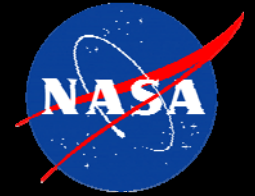


National Aeronautics and Space Administration



NASA Conjunction Assessment Organizational Approach and the Associated Determination of Screening Volume Sizes

Lauri K. Newman

NASA Robotic Conjunction Assessment Manager

Matthew D. Hejduk

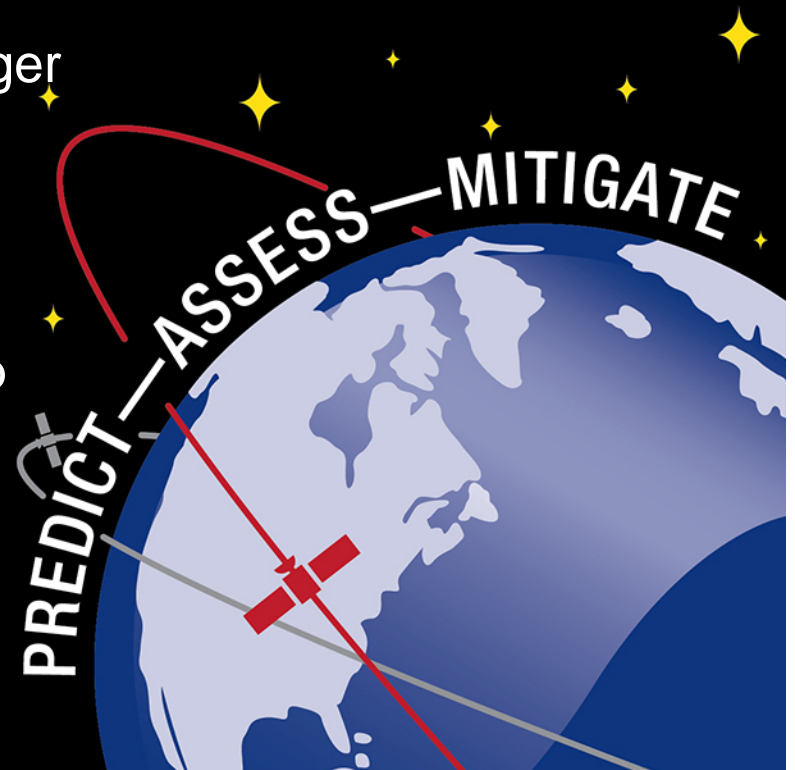
NASA Robotic CARA Chief Engineer

International CA Risk Assessment Workshop

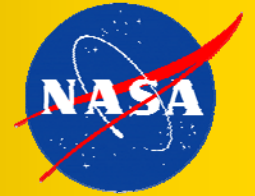
19-20 MAY 2015

NASA ROBOTIC CARA

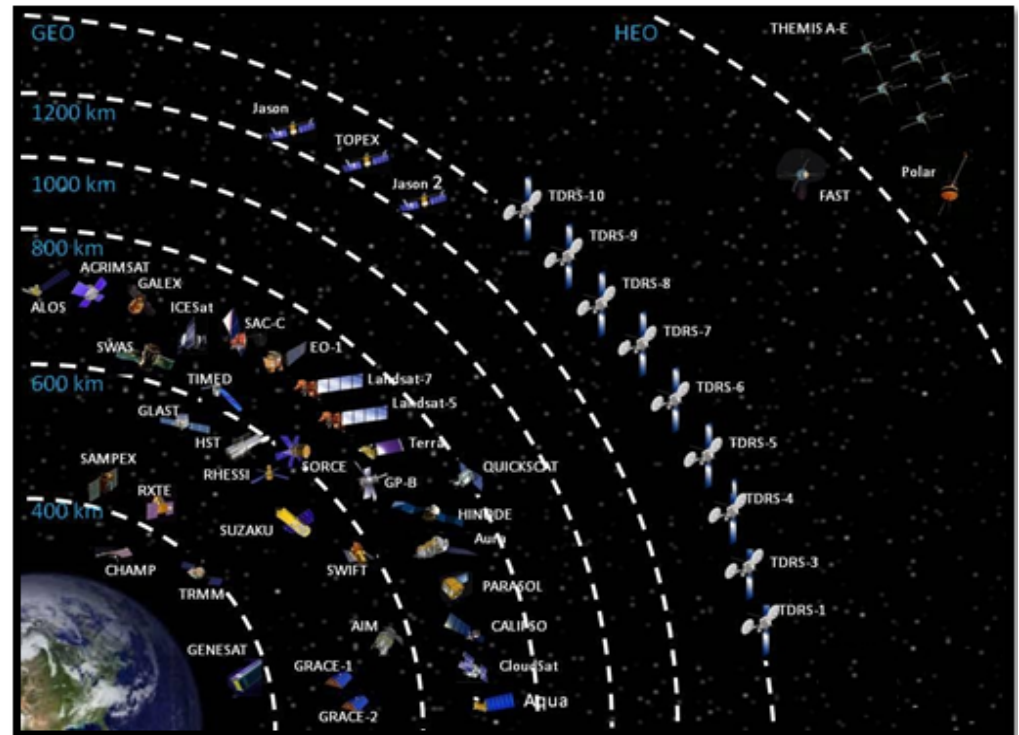
www.nasa.gov



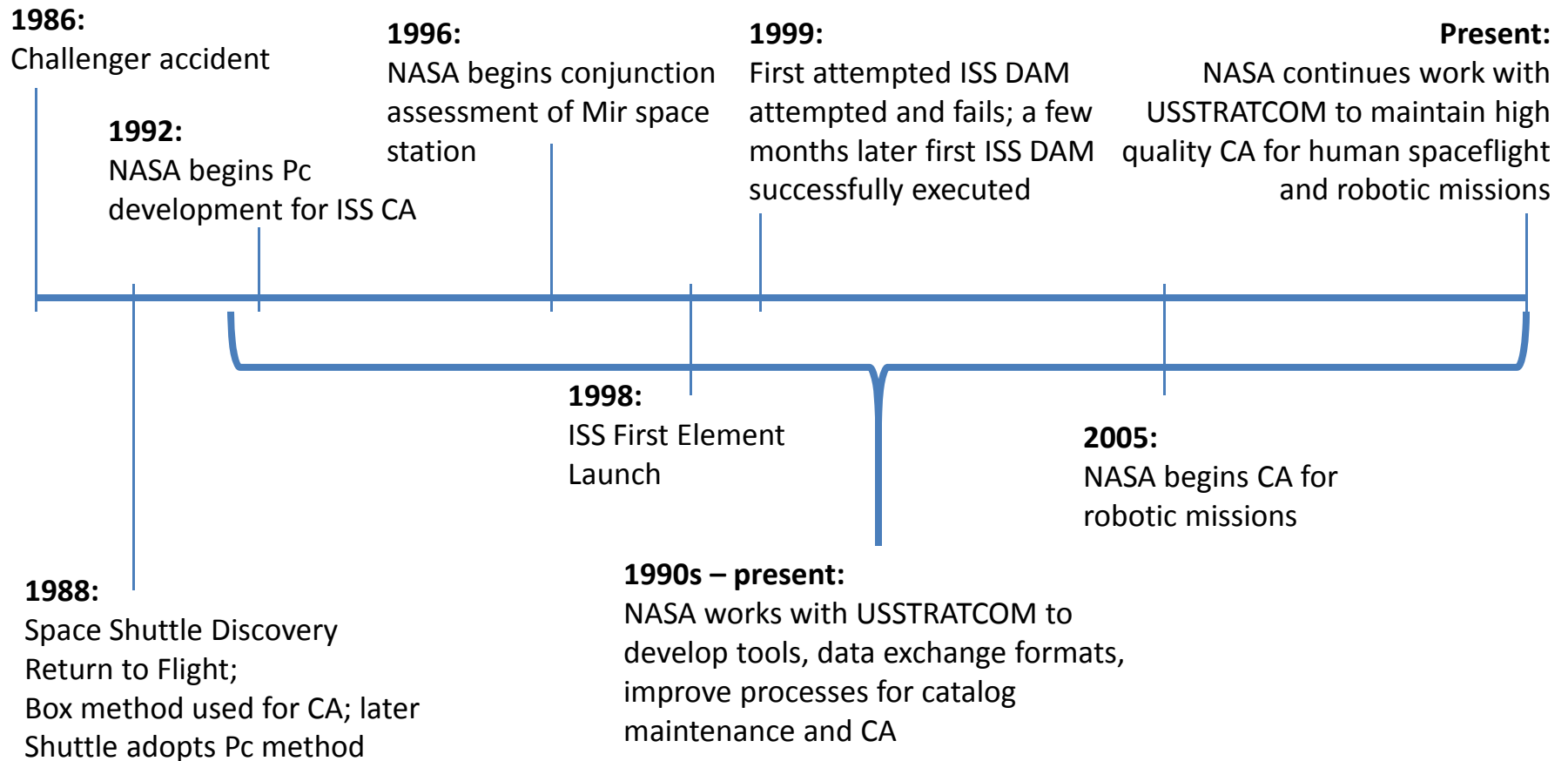
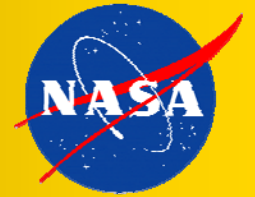
NASA's Process: CARA



- NASA is committed to safety of flight for all of its operational assets
 - Performed by CARA at NASA GSFC for robotic satellites
 - Focus of this briefing
 - Performed by TOPO at NASA JSC for human spaceflight
- The Conjunction Assessment Risk Analysis (CARA) was stood up to offer this service to all NASA robotic satellites
 - Currently provides service to ~70 operational satellites
 - NASA unmanned operational assets
 - Other USG assets (USGS, USAF, NOAA)
 - International partner assets

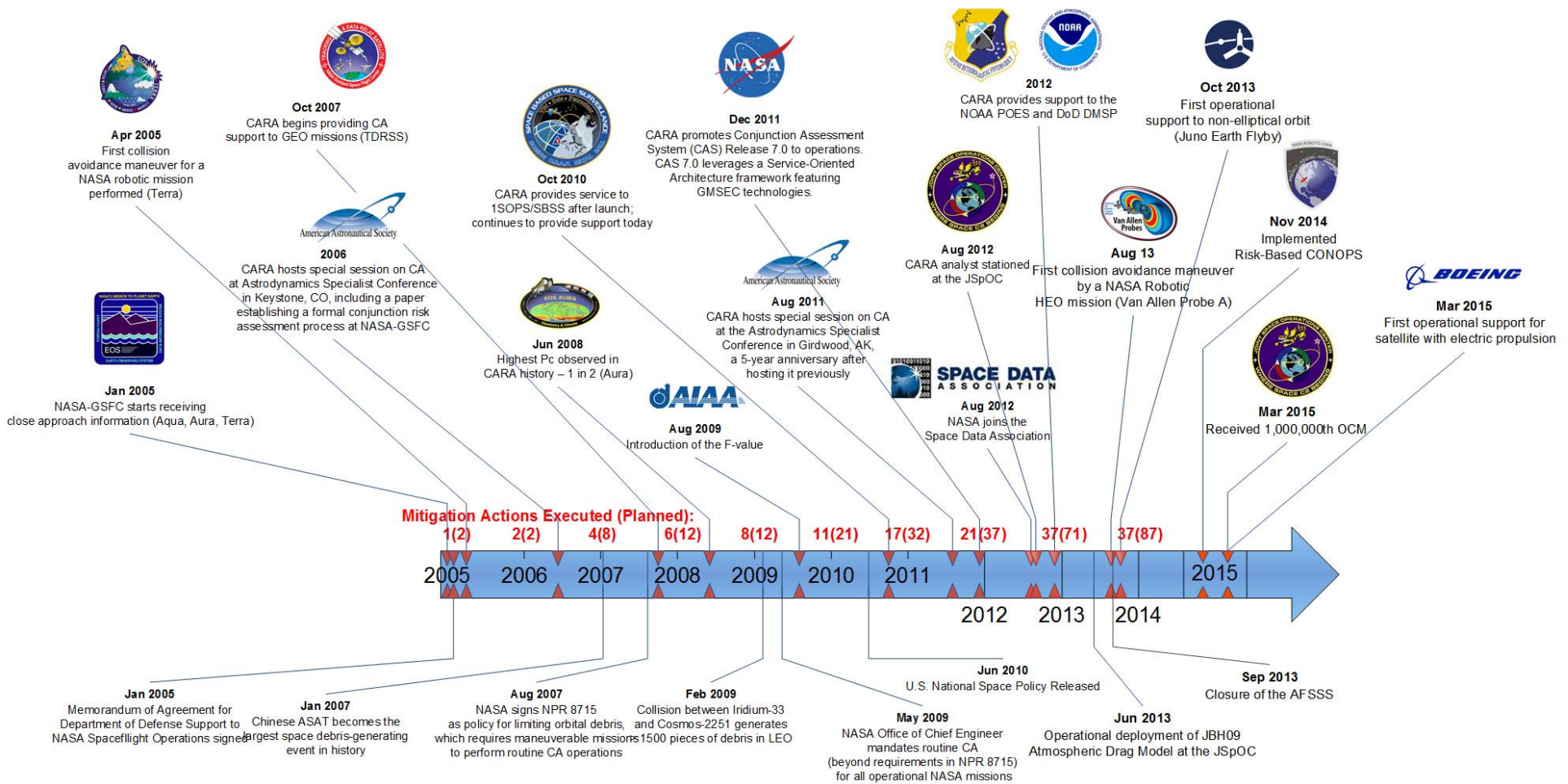


NASA Human Spaceflight Conjunction Assessment (CA) History

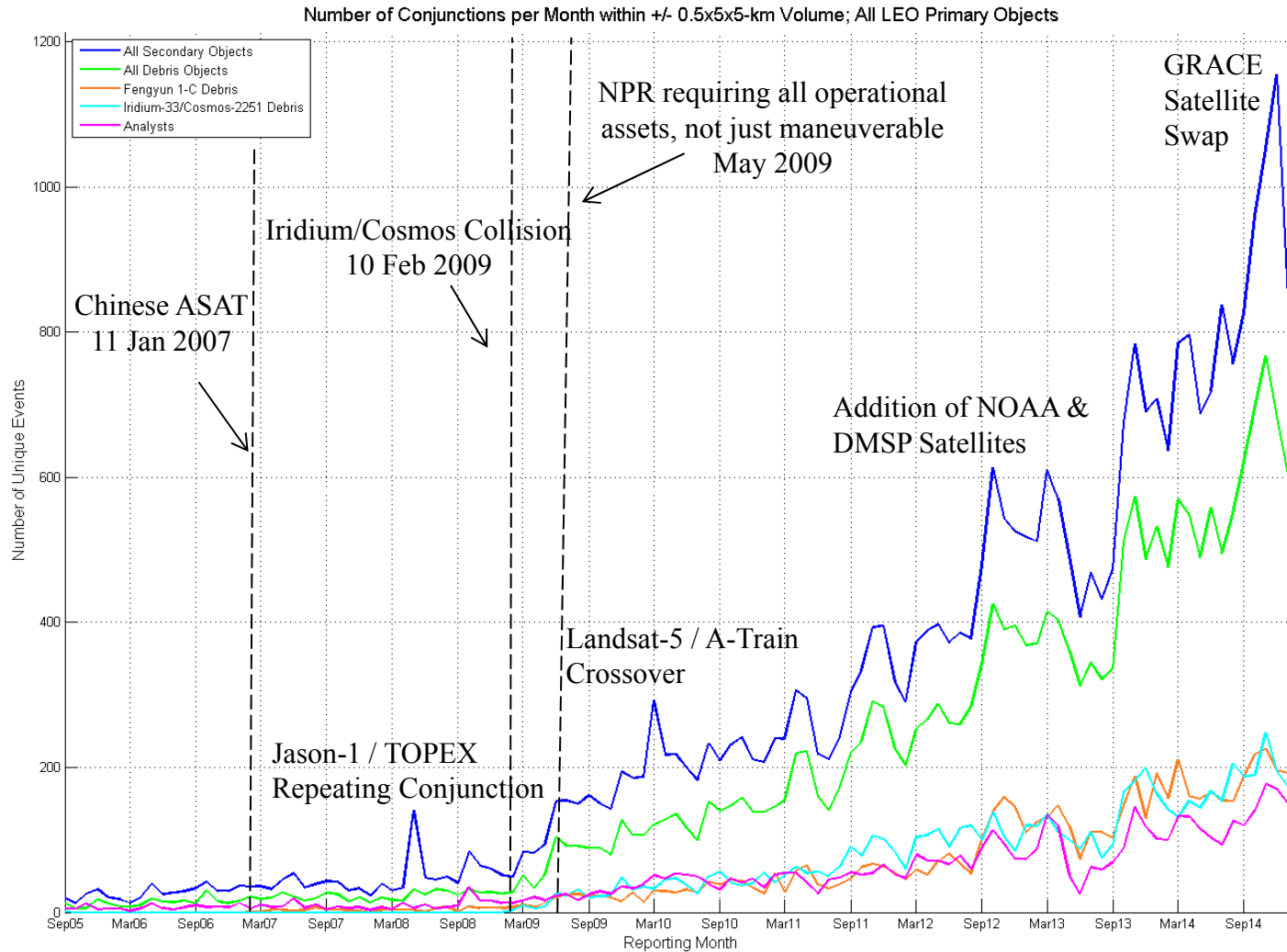
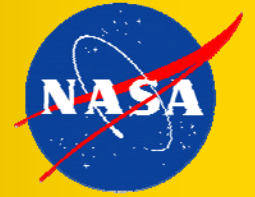


NASA has performed CA for 25 years. Initial USSTRATCOM capability developed with NASA.

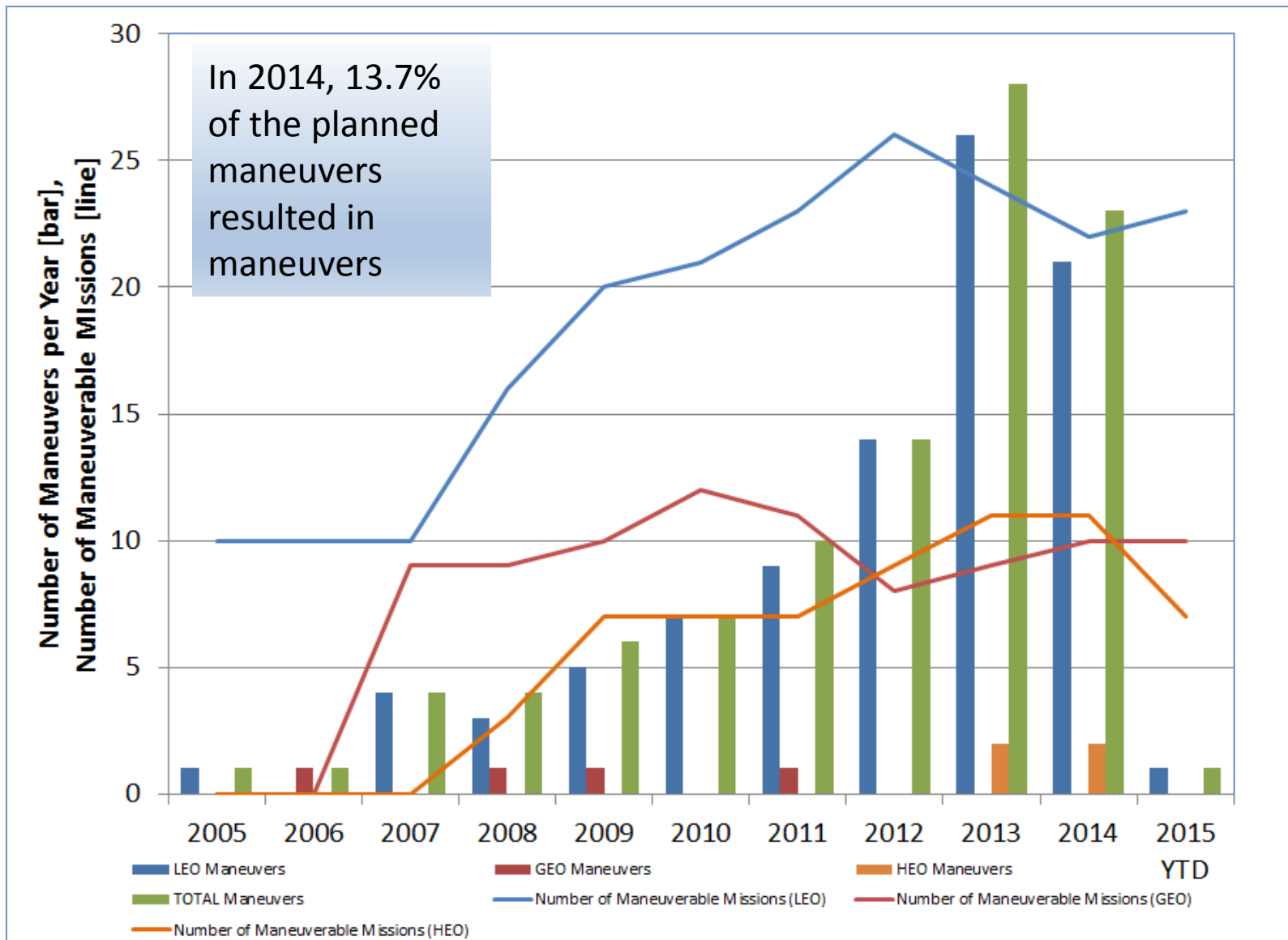
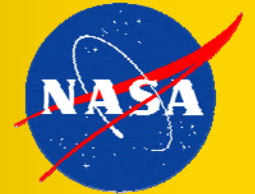
NASA Robotic CARA History



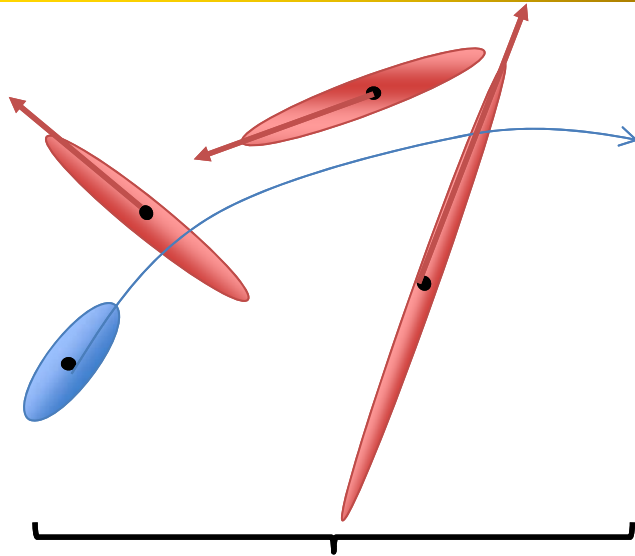
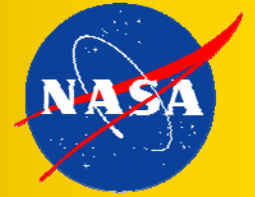
Mission Context: Number of Conjunctions in LEO



Collision Avoidance Maneuvers History

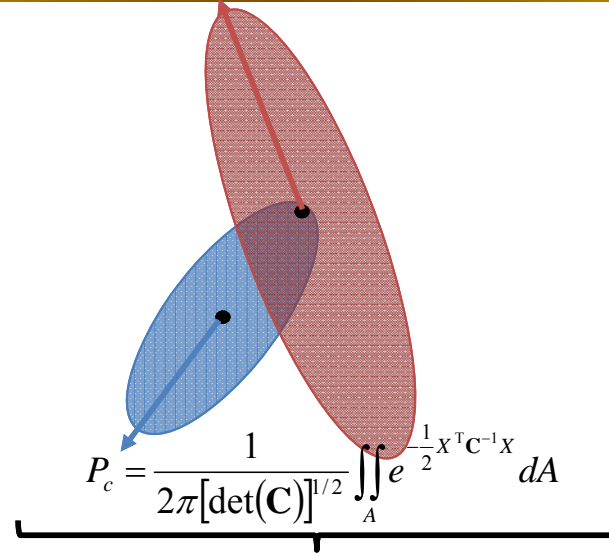


The CARA Process Helps Manage On-Orbit Collision Risk



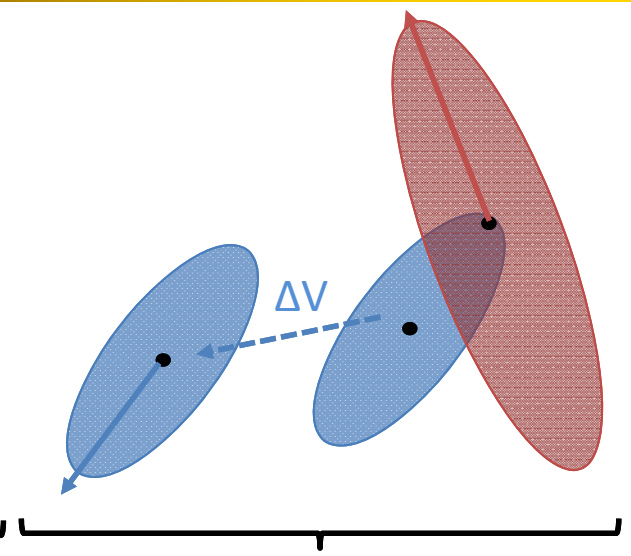
Conjunction Assessment (CA) is the process of identifying close approaches between two orbiting objects; sometimes called conjunction “screening”

The **Joint Space Operations Center (JSpOC)** – a USAF unit at Vandenberg AFB, maintains the high accuracy catalog of space objects, screens CARA-supported assets against the catalog, performs OD/tasking, and generates close approach data



CA Risk Analysis (CARA) is the process of assessing collision risk and assisting satellites plan maneuvers to mitigate that risk, if warranted

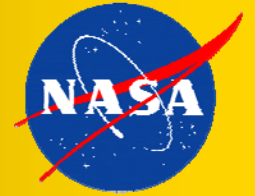
The **CARA** Team at NASA-GSFC provides CARA for all NASA operational robotic satellites, as well as a service provider for some other external agency/organizations



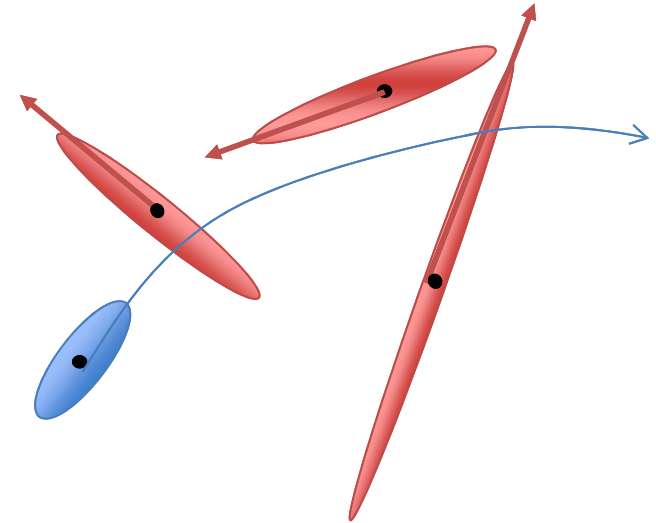
Collision Avoidance (COLA) is the process of executing mitigative action, typically in the form of an orbital maneuver, to reduce collision risk due to a conjunction

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

CARA Operational Process: Close Approach Predictions at the JSpOC



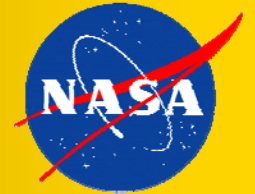
- The JSpOC maintains an accurate state for all trackable objects
- In support of CARA, the Goddard-dedicated Orbital Safety Analysts (OSA)
 - Perform routine screenings – 2x day for LEO, 1x for GEO/HEO
 - Against JSpOC’s Astrodynamics Support Workstation (ASW) solution and the O/O solution if available
 - Inspect orbit determination; perform manual orbit determination, if warranted
 - Adjudicate tasking level of secondary objects; request increased tasking, if warranted
 - Generate and deliver necessary data products
- JSpOC is staffed by Goddard-dedicated OSA 18 hours/ day



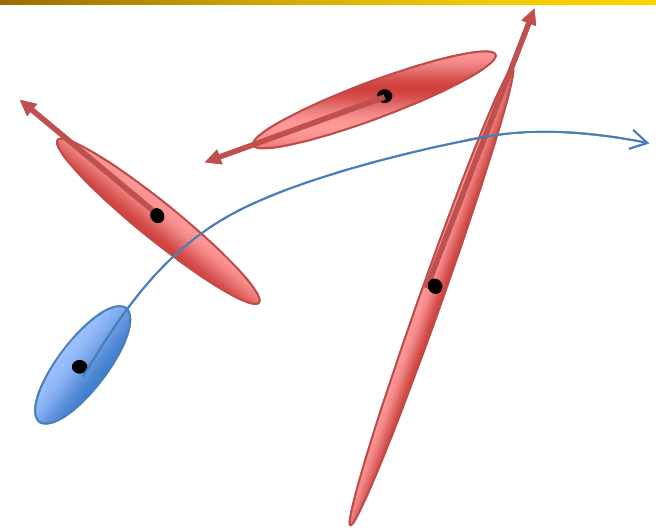
The **Screening Duration** is the “lookout” period of time for which conjunctions are identified. This is 7 days for LEO assets and 10 days for GEO/HEO assets

The **Screening Volume** is the geometric volume placed around the asset during the conjunction screening process; any objects that violate this volume trigger data products to be generated and delivered. The screening volumes are re-sized annually by CARA using a 95% capture of the relative uncertainties in each orbital regime based two-year moving window historical conjunction data

CARA Operational Process: Close Approach Predictions at the JSpOC



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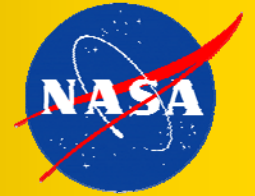
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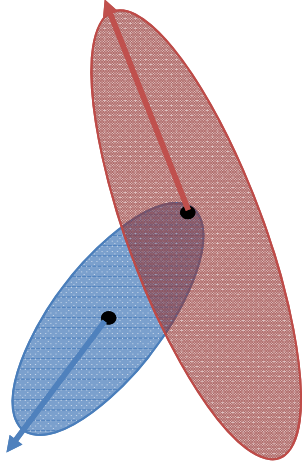
Approach described in later charts



CARA Operational Process: Collision Risk Analysis at NASA-GSFC



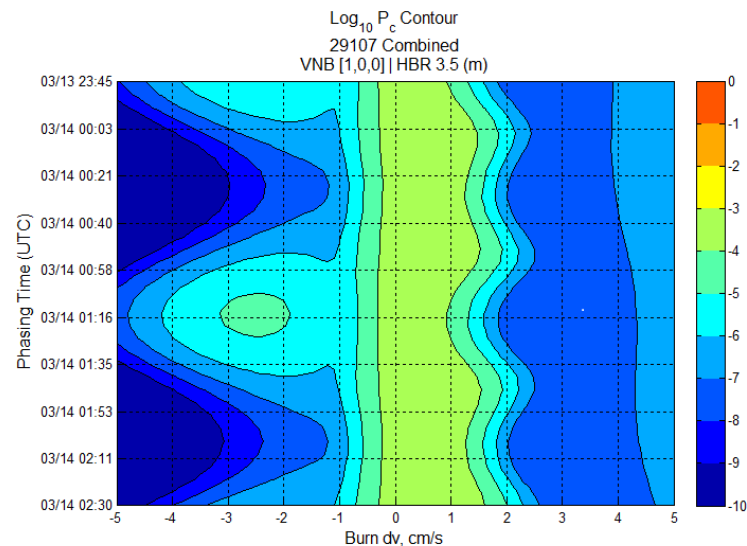
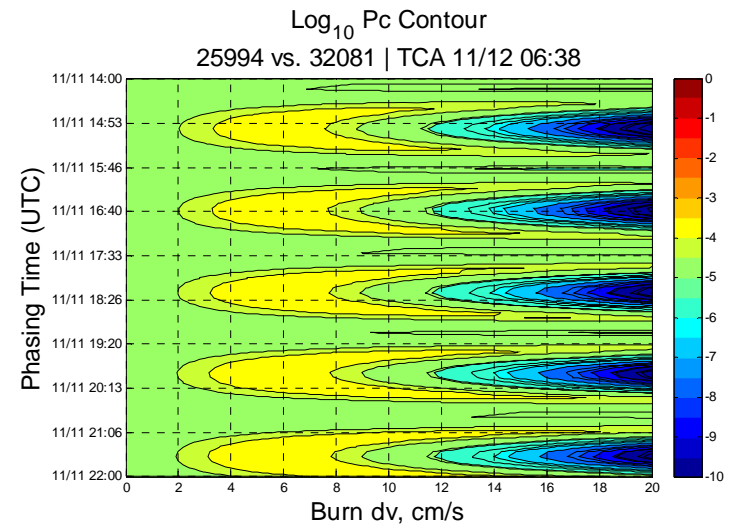
- CARA is responsible for assessing, communicating, and assisting with mitigation of on-orbit collision risk
- As data is received, the CARA system automatically processes that data, and generates & delivers
 - **CARA Summary Reports** to O/O
 - **Work List** to JSpOC OSAs
- CARA team performs routine risk analysis
 - P_c ; P_c sensitivity
 - Conjunction Geometry
 - OD Evaluation / Solution Consistency
 - Space Weather Sensitivity
 - Maneuver planning & evaluation
- For high-risk conjunctions, CARA builds and delivers a **High Interest Event (HIE) briefing** with detailed analyses, and planning & decision information


$$P_c = \frac{1}{2\pi[\det(\mathbf{C})]^{1/2}} \iint_A e^{-\frac{1}{2}\mathbf{x}^T\mathbf{C}^{-1}\mathbf{x}} dA$$

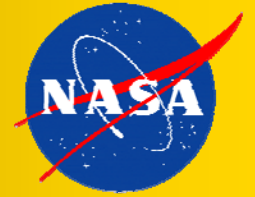
The **Collision Probability (P_c)** is the probability that, given the uncertainty in the two objects' positions as described by their covariance matrix, that the actual miss distance is less than the hard-body region

Maneuver Planning

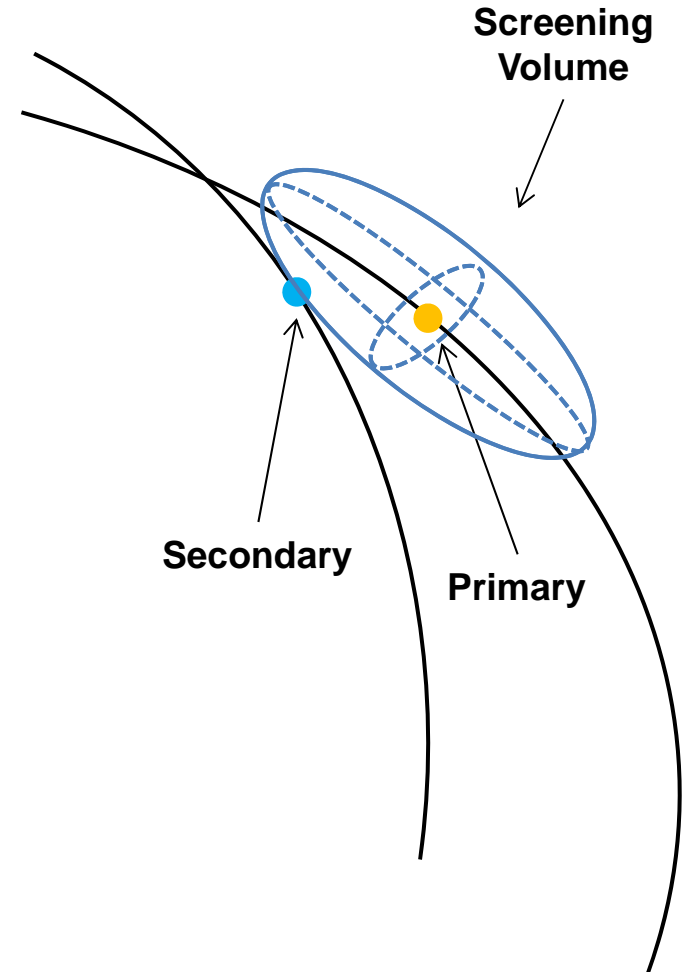
- A trade-space contour plot shows the effect that a range of phase times and delta-v magnitudes have on miss distance
 - Single conjunction event (top)
 - Multiple events (bottom)
- Assists with initial maneuver planning
 - Save time-expensive iteration cycles for high fidelity maneuver planning
 - Does not presume any constraints about satellite maneuver capability or conjunction mitigation strategies—allows flight support teams to decide on course of action



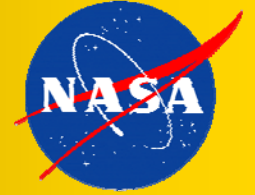
JSpOC CA Screening and CDM Generation Approach



- First, perform screening to find close approaches to primary
 - Filter out secondaries that cannot possibly collide with primary
 - Generate ephemerides for primary and secondaries that are possible threats
 - Construct screening volume about primary
 - “Fly” the ellipsoid along the primary’s ephemeris
 - 7 days for LEO
 - 10 days for HEO/GEO
 - Any penetrations constitute possible conjunctions
- Once conjunctions identified, generate initial risk information for each
 - Determine time of closest approach (TCA)
 - Calculate probability of collision (P_c)
- Because gatekeeper for further processing, screening portion important
 - Size of volume determines the objects discovered

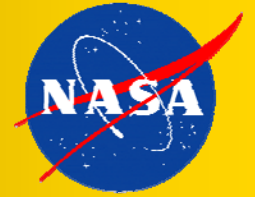


Screening Volume Sizing Approach: Constituent Elements



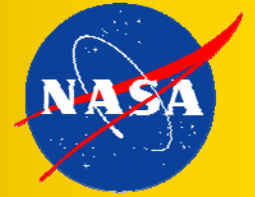
- Appropriate sampling dataset
- Screening volume sizing definition
- CDM data use: assumptions
- Screening volume shaping approaches
- Presentation of results

Screening Volume Sizing Approach: Appropriate Sampling Dataset (1 of 2)



- Historical CDMs suggest themselves as investigation dataset
 - Contain conjunction information, so number of analytical criteria available
 - However, dataset a function of past screening volume size—circularity risk
- Limit dataset to events that showed some propensity for severity
 - Screening volumes to capture certain percentage of potentially serious events
 - Highest P_c observed during event good indication of this
- However, set P_c at fairly “generous” value to ensure consideration of nearly all potentially worrisome events
 - $P_c > 0$ (for MATLAB numerical integrator, equivalent to $P_c > 1E-324$)
 - For 2013-14, about 70% of events contained a $P_c > 0$
 - About 56% (333,000) of all CDMs

Screening Volume Sizing Approach: Appropriate Sampling Dataset (2 of 2)

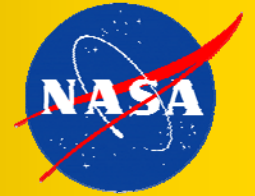


- Divide primaries into orbital regimes and analyze CDMs from each orbital regime separately:

Orbital Regime	Definition
LEO #1	Perigee \leq 500 km & Eccentricity $<$ 0.25
LEO #2	500 km $<$ Perigee \leq 750 km & Eccentricity $<$ 0.25
LEO #3	750 km $<$ Perigee \leq 1200 km & Eccentricity $<$ 0.25
LEO #4	1200 km $<$ Perigee \leq 2000 km & Eccentricity $<$ 0.25
MEO	600 min $<$ Period $<$ 800 min & Eccentricity $<$ 0.25
GEO	1300 min $<$ Period $<$ 1800 min & Eccentricity $<$ 0.25 & Inclination $<$ 35°
HEO #1	Perigee $<$ 2000 km & Eccentricity $>$ 0.25
HEO #2	Perigee $>$ 2000 km & Eccentricity $>$ 0.25

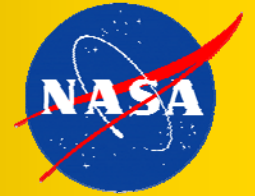
- Divide CDMs for each primary into different “Time to TCA” bins
 - Map roughly to propagation times
 - Proposed bins are 0-2 days, 3-4 days, and 5-7 days

Screening Volume Sizing: Definitional Premise



- If a particular CDM were to represent an actual collision, would want screening volume sized to capture this event $x\%$ of the time
 - Since screenings run twice per day seven days into the future, some flexibility in the value of “ x ” to still get a very high capture percentage
 - If screenings were not correlated events, formula for total probability of collision (TPC) could be used
 - $TPC = 1 - \prod(1 - x)^n$; which would push the total probability rapidly to unity
 - However, subsequent screenings are correlated events, so cumulative effect will be less than this theoretical maximum
- Probably want each screening’s capture percentage somewhere in the range of 75 – 95%
 - In explicit language: “If the two objects were actually to collide, would want to find this event with a single screening $x\%$ of the time”
 - This should provide a reasonably high total probability from multiple screenings over several days

CDM Data Use Assumption #1: Zero-Miss Alteration



- CDM represents a close approach between two satellites, but in nearly all cases not a reported actual collision at the mean value
 - i.e., there is a non-zero miss distance $>$ the combined hard-body radius
- However, a very small change in trajectory (especially several days before TCA) could transform event into a collision
 - This would alter the event so as to drive the miss distance to $<$ HBR
- This “small change” has very little effect on the objects’ covariances
 - Can presume both covariances to be unaltered by it
- Combined primary and secondary covariance thus a statement of the uncertainty of the secondary about the primary’s position in the case of an actual collision
 - Monte Carlo draws on such a covariance yield an uncertainty “cloud” of positions about the primary that would still yield a collision (at the mean value)
 - Screening volume should be sized to capture x% of such a set of position uncertainties

CDM Data Use Assumption #2: Relative Velocity Component Elimination



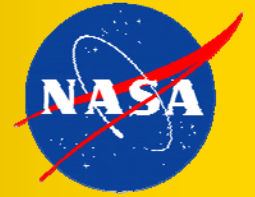
- If conjunction is high velocity and short duration, a collision, should it occur, will take place in “conjunction plane”
 - Plane normal to the two satellites’ relative velocity vector
- Basis for 2-d probability of collision calculation paradigm
 - Collision geometry and combined covariance projected into this plane
 - Covariance components in relative velocity direction contribute nothing to the P_c calculation—they lie outside of this plane
- Can take advantage of this fact in setting screening volume sizes
 - Can eliminate relative velocity components of combined covariance
 - These components will not affect the P_c
- Will have the effect of shrinking the screening volume size necessary to achieve a certain capture percentage

Screening Volume Sizing Procedure

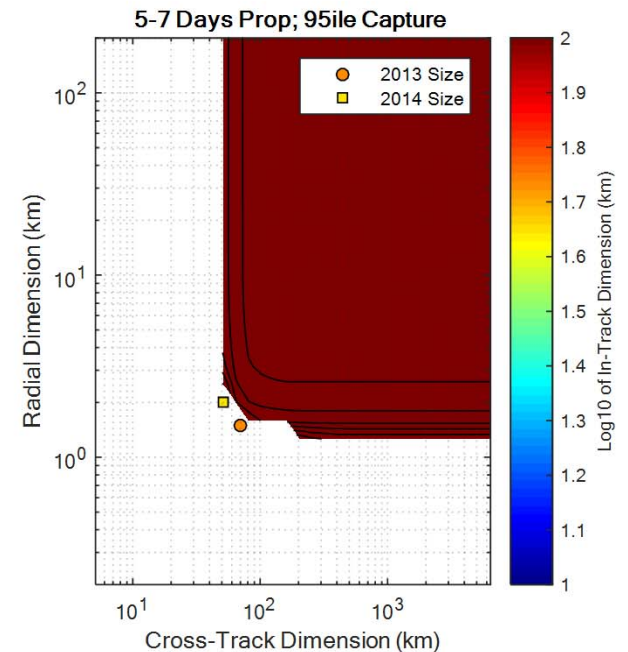
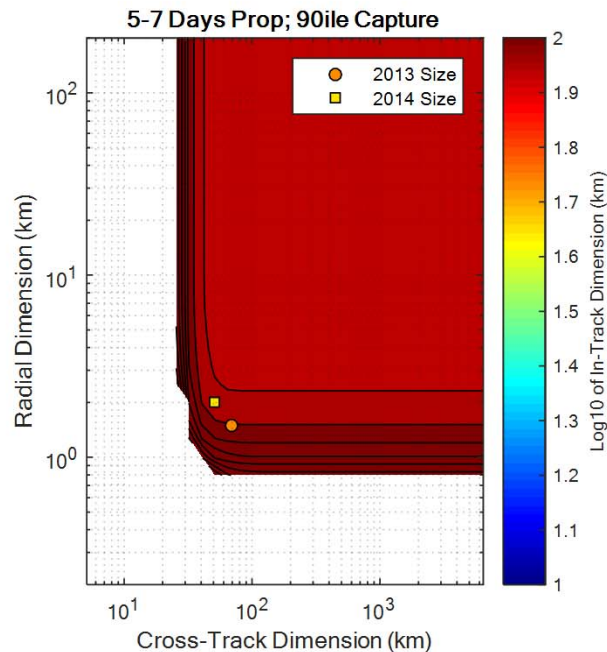
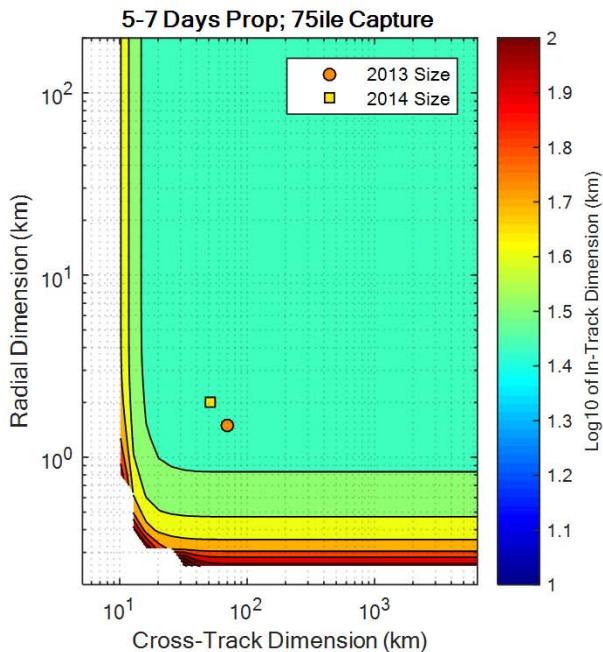


- Assemble set of CDMs for particular orbit regime and time group
- Combine primary and secondary covariances for each CDM and project into conjunction plane
- Use projected covariances to create Y perturbation points for each; rotate these points back to 3-d coordinate frame
 - Present analysis experimenting with using between 5,000 to 10,000 perturbation points per CDM; limited by machine memory
- Construct screening volumes that capture x% of this set of points
 - Apply nested application of radial and then cross-track sizes
 - For each, use iterative solution to determine size of in-track component that brings the volume to a x% capture level (if this is possible)
 - Example: construct an ellipsoid (centered at origin in RIC system) that has a radial component of 1km and an in-track component of 20km
 - Iterate to find the in-track component that captures 90% of the perturbation points
- Construct a trade-space of these results

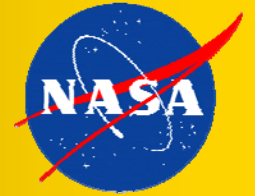
Sample Output: Orbit Regime 1 (High Drag)



- Y-axis radial component of screening volume; X-axis is cross-track
- Color (“Z-axis”) is in-track component
- All axes in log space
- Symbols show 2013 and 2014 screening volume sizes
- Many different ways to achieve desired capture percentage
 - Can thus consider other factors, such as desired volume shape



Current Status



- Analysis continuing
 - CDM database being expanded
- Final results should be complete by this summer
 - Will present results and way forward at Users Forum