Supplemental Tracking Data for LEO CA

M.D. Hejduk
The Aerospace Corporation

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Question/Purpose

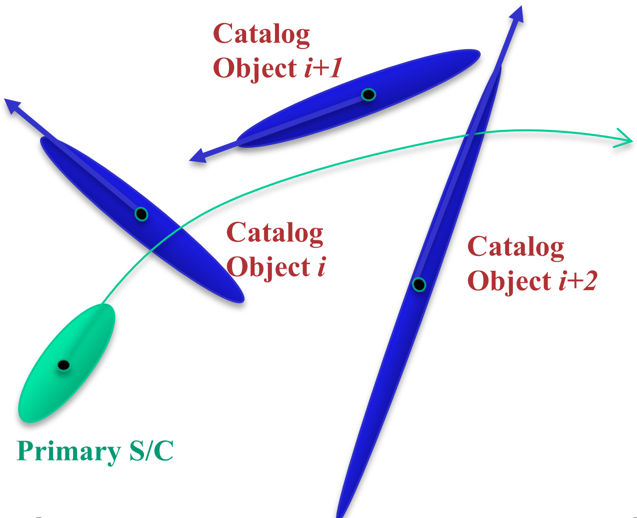
- **Because SSA is driven by space object tracking, stands to reason that more and better tracking will improve SSA**
  - Since SSA includes satellite conjunction assessment (CA), presumption is that additional tracking will improve CA mission
- **Because commercial tracking involves O/O or government allocation of resources, will need more specificity about advantages**
  - Which specific aspects of CA/SSA enterprise will be improved
  - Expected degree of such improvement
- **Such questions difficult to answer definitively**
  - Generally need large simulation for fully durable answers
    - Difficult to simulate actual miss distances and covariance evolution
  - However, can establish some things with empirical investigations
- **Present analysis attempts to provide more specific answers in the absence of a full simulation**

Agenda

- **BRIEF on-orbit CA introduction**
- **Examination of proposed supplemental tracking data advantages, by category**
  - Augmented space catalogue (adding many more small objects to catalogue)
    - Debris production abatement
    - Mission loss avoidance
  - Increased/improved tracking on presently-catalogued space objects
    - Better epoch accuracy, leading to reduction of “dilution region” situations in which collision risk is understated
    - Better advance prediction of serious conjunctions
  - Other SSA improvements that indirectly benefit CA
- **Recommendations for how to frame/understand supplemental tracking advantages**

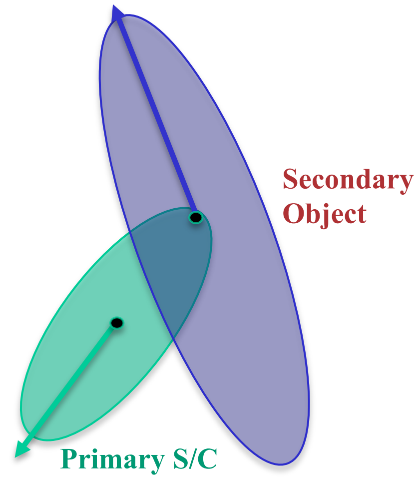
BRIEF CONJUNCTION ASSESSMENT OVERVIEW

Conjunction Assessment: Basic Definitions and Responsibilities



Conjunction Assessment (CA) is the process of identifying close approaches between two orbiting objects; sometimes called conjunction "screening".

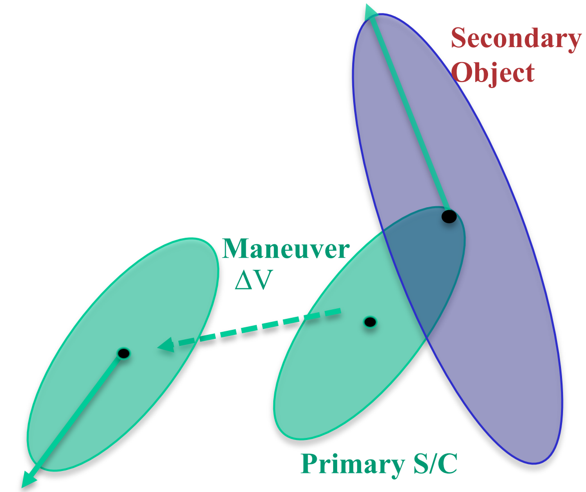
The **18th Space Control Squadron (18 SPCS)** at Vandenberg SFB maintains the high accuracy catalog of space objects. Orbital Safety Analysts (OSAs) at VSFB screen protected assets against the catalog, perform tasking requests, and generate close approach data.



CA Risk Analysis is the process of assessing collision risk and assisting satellites in planning maneuvers to mitigate that risk, if warranted.

The NASA **CARA** program performs risk assessment for all NASA operational non-HSF satellites, and some partner missions.

JSC FOD performs risk assessment for all NASA HSF program assets and is the O/O for maneuver decisions and execution.



Collision Avoidance is the process of executing mitigative action, typically in the form of an orbital maneuver, to reduce collision risk.

Each satellite **Owner/Operator (O/O)** – mission management, flight dynamics, and flight operations – is responsible for making maneuver decisions and executing the maneuvers.

NASA CARA CA: Major Terms and Nominal Operational Timeline

TCA = Time to Closest Approach between the two conjuncting objects
Pc = Probability of Collision – the likelihood of the two objects actually colliding
Maneuver Go/No-GO – point at which mitigation decision must be made

7 Days > TCA = 3 Days All Identified Events	Event Notification if **TCA ≅ 3 Days** and **Pc = 3E-5**	Maneuver Planning if **TCA ≅ 2 Days** and **Pc = 3E-5***	Maneuver Go / No-Go if **TCA = .5 Day** and **Pc = 1E-4**	
0. Conjunction Identification, Internal Analysis, and Monitoring	1. Initial Notification and Request for Planning Timeline	2. Maneuver Planning	3. Maneuver Execution	TCA

0. CARA internally reviews the event including

- Increased tasking, OD Check, OD Actionability, BFMC request, review of secondary payload status and contact plans

1. CARA notifies mission of event and mission provides times for maneuver planning actions

- Maneuver planning actions should nominally begin the following day
- Support times may begin earlier so that contact and planning activities occur during business hours

2. CARA Supports all maneuver planning activities as identified in Step 1. Activities include:

HIE Briefing	Ephem Delivery	Maneuver Screening #1	Ephem Delivery/Screening #2 (if needed)	Maneuver Commit

- *If Pc < 3E-5 but > 1E-7 CARA will continue to support maneuver planning activities at mission preference
- Second ephemeris delivery/screening needed if first set does not mitigate event of concern, introduces other secondaries, etc.
- Minimum maneuver screening time 1-2 hours; up to 4 hours for CARA analysis
- On a case-by-case basis additional planning activities can be undertaken

3. CARA makes a recommendation for the maneuver Go/No Go based on latest screening data

- If Pc > 1E-4 recommendation to maneuver OR If Pc < 1E-4 recommendation to not maneuver

AUGMENTED CATALOGUE

Small Object LEO Catalogue Augmentation: Vital Statistics

- **SSN LEO tracking limit prior to Space Fence (SF) given as ~10cm**
- **Advent of Space Fence (SF) reduced this limit**
  - However, generally at least two dispersed geographical sensor locations required for reliable catalogue maintenance, and three preferred
  - No present effort to exercise SF second-site option
- **SF-only objects may not be well maintained with only one site; potentially not usable for CA**
- **Supplemental tracking capability can enable catalogue maintenance of these small objects**
  - Multiple, geographically-dispersed LEO small-debris sensors allow for regular detection/tracking that supports cataloguing of small debris
- **Two main advantages claimed for tracking small objects for CA**
  - Small objects can cause large debris-producing collisions
  - Small objects can, through collisions, cause mission failure
- **Each potential advantage examined separately**

Will Small Objects Create Large Debris-Producing Events?

AUGMENTED CATALOGUE ADVANTAGE #1

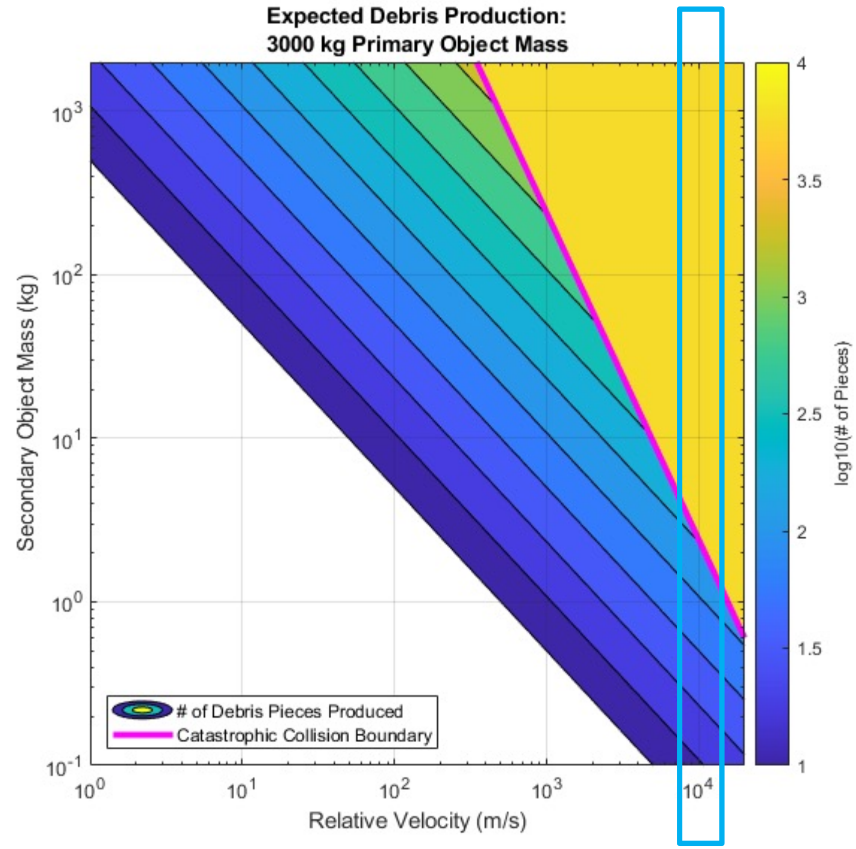
How Much Debris will a Collision Generate: NASA Evolve 4.0 Model*

- **Empirical model based on hyperkinetic destruction of satellites in a vacuum chamber and analysis of generated fragments**
- **Articulates basic distinction between collision types**
  - "Catastrophic" collisions, in which both objects are completely fragmented
  - "Non-catastrophic" collisions, in which smaller (lighter) object is fully fragmented but larger (heavier) object only cratered
- **With estimates of both objects' masses and their relative velocity, can estimate collision's expected number of fragmentation pieces**
  - Collision type (catastrophic or non-catastrophic) estimated based on objects' relative kinetic energy
  - Empirical relationship: # of fragments = $0.1(M)^{0.75}L_c^{-1.71}$
    - Lc is the object size above which one wishes to know the number of fragments
    - M is a momentum term that differs based on collision type

*Johnson, N.L., Krisko, P.H., Liou, J.C., and Anz-Meador, P.D. "NASA's New Breakup Model of EVOLVE 4.0." *Advances in Space Research*, Vol. 28 No. 9 (2001), pp. 1377-1384.

Expected Quantity of Collision Debris: Evolve 4.0 Profiled Output (Pieces > 5cm)

- **Primary object mass of 3000km**
  - Secondary mass on y axis
- **Catastrophic / non-catastrophic regions distinct (magenta line)**
  - Catastrophic region in yellow
  - Non-catastrophic region layered
- **Aqua box is region of typical LEO conjunction relative velocities**
  - Light secondaries produce little debris
  - When secondary mass greater than a few kg, catastrophic collisions begin
- **To assess situation for actual catalogue, need broader profiling**
  - Different primary object masses
  - Estimated masses for real debris objects



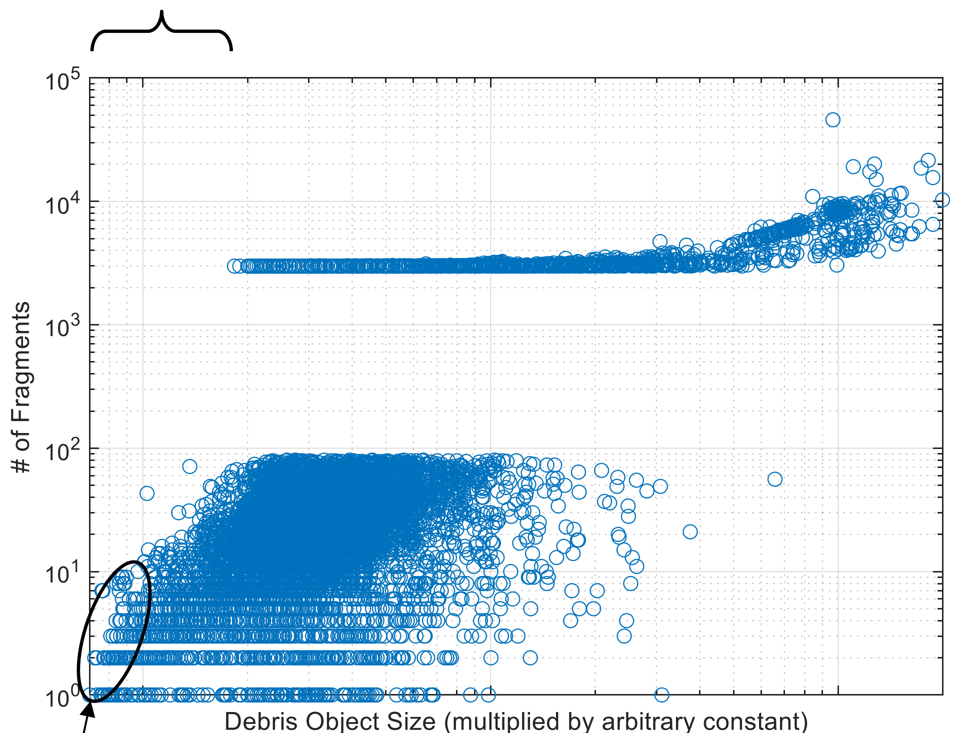
Will Small Objects Cause Large Debris Events? Explored through NASA CA Database

- **Range of plausible primary object masses selected**
  - 10kg up to 3000kg, in logarithmic spacing
    - Many NASA “older” satellites in 2000kg – 3000kg range
- **Sizes and masses estimated for all debris objects in catalogue**
  - “Debris” and “unknown” object types
  - These would be the types of objects added to an augmented catalogue, except augmented catalogue objects are expected to be even smaller
- **Typical LEO relative velocity of 10km/sec used**
- **For each primary object mass, each debris object in catalogue put into simulated collision with it**
  - Number of debris pieces from each such simulated collision noted
- **Output statistics for each primary object mass collected**

Full Profiling Result for One Primary Mass (1000kg Used in Present Example)

- **Each circle in graph is collision between 1000kg primary and one of the objects in the debris catalogue**

Gap between Edge of Detection for small debris and object size at which end of Catastrophic Region observed



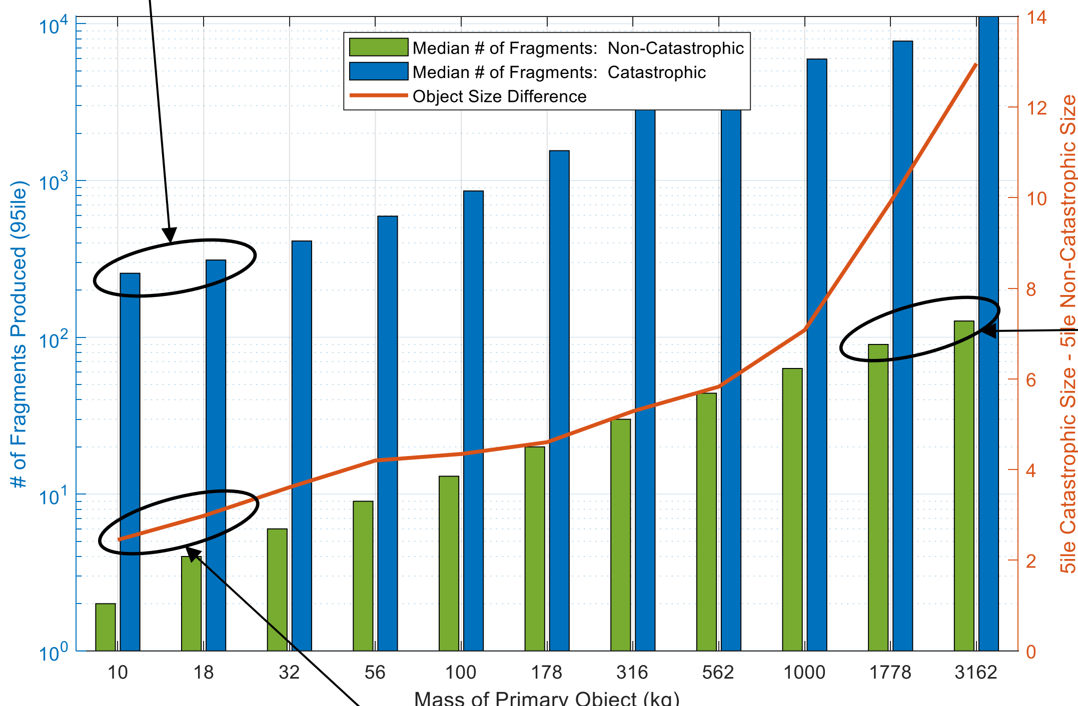
Catastrophic Collisions form separate distribution; stop when secondary object becomes too small to cause them

Non-Catastrophic Collisions form separate distribution; never produce more than ~100 pieces

Edge of Detection

Summarized Debris Production Profiling Results: All Primary Masses (10kg – 3000kg)

For small primaries, catastrophic collisions produce relatively modest debris counts (200-300 pieces)



Even for large primaries, non-catastrophic debris production never more than ~100 pieces

Always ~3cm or greater difference between minimum secondary size for catastrophic collisions and minimum detectable debris piece size

Small Object LEO Catalogue Augmentation: Summary of Effect on Debris Production

- **Non-catastrophic collisions never generate much debris**
  - ~100 pieces when small debris collides with large primaries
  - Only a handful of objects when small debris collides with small primaries
- **Catastrophic collisions always require a secondary object a few centimeters larger than the minimum detectable size (MDT)**
  - 2.5 – 3 cm larger than typical SSN MDT when colliding with small primaries
  - 10 – 13 cm larger than typical SSN MDT when colliding with large primaries
- **So adding smaller objects to space catalogue does not significantly advance the cause of debris production abatement**
  - When small debris constitutes one of the two objects in either a catastrophic nor non-catastrophic collisions, only small amounts of debris generated

Will Collisions with Small Objects Cause Loss of Mission?

AUGMENTED CATALOGUE ADVANTAGE #2

Loss-of-Mission from Collision with Small Objects: Overview

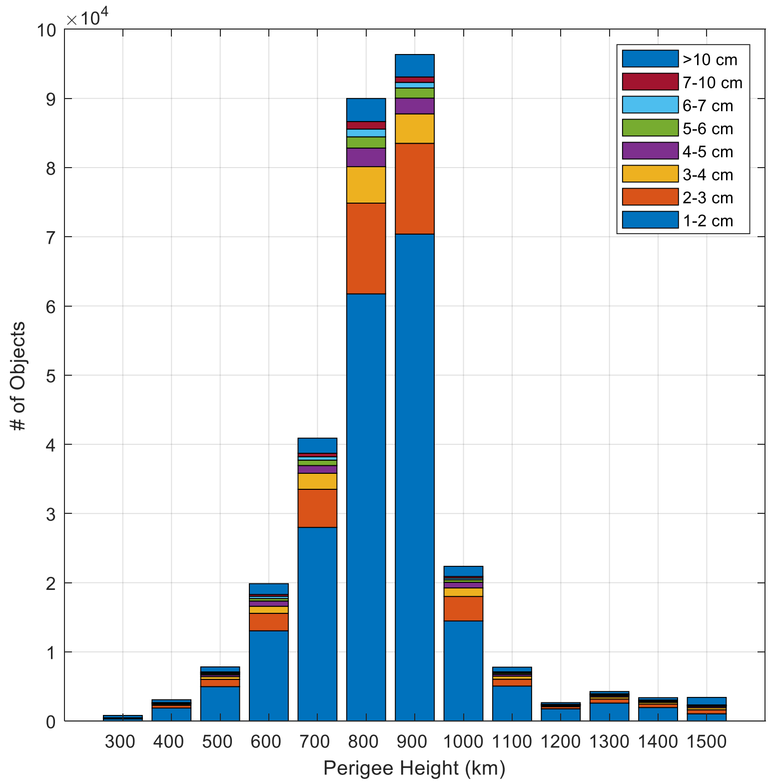
- **NASA shields spacecraft to "survive" impacts with objects < 1cm**
  - Mission potentially affected, but satellite can meet ODMSP deorbit requirements
  - Many other O/Os follow same design guidance
- **Implication is that collisions with objects > 1cm will cause mission and disposal failure**
  - Active CA against such objects thus desirable
- **However, always expected to be objects > 1cm that are not trackable**
  - Extremely powerful radars needed to track 1-2cm objects
  - Characteristics of such objects largely unknown
    - May have such high area-to-mass ratios that, even if tracked, cannot be reliably catalogued/maintained
- **Need to examine what proportion of presently untracked debris catalogue augmentation would actually address**

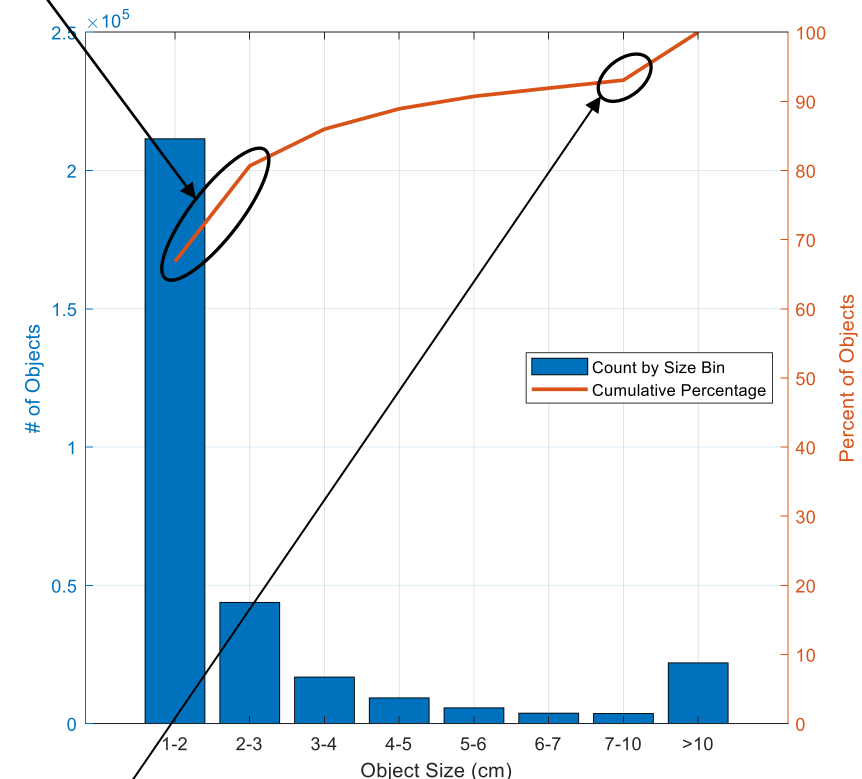
What is the Size Distribution of Small Debris?

- **In 2016, NASA Orbital Debris Program Office (ODPO) executed series of ORDEM-3 runs in support of Space Fence radar studies**
  - ORDEM is USG's principal debris model
  - Agrees reasonably well with other models for objects 1cm and larger
- **Executed ~120 Monte Carlo runs**
  - To consider differences in launch rates and debris-producing events
  - Goal was to model environment in 2020
- **Concerned only with results for 1cm – 10cm objects**
  - Differences in actual launch rates thus not particularly important
- **Monte Carlo result chosen that was most in continuity with actual satellite catalogue for 2016**

ODPO 2020 Debris Catalogue By Perigee Height and Size

- Two-thirds of debris > 1cm between 1 and 2cm; probably never trackable/maintainable
- 80% of debris is < 3 cm, which is also likely not to be maintainable





Only ~8% of objects > 10cm

Small Object Catalogue Augmentation: Protection against Loss of Mission

- **Non-S-band SSN can perform CA against ~8% of objects that can cause mission failure**
  - Not a particularly large number
  - But these are the objects most likely to generate large amounts of debris—definitely the most desirable 8%
- **Catalogue augmentation with S-band augmenting radars can improve number to range of 20% to 30%**
  - Notable improvement: increase by factor of ~3
  - Nonetheless, 70% to 80% of death-dealing collisions will still not be detected and potentially mitigated
  - Large amount of risk still will need to be accepted by space operators
- **Augmentation with S-band radars definitely helps**
- **However, still does not mitigation the majority of the problem**

Small Object Catalogue Augmentation: Summary of Effect on CA

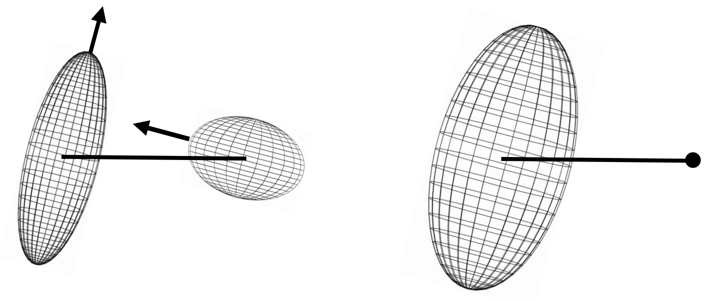
- **Will have little *direct* effect on debris production problem**
  – Collisions with small debris do not result in large debris-generating events
- **Will improve loss-of-mission situation**
  – Perhaps by a factor of three—not minor
  – However, can still address only the minority of the collision risk
    - O/Os will still have to accept collision risk with 1-2cm objects as an inherent risk of operating in space
- **Loss-of-mission improvements will have *indirect* positive effect on debris mitigation**
  – Large derelict objects are sitting ducks for large-debris-producing collisions with other objects
  – Ensuring that missions survive to proper disposal is important

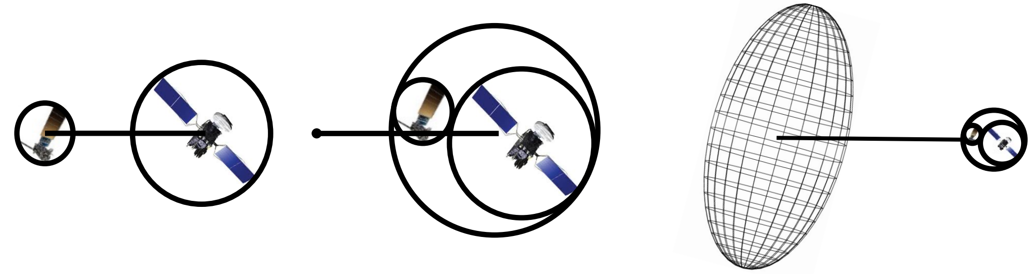
IMPROVED STATE/ COVARIANCE AT MCP

Agenda

- One-chart review of Pc calculation
- "Dilution region" basics and dynamics
- Dilution region prevalence at Maneuver Commitment Point (MCP)
- Mitigation improvements with increased tracking

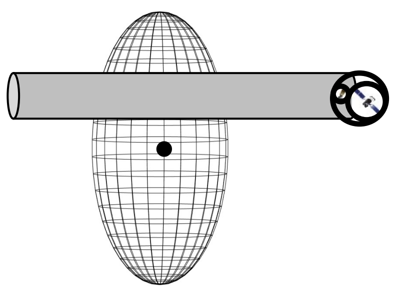
Satellite Pc Calculation (condensed to one chart)

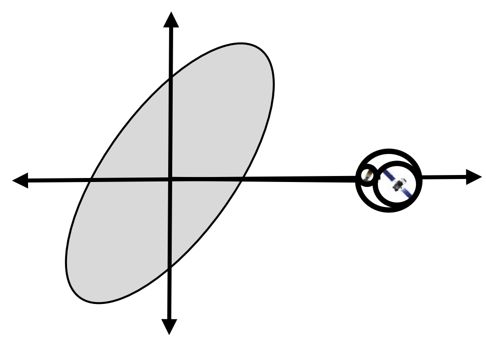




Step I: Primary and Secondary uncertainties combined and placed at position of secondary

Step II: Primary and Secondary object sizes combined with circumscribing sphere and placed at position of primary





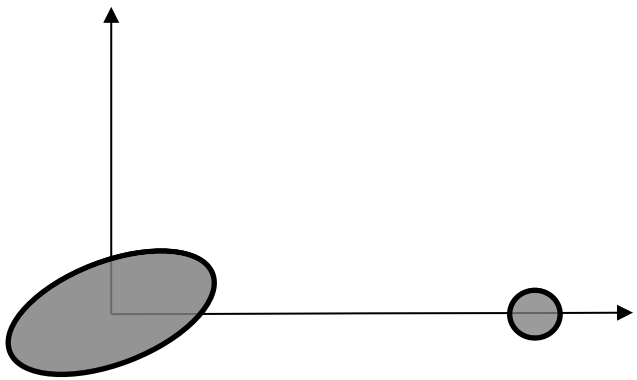
$$P_C = \frac{1}{\sqrt{(2\pi)^2\left|C^*\right|}} \iint_A \exp\left(-\frac{1}{2}\vec{r}^{\,T} C^{*-1}\vec{r}\right) dXdZ$$

Step III: If collision hyperkinetic, motion approximated as rectilinear. Primary's motion can be considered a straight cylinder, which marginalizes out that component's contribution to probability--can then project situation into plane

Step IV: Probability of collision is portion of covariance probability density that falls within HBR circle; as given by above integral

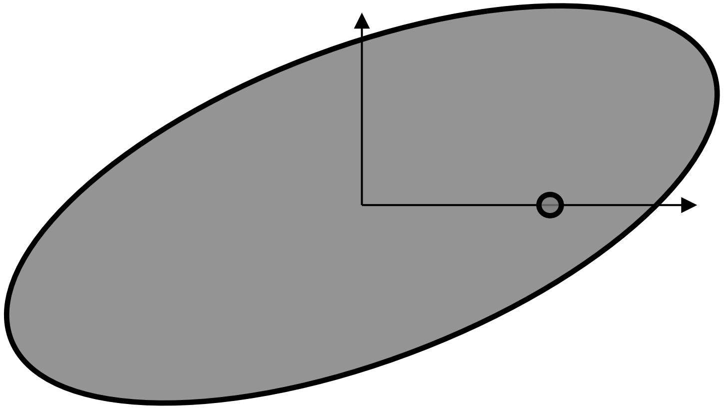
Pc Dynamics with Changing Conjunction Parameters (1 of 2)

- **If combined covariance very small, then very little probability density in HBR circle, and Pc is therefore small**
  - Robust result—uncertainties are small, so “true” miss distance should be close to estimated value
  - If estimated value larger than the HBR, then situation is safe

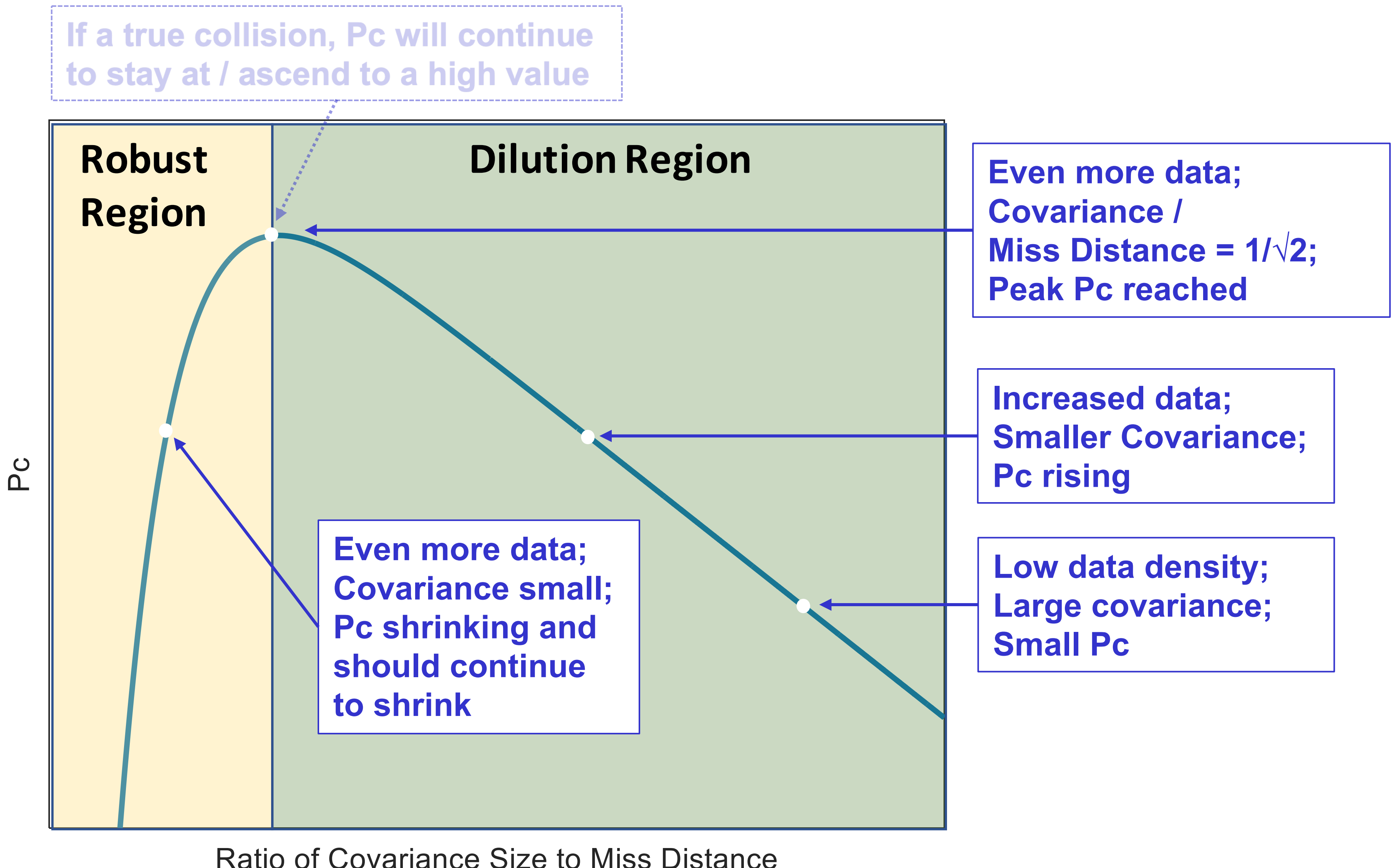


Pc Dynamics with Changing Conjunction Parameters (2 of 2)

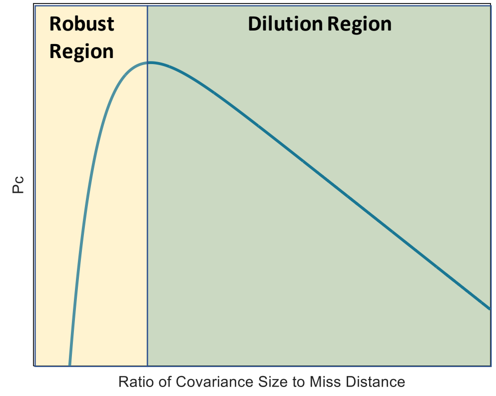
- **However, if combined covariance very large, then probability density spread over very large area, so very little actually falling within HBR circle, so Pc also small**
  - Here, Pc is low not because of high confidence in estimated miss distance; but because miss locations could take on so many different values, unlikely that it will actually be within the HBR
  - Pc is **“diluted”** by large uncertainties—low Pc not due to established safety but because so little known about situation
  - In this case, low Pc does not guarantee safety, just that data at hand not certain enough to establish a risky situation



Dilution Region Dynamics: Pictorial Illustration



Dilution Region: Implications for Risk Assessment



- **Robust region**
  - If Pc high, situation risky; if Pc low, situation safe
- **Dilution region**
  - If Pc is high, situation risky
  - If Pc is low, difficult to know what to say
    - In particular, CANNOT say that the situation is safe, for risk expected to increase with more data taken before ultimately decreasing
- **What if conjunction in the dilution region at decision time?**
  - Legitimate to act on "diluted" Pc—best estimate of the collision likelihood, given the data at hand
  - Can calculate "maximum Pc" at curve peak and act on that
    - Substantially increases number of unnecessary mitigation actions, as nearly all events will fall off to low-risk values
    - Poor operational solution for most situations
- **Best approach is not to end up in this situation**
  - Additional tracking data can eliminate many dilution region presentations

How Much will Additional Tracking Help? NASA CARA CA Data Profiling

- **Analyzed four years of CA data for “A-Train” satellites**
  - Ten protected assets in ~700km circular orbits
- **Examined all events at different maneuver commitment points (MCP)**
  - MCP is point at which CA mitigation decision must be made; risk assessment at that point is thus determinative
  - MCP is dependent on particular O/O; governed by procedural requirements and ground-contact situation for maneuver upload and verification
  - Common MCPs used for present analysis are 0.5, 1, and 1.5 days to time of closest approach (TCA)
- **Key calculations performed at each event’s MCP**
  - Probability of collision
  - Whether event was in dilution region at MCP
    - The one point at which dilution region status truly problematic, because collision risk could be understated
  - If in dilution region, then “Max Pc” calculation (Pc at curve peak)

NASA CARA Data Profile: High-Level Results

Maneuver Commit Point (MCP) (Days to TCA)	# of Events (all Pc values)	Pc > 1E-07 at MCP ("Yellows")	Pc > 1E-07 in Dilution Region	% of Yellows In Dilution Region	Pc > 1E-04 at MCP ("Reds")	Pc > 1E-07 and MaxPc > 1E-04: "Yellow-to-Red"	% of High-Risk Events Yellow-to-Red
0.5	23833	1435	538	37.5%	135	71	34.5%
1	23833	1524	548	36.0%	154	70	31.3%
1.5	23833	1661	568	34.2%	182	74	28.9%

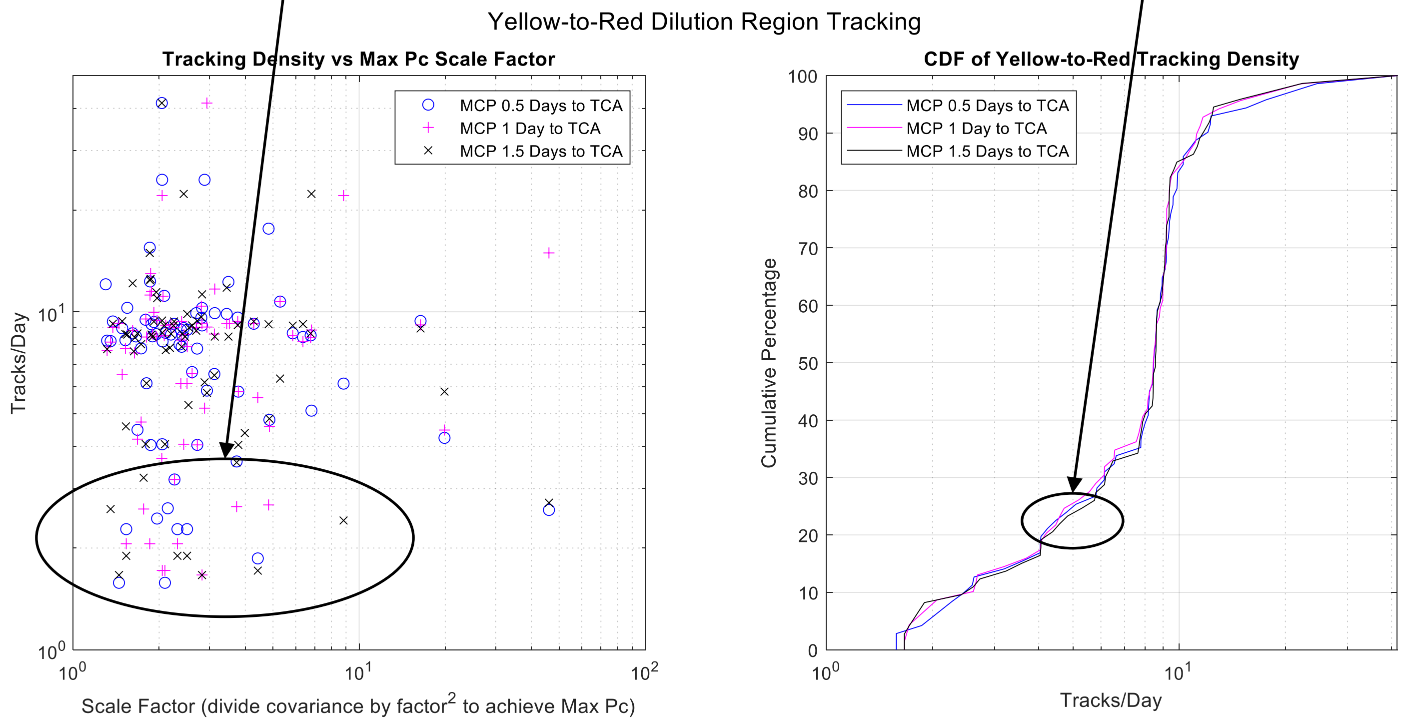
- **"Yellow" events are those with Pc > 1E-07; these get ops attention**
  - ~16% of all events are yellow at MCP; ~35% of yellows are in dilution region
- **"Red" events are those with Pc > 1E-04; these require mitigation**
  - ~0.5% of all events are red at MCP
  - ~13% of dilution region yellow events have Max Pc > red threshold (1E-04) and thus potentially are red events—called "Yellow-to-Reds"
- **If Yellow-to-Reds considered part of red events, then about 1/3 of red events are in yellow-to-red dilution region situation**
  - These should be resolved with additional tracking, if possible
  - Is this likely to be easy or difficult?

Yellow-to-Red Tracking Status: Profiling

- **~71 Yellow-to-Red cases identified in previous profiling effort**
- **Following parameters calculated for each**
  - Tracking density for each secondary's OD (tracks/day)
    - If tracking densities low, then should be straightforward to improve them
    - If tracking densities already high, then much more difficult to remediate—covariances improve with the square root of the number of tracks
  - Scale factor needed to achieve Max Pc
    - If small, then desired covariance shrinkage more easily achievable
    - If large, then probably cannot be achieved via increased tracking alone

Yellow-to-Red Tracking Status: Annotated Results

Tracking density low enough to be improved easily, but only about 25% of cases



Remainder will be difficult to remediate through tracking increases alone

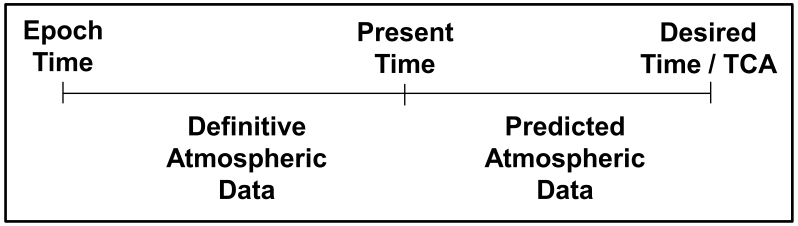
Dilution Region Remediation: Assessment

- **Perhaps ~25% of problematic dilution region cases could be straightforwardly resolved with improved tracking**
- **If NASA profiling is scalable, then ~2 problematic dilution region cases per payload per year**
  - If 25% addressable with more tracking, one such case per payload every two years remedied this way
  - Sounds small when stated as above; but if 10,000 active payloads in LEO, then ~5000 critically understated risk situations arise each year
    - These can be addressed with reasonable increase in tracking density
  - Even greater improvement probably obtained in denser region of atmosphere, such as 400-500 km

CA WARNING TIMES

Will Increased Tracking Improve CA Warning Times?

- **States and covariances for primary and secondary objects are predicted forward to TCA**
  - For advanced warning, this propagation is for days into the future
- **Increased tracking typically yields smaller epoch covariances**
- **Because propagated covariances begin with the epoch covariance, reducing epoch covariance size reduces propagation errors also**
  - For propagation from epoch to the present, perhaps true
  - For propagation into the future, atmospheric density forecast error largely to entirely dominates the propagation error
  - Situation as shown at right:



- **For propagations longer than 1-2 days, in most cases any epoch error improvement swamped by density forecast error**
  - Driven by inability to predict future solar behavior well

Both Additional Tracking and Improved Services

CA-RELATED AREAS

Potential Commercial SSA Improvement To CA-Related Areas (1 of 2)

- **“COLA Gap”**
  - Period between launch injection and full cataloguing of objects
    - Usual on-orbit CA mechanisms not possible during this period
  - Can perform CA from launch burnout vectors (and perhaps any associated tracking received), providing at least some safety products during this period
    - Some additional study of burnout vector accuracy required
- **Launch cataloguing support**
  - Often difficult to separate/catalogue groups of payloads all deployed together
    - Improved initial and follow-up tracking, and better association algorithms, can facilitate cataloguing times and initial cataloguing accuracy substantially
- **Immediate additional tracking for late-notice CA events**
  - Obtaining additional SSN tasking not always possible for CA events that first appear very close to their TCA
  - Ability to muster additional tracking quickly extremely helpful for satisfactory event resolution

Potential Commercial SSA Improvement To CA-Related Areas(2 of 2)

- **Improved atmospheric density modeling**
  - 18 SPCS model consists of three parts
    - Jacchia-Bowman 2008 (JB2008) density model
    - High-Accuracy Satellite Drag Model (HASDM) debiasing approach
    - *Anemomilos* solar storm prediction module
  - CNES Drag Temperature Model (DTM) outperforms JB2008*
  - With tracking data on properly-chosen satellites, can recreate HASDM**
  - Would be useful to be able to engage/disengage *Anemomilos* model at will
  - In short, could provide improved CA products through upgraded and more versatile density model

*S.L. Burinsma *et al.*, “Evaluation of the DTM-2009 Thermosphere Model for Benchmarking Purposes,” *Journal of Space Weather and Space Climate*, Vol. 2 (2012), A04.

**S.J. Casali and W.N. Barker, “Dynamic Calibration Atmosphere (DCA) for the High Accuracy Satellite Drag Model (HASDM),” 2002 AAS/AIAA Astrodynamics Specialist Conference (Paper # 2002-4888), Monterey CA, August 2002

SUMMARY

Summary

- **Catalogue augmentation with additional small objects**
  - Unlikely to make a substantial difference in controlling debris production
  - Can double or triple ability to guard spacecraft against low-debris collisions that nonetheless are likely to result in loss of mission / subsequent debris
    - However, 70% of such conjunctions still not trackable/mitigatable
- **Additional tracking to improve epoch state estimate / covariance**
  - Will identify one additional “must mitigate” event per payload every two years
    - Perhaps even better performance in denser atmosphere
  - Not transformative for single payload, but for large numbers of primary objects could be significant
- **Additional tracking alone unlikely to improve CA warning times**
- **CA-related areas that combine tracking and algorithms/services**
  - Launch and early-orbit: COLA Gap and cataloguing
  - Rapid late-notice CA event follow-up
  - Improved atmospheric density modeling, which combined with increased tracking would improve CA warnings

Understanding the Value of Increased Tracking: "Cumulative Case Argumentation"

- **No single area of CA enterprise so transformed by increased tracking that makes full case for it on its own**
- **However, increased tracking, especially when combined with improved services, is demonstrably helpful in most CA areas**
- **When all these advantages taken together, the cumulative case for increased tracking becomes strong**
  - In an STM setting, number of payloads to which such improvements would apply is large
  - Small(er) benefits spread over a large number of satellites become large benefits