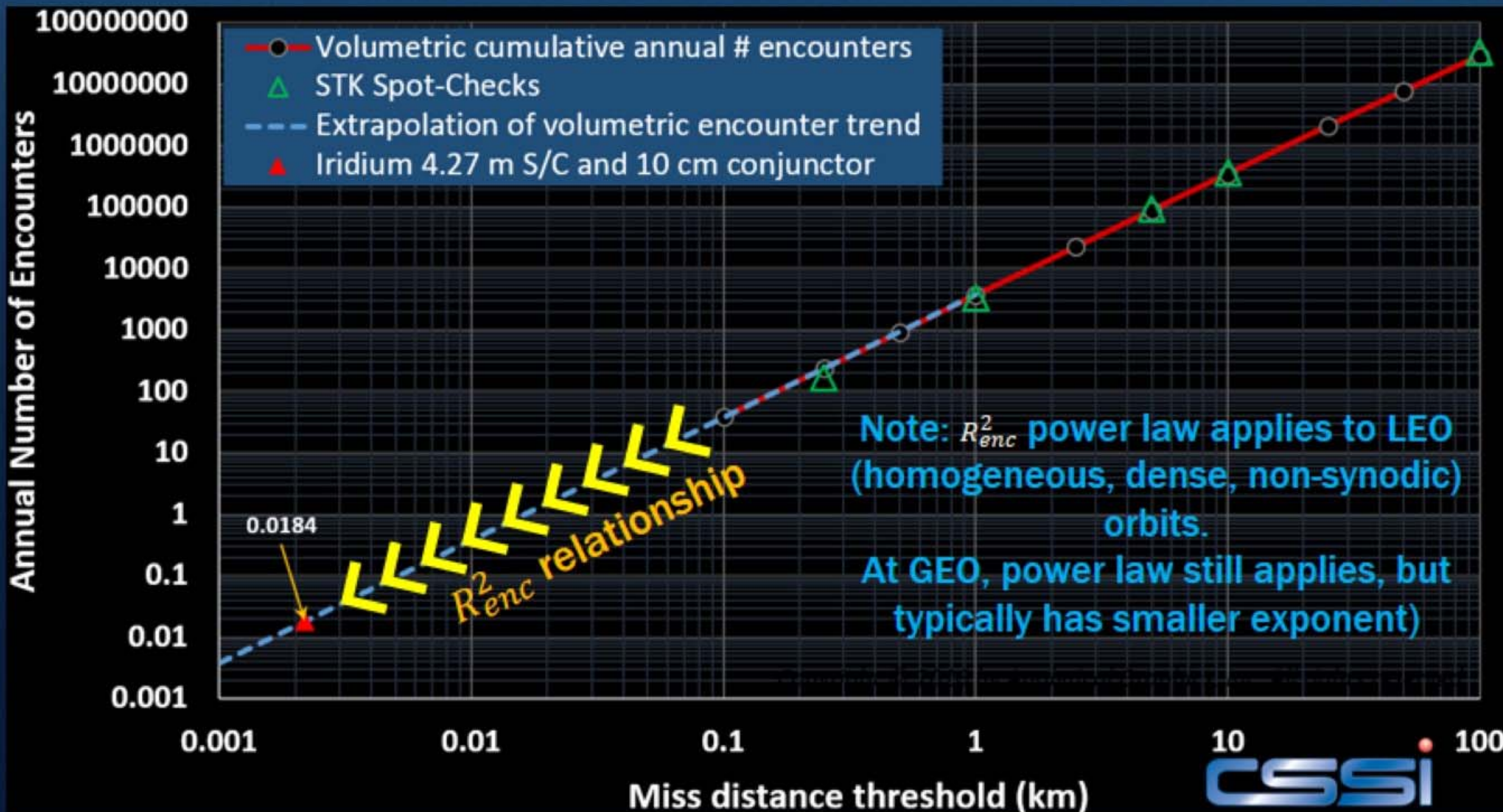
**Alfano, S. & Oltrogge, D., "Volumetric Encounter Analysis Enhancements," AAS 15-581, 2015 Astro Specialist Conference, Vail, CO



Sample: Iridium Volumetric Encounter Rates



Can also estimate average collision rate !

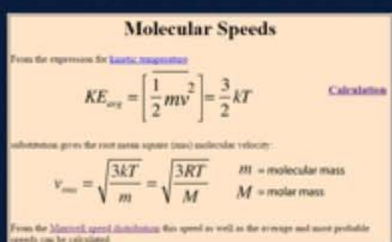


Encounter rate similarities w/molecular gas dynamics

- Analogous to molecular "Mean Free Path" (λ) in gas dynamics
  - On <u>average</u>, molecules travel distance of λ between collisions as f(density $\rho = \frac{n}{V} = \frac{P}{RT}$)

$$\overline{\Delta t}_{molecular\ collision} = \frac{\lambda}{v_{rms}} = \frac{1}{v_{rms}\,\sqrt{2}\,\pi\, d^2 \rho}$$

- "Average collision rate" <u>cannot</u> indicate if, or when, a particular molecule (or satellite) will collide with another
- But does yield avg. collision risk $\alpha(Radius^2)$!


Molecular Speeds

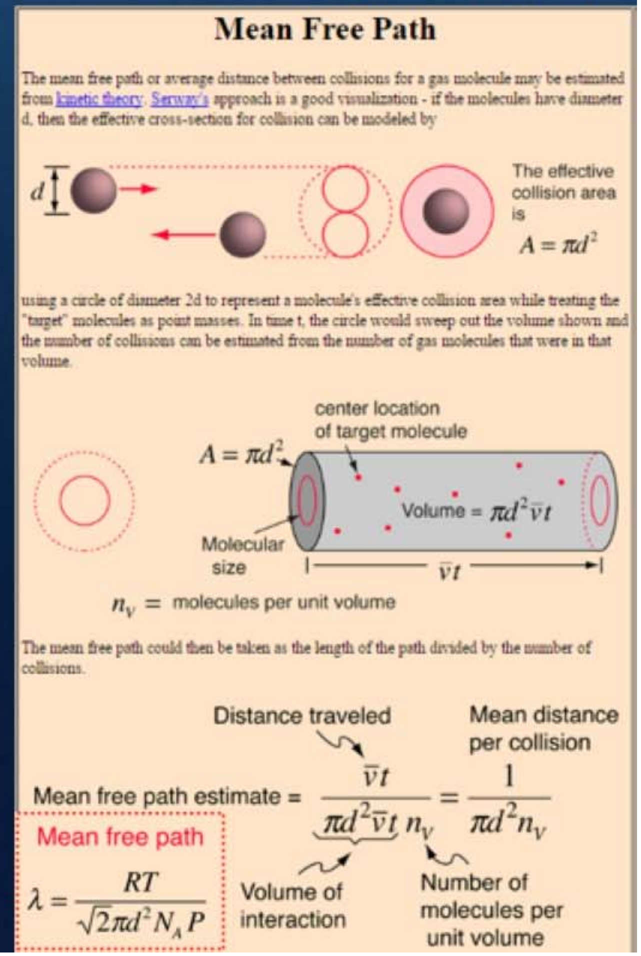
$$KE_{avg} = \left[\frac{1}{2} m \overline{v^2}\right] = \frac{3}{2} kT$$

Calculation

$$v_{rms} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M}}$$

m = molecular mass
M = molar mass

http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/menfre.html


Mean Free Path

The mean free path or average distance between collisions for a gas molecule may be estimated from kinetic theory. Serway's approach is a good visualization - if the molecules have diameter d, then the effective cross-section for collision can be modeled by

using a circle of diameter 2d to represent a molecule's effective collision area while treating the "target" molecules as point masses. In time t, the circle would sweep out the volume shown and the number of collisions can be estimated from the number of gas molecules that were in that volume.

The mean free path could then be taken as the length of the path divided by the number of collisions.

Encounters in 10 years of non-intervention ops

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#	Operator	# S/C	Current RSO Catalogue: Avg # Collisions in 10 yrs	Current RSO Catalogue: Avg # 3km Warnings in 10 yrs	Current RSO Catalogue: Avg # 1km Mnvrs in 10 yrs	200K-RSO 2 cm Catalogue: Avg # Collisions in 10 yrs	200K-RSO 2 cm Catalogue: Avg # 3km Warnings in 10 yrs	200K-RSO 2 cm Catalogue: Avg # 1km Mnvrs in 10 yrs
1a	Boeing V-band	1120	0.1053	394,426	43,825	2.2404	8,392,631	932,515
1b	Boeing V-band	828	0.0816	305,630	33,959	1.7725	6,640,044	737,783
1c	Boeing V-band	1008	0.5155	1,931,184	214,576	8.514	31,893,494	3,543,722
1	Boeing V-band	2956	0.7024	2,631,240	292,360	12.527	46,926,169	5,214,020
2	CubeSat 380	100	0.0001497	33,687	3,743	0.00115	259,532	28,836
3	CubeSat 600 (≈ Planet)	100	0.00075	169,376	18,819	0.0114	2,556,868	284,096
4	CubeSat 800	100	0.00174	391,512	43,501	0.0226	5,086,080	565,120
5	Globalstar	40	0.0637	23,871	2,652	1.3566	508,527	56,503
6a	HawkEye 360	6	0.0000816	11,744	1,305	0.00128	184,271	20,475
6b	HawkEye 360	6	0.0000746	10,739	1,193	0.0008421	121,239	13,471
6c	HawkEye 360	6	0.0000681	9,807	1,090	0.000972	139,954	15,550
6	Hawkeye 360	18	0.00022422	32,289	3,588	0.003094	445,464	49,496
7	Iridium	71	0.184	369,385	41,043	2.0483	3,843,728	427,081
8	LeoSat	140	0.0129	105,405	11,712	0.2795	2,281,475	253,497
9	OneWeb	648	0.0363	296,613	32,957	0.8126	6,633,300	737,033
10	Orbcomm	31	0.2953	94,602	10,511	3.0618	981,006	109,001
11	SpaceX	4000	0.4866	3,971,912	441,324	8.8417	72,177,201	8,019,689
12	Spire	100	0.000868	195,348	21,705	0.0136	3,070,006	341,112
13	Terra Bella	28	0.0022	30,878	3,431	0.0460	646,144	71,794

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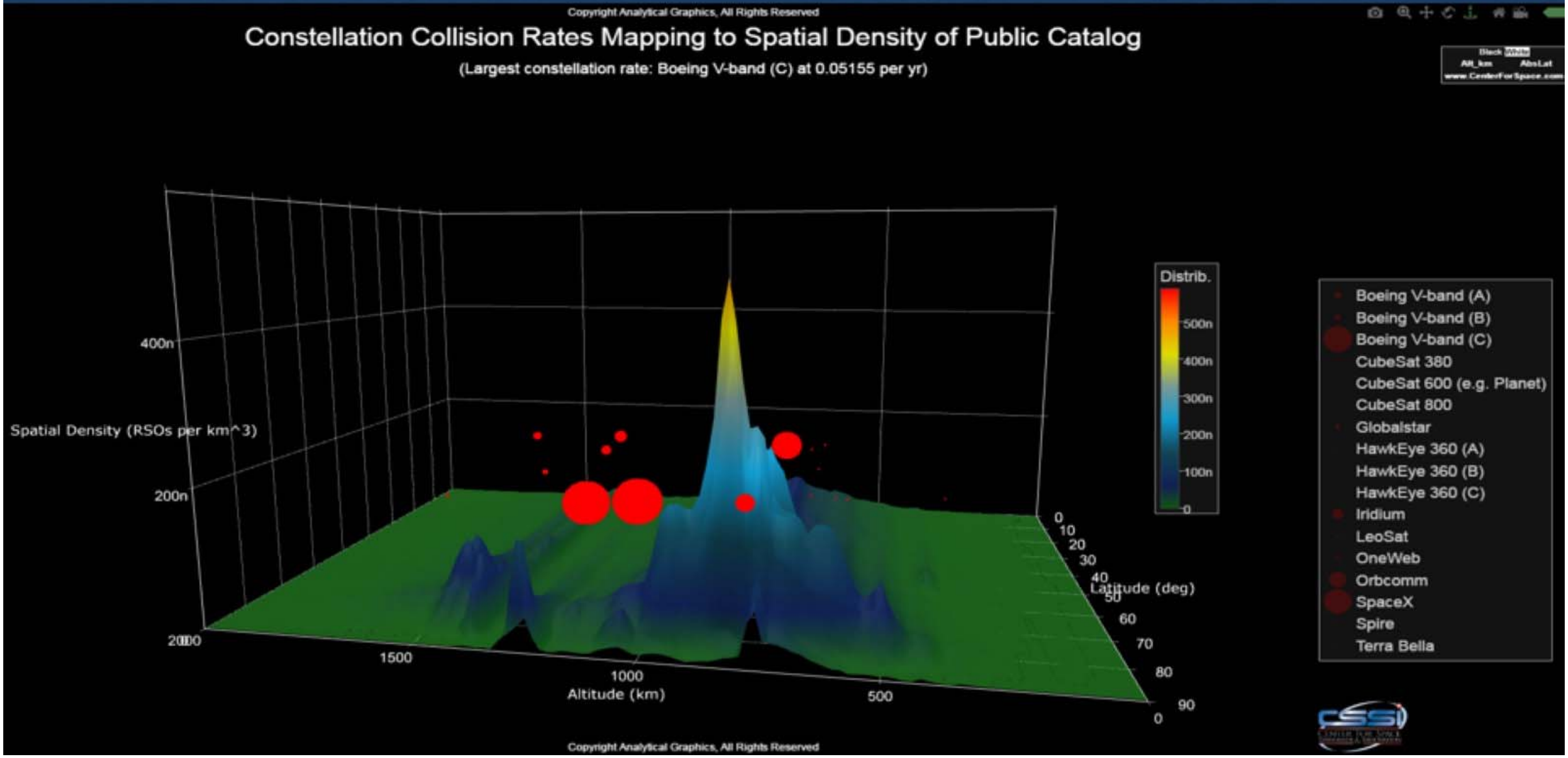
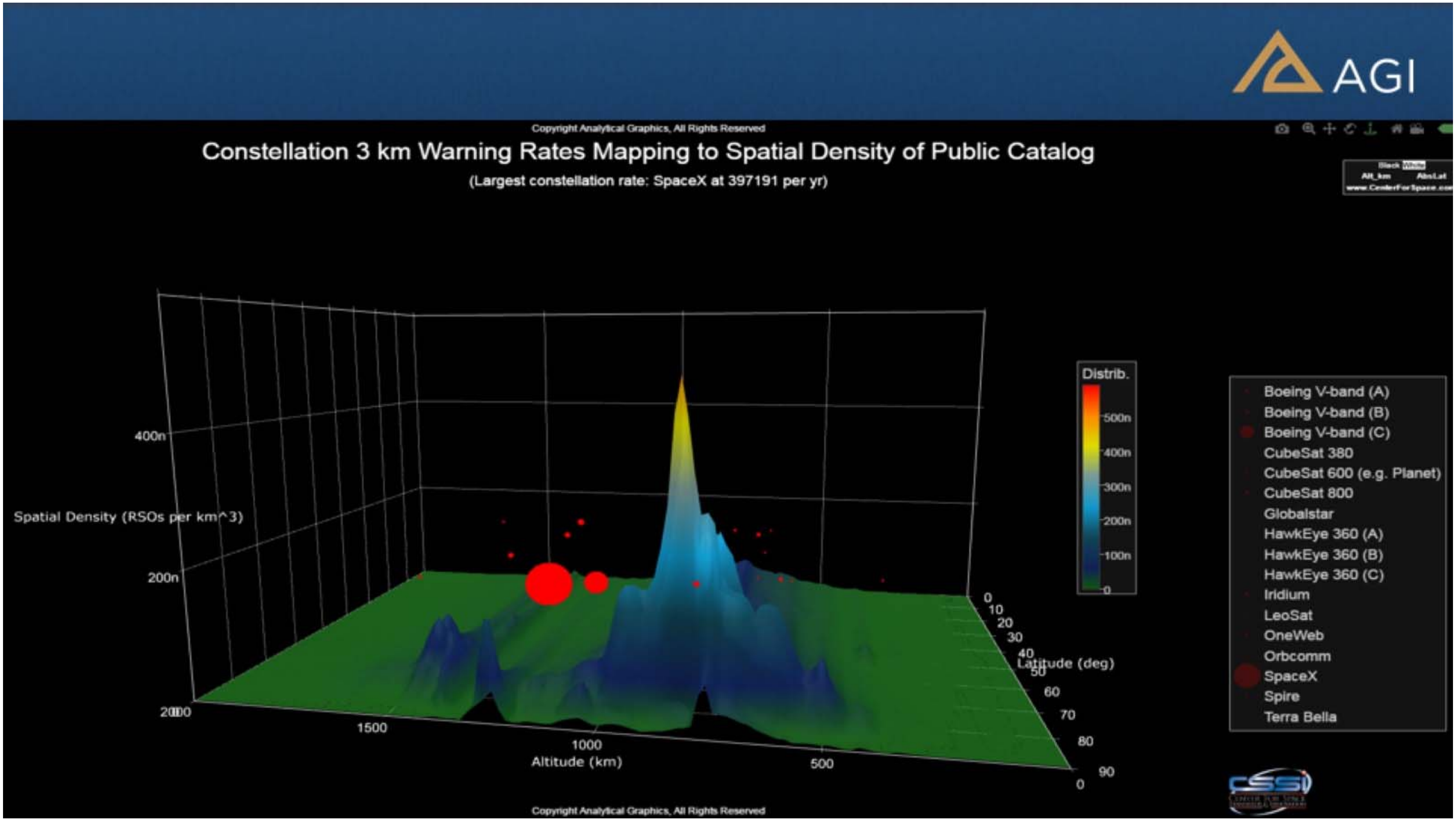
Public RSO Catalogue: Who is at greatest risk?

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Constellation 3 km Warning Rates Mapping to Spatial Density of Public Catalog
(Largest constellation rate: SpaceX at 397191 per yr)
Spatial Density (RSOs per km^3)
400n
200n
2000
1500
1000
500
Altitude (km)
0
10
20
30
40
50
60
70
80
90
Latitude (deg)
Distrib.
500n
400n
300n
200n
100n
0
Boeing V-band (A)
Boeing V-band (B)
Boeing V-band (C)
CubeSat 380
CubeSat 600 (e.g. Planet)
CubeSat 800
Globalstar
HawkEye 360 (A)
HawkEye 360 (B)
HawkEye 360 (C)
Iridium
LeoSat
OneWeb
Orbcomm
SpaceX
Spire
Terra Bella
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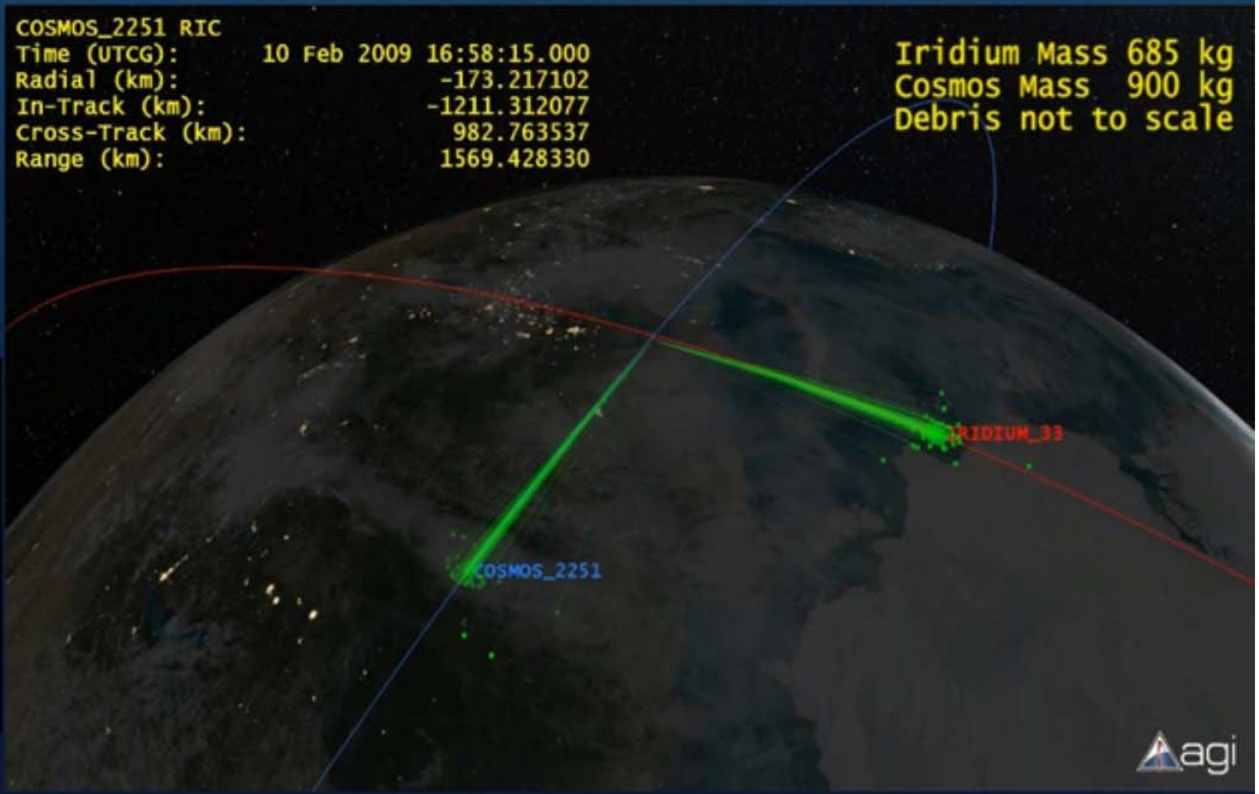
Collision Risk: Why We Should Care

LEO case: Iridium 33/Cosmos 2251 collision

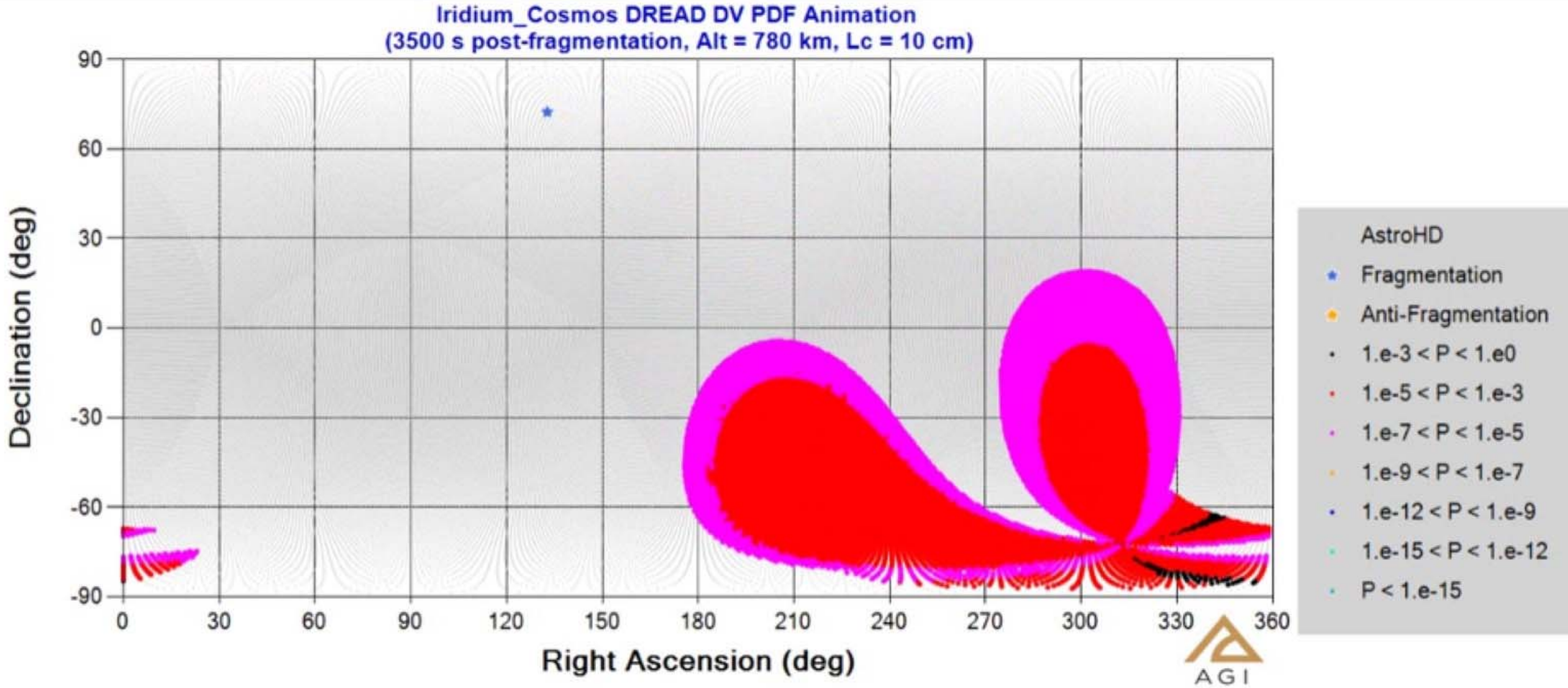
- 10 Feb 2009 at 16:56 UTC
- 11.647263 km/s relative velocity

DebriSat Video courtesy NASA Orbital Debris Program Office

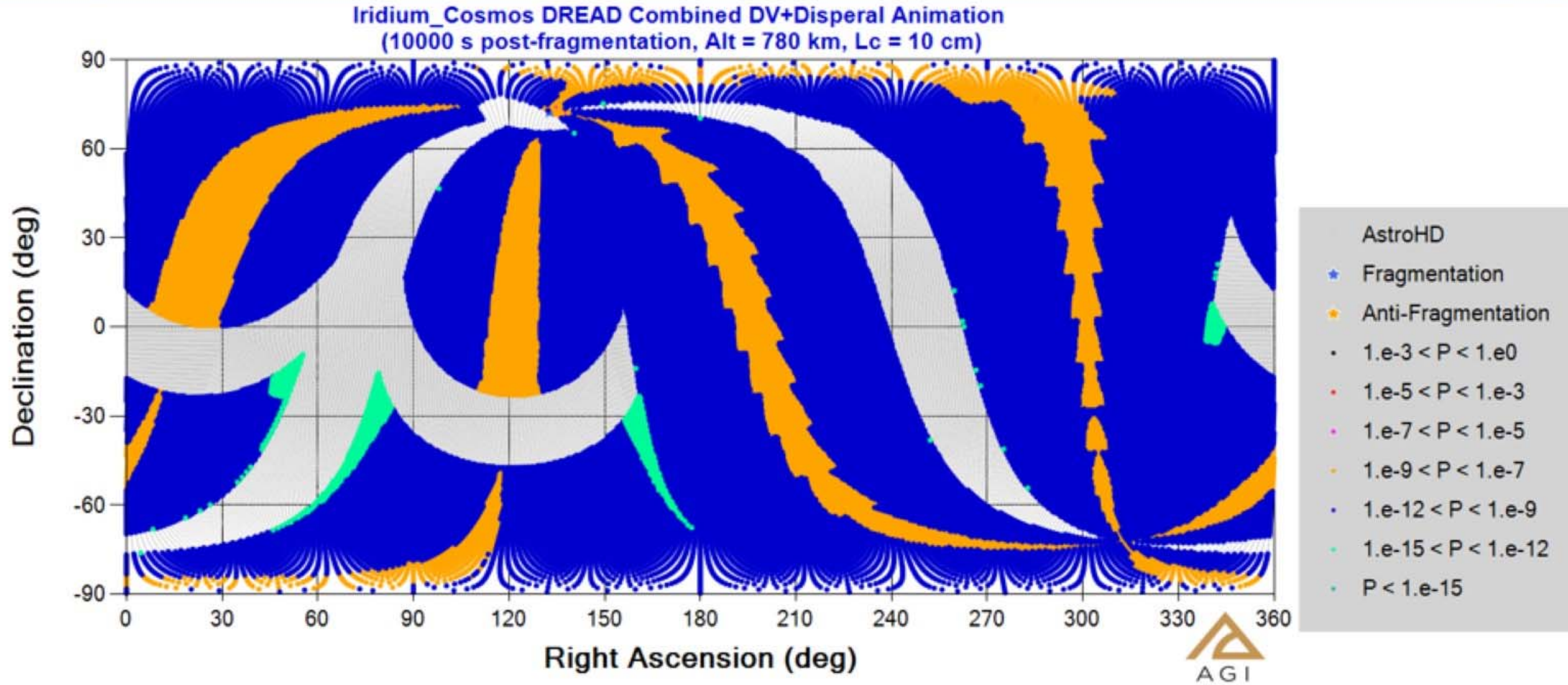


DEBBIE simulation of Iridium 33/Cosmos 2251 Collision

LEO collisions: Where can the fragments go ?



Composite fragment locations thru t + 10,000 s

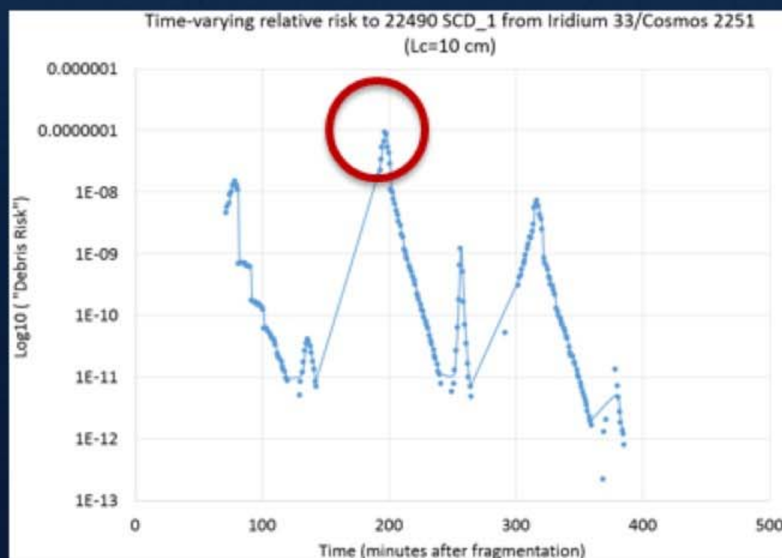


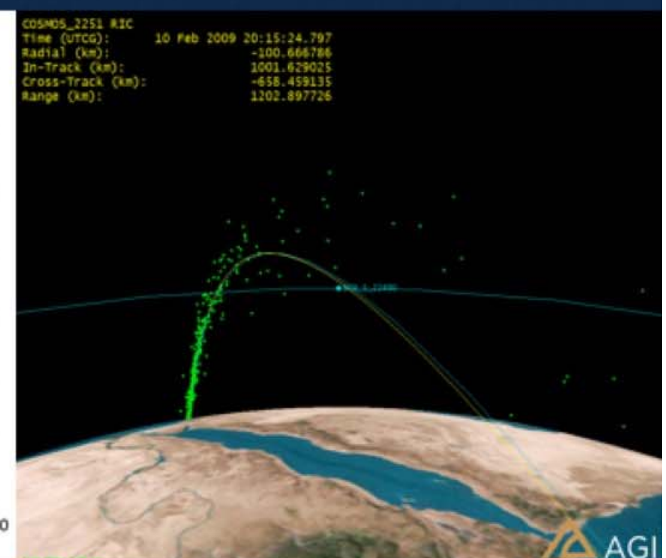
Fragmentation then puts other satellites at risk

"Top 20" at-risk S/C

SSC	Intl Desig	Risk to S/C
22490	SCD 1	7.32E-07
24949	IRIDIUM 30	3.06E-07
25274	IRIDIUM 58	2.51E-07
25475	ORBCOMM FM21	2.05E-07
24869	IRIDIUM 15	2.02E-07
15427	NOAA 9	1.87E-07
27375	IRIDIUM 95	1.76E-07
27374	IRIDIUM 94	1.72E-07
24950	IRIDIUM 31	1.53E-07
25272	IRIDIUM 55	1.38E-07
25414	ORBCOMM FM18	1.35E-07
31118	SAUDISAT 3	1.28E-07
27372	IRIDIUM 91	1.21E-07
25275	IRIDIUM 59	1.17E-07
31124	SAUDICOMSAT 5	1.03E-07
24795	IRIDIUM 5	1.01E-07
25117	ORBCOMM FM05	1.01E-07
29499	METOP-A	9.66E-08
25276	IRIDIUM 60	9.06E-08
33321	HUANJING 1B (HJ-1B)	7.03E-08

- Debris Risk Evolution And Dissipation (DREAD) evaluates satellites at risk
- SCD 1 flies thru debris field at peak risk

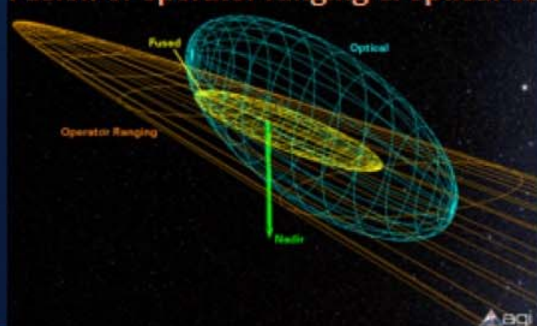


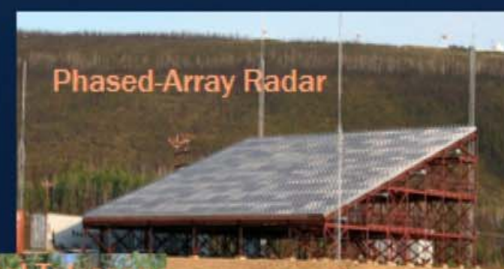


How can operators help prevent collisions?

- First & foremost: Be a responsible operator!
- JSpOC SSA Data Sharing Agreement (free service)
- Commercial services exist to refine tracking & SoF
  - Space Data Association (SoF & RFI mitigation)
    - Small satellite-leaning membership fee structure
  - AGI Commercial Space Operations Center (ComSpOC) is the first commercial multi-phenomenology SSA service, merging state-of-art processing w/data fusion, sensors
    - Extensive optical, radar and passive RF sensor network

Fusion of operator ranging & optical obs

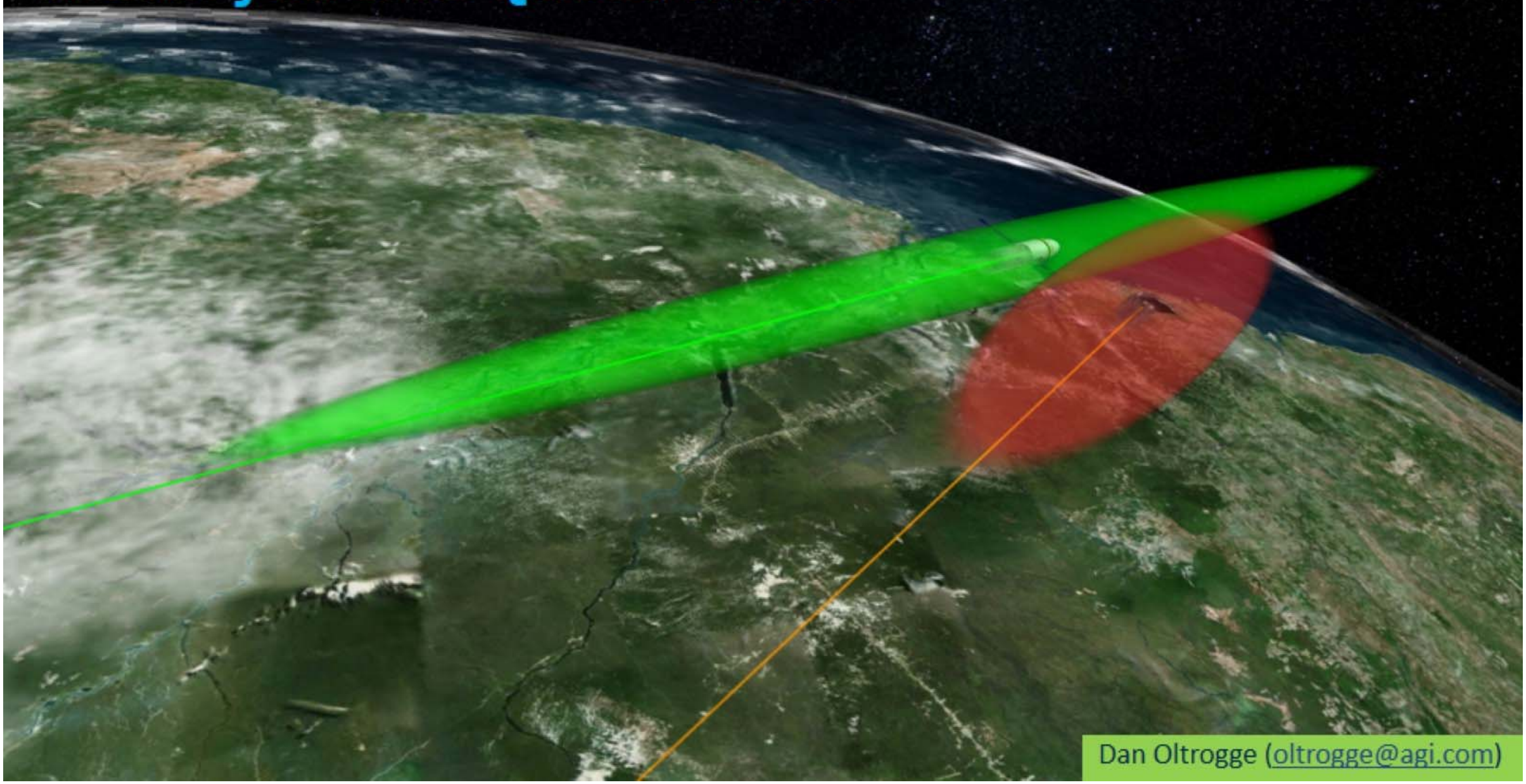




Concluding Remarks

- LEO will continue to get increasingly crowded
- CubeSats dominating newly-deployed objects due to their ease, low cost and rapidity of manufacture/launch/deploy/dispersion
- "Mega constellations" pose serious challenges & collision risk
  - Imperative to seek authoritative, actionable SSA, CA and RFI analysis
  - Automation of CA and RFI mitigation processes an absolute "must have".
- CubeSats generally NOT the collision risk some portray;
- But: many CubeSat CA warnings if in highly-populated orbits
  - CA warnings warrant intense satellite operator scrutiny
  - CA warnings can lead to avoidance maneuvers
  - CubeSat ISS deploy minimizes post-mission lifetime AND ISS collision risk

Thank you and Questions ...



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