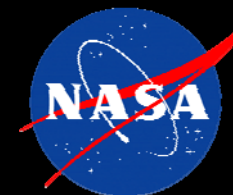National Aeronautics and Space Administration

# Conjunction Assessment Past, Present, and Future

Lauri K. Newman
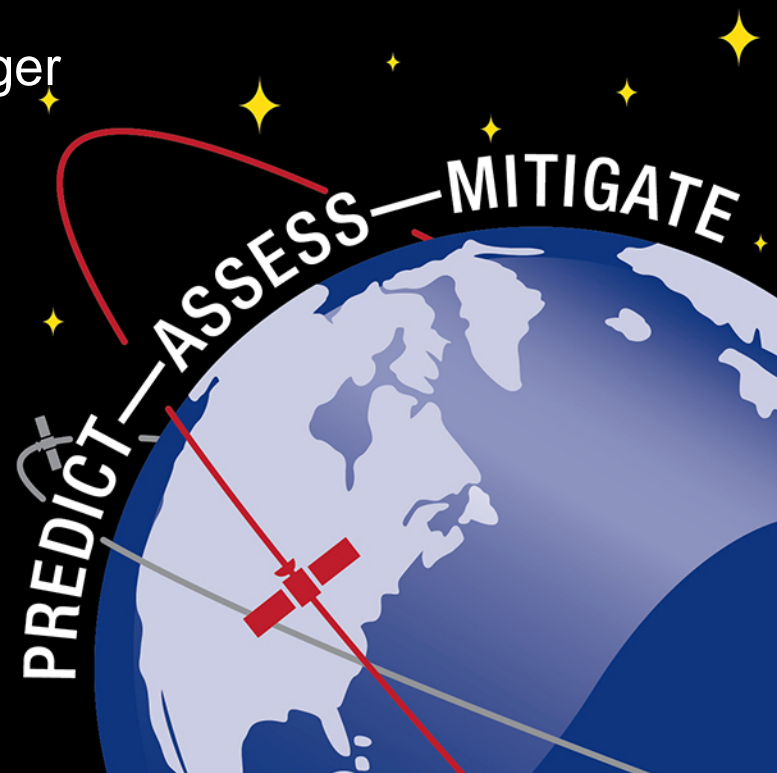
NASA Robotic Conjunction Assessment Manager
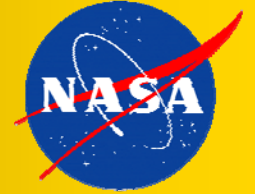
Space Situational Awareness 2015

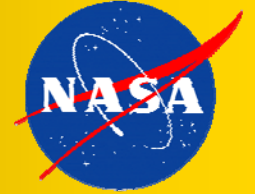12 MAY 2015

**NASA ROBOTIC CARA**
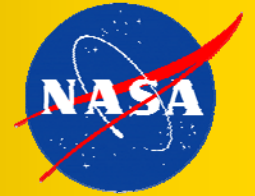
www.nasa.gov

# Overview

- ***Learning from Yesterday:*** *On-orbit collisions are a real and increasing mission risk*

- ***Where we are Today:*** *Collision risk management requires more than just predicting close approaches*

- ***Looking to Tomorrow:*** *What challenges are anticipated in the future*

# Humankind's Reliance on Space

- Since 1957, humankind's reliance on the space domain for military, humanitarian, and commercial applications has continued to increase
  - 1960—first successful use of a meteorological satellite
  - 1963—first use of a geosynchronous communications satellite
  - 1985—Block I of GPS fielded
  - 1998—first module of ISS
  - 2001—first satellite radio broadcast over North America

# Space is a Finite Resource

- Although expansive, the space domain is not limitless
- Access to space cost, desired science/mission, and physics—often in that order—dictate the location of a particular satellites
- Some orbit regimes have become popular destinations; for example:
  - Low-Earth Orbit for Earth Observation
  - Semi-Synchronous for position, navigation, and timing
  - Geosynchronous for Telecommunications

# One New Satellite ≠ One New Object in Space

- What you take into space, stays in space
  - Launch vehicle / Rocket-Bodies
  - Mission-related debris
- Debris can also be generated on-orbit
  - Fuel/Battery Explosions
  - Collisions
- Only naturally-occurring retarding effect is orbital decay due to atmospheric drag
  - Some remediation measures available
  - Active debris removal not yet viable option
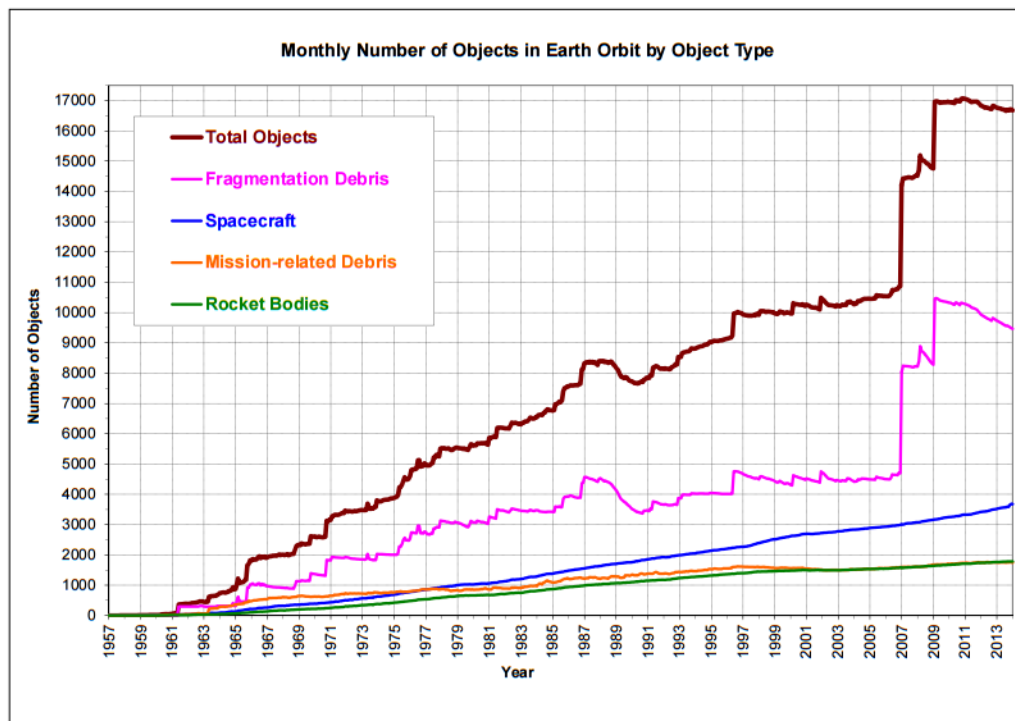


Monthly Number of Cataloged Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.

Graphic from Orbital Debris Quarterly New, Volume 18, Issue 1

# On-Orbit Collision is *Real* Mission Risk

- Because of our reliance on space and the fact that space really isn't limitless, the "Big Sky" theory is no longer an acceptable risk posture
- There have been eight (8) on-orbit collision reported to date, half of which occurred in the last 10 years

| Year | Event |
|---|---|
| 1991 | Inactive Cosmos 1934 satellite hit by cataloged debris from Cosmos 296 satellite |
| 1996 | Active French Cerise satellite hit by cataloged debris from Ariane rocket stage |
| 1997 | Inactive NOAA 7 satellite hit by uncataloged debris large enough to change its orbit and create additional debris |
| 2002 | Inactive Cosmos 539 satellite hit by uncataloged debris large enough to change its orbit and create additional debris |
| 2005 | U.S. rocket body hit by cataloged debris from Chinese rocket stage |
| 2007 | Active Meteosat 8 satellite hit by uncataloged debris large enough to change its orbit |
| 2007 | Inactive NASA UARS satellite believed hit by uncataloged debris large enough to create additional debris |
| 2009 | Active Iridium satellite hit by inactive Cosmos 2251 |

Compiled by Dr. David Wright of the Union of Concerned Scientists, reused by Brian Weeden in **"Billiards in space", The Space Review** *February 23, 2009.*

# Collisions Exacerbate the Problem
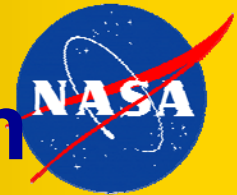
- The space object environment continues to *incrementally* increase over time
  - Launches continue unabated, and are even accelerating
  - Launching satellites leave other objects behind
  - On-orbit failure can create additional debris
- One on-orbit phenomenon that can *fundamentally* increase the space object environment is hypervelocity impacts
  - Could occur through intentional means (anti-satellite demonstrations, like FY-1C destruction in 2007) or natural means (collisions, like Iridium-Cosmos collision in 2009)
- These events are rare but have severe consequences
  - Catastrophic loss of mission
  - Significant debris generation



Low Earth Orbit Height Distribution (July 2014)
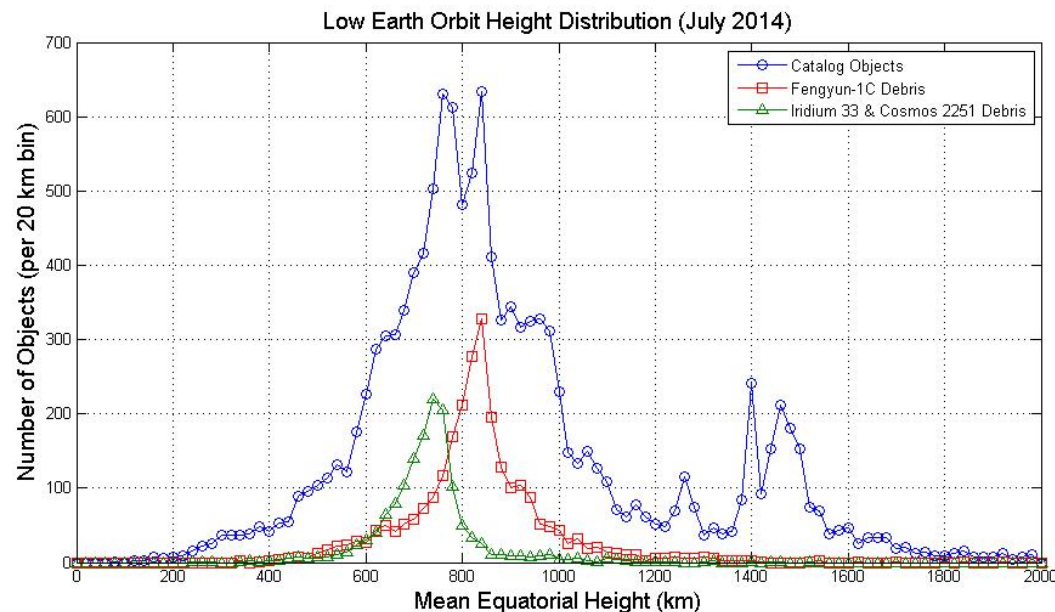
# Collisions are Preventable
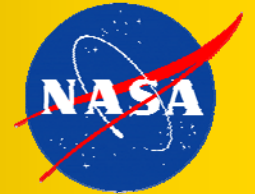
- The United States maintains a catalog of trackable space objects
  - Catalog maintained by the USAF's Joint Space Operations Center (JSpOC)
  - Uses non-O/O (radar and optical) observations from the Space Surveillance Network
  - Current catalog > 20,000 space objects
- Using this catalog, or other high accuracy space catalogs, predicting close approaches between orbiting objects is possible
  - Process of identifying close approaches is called conjunction assessment (CA)
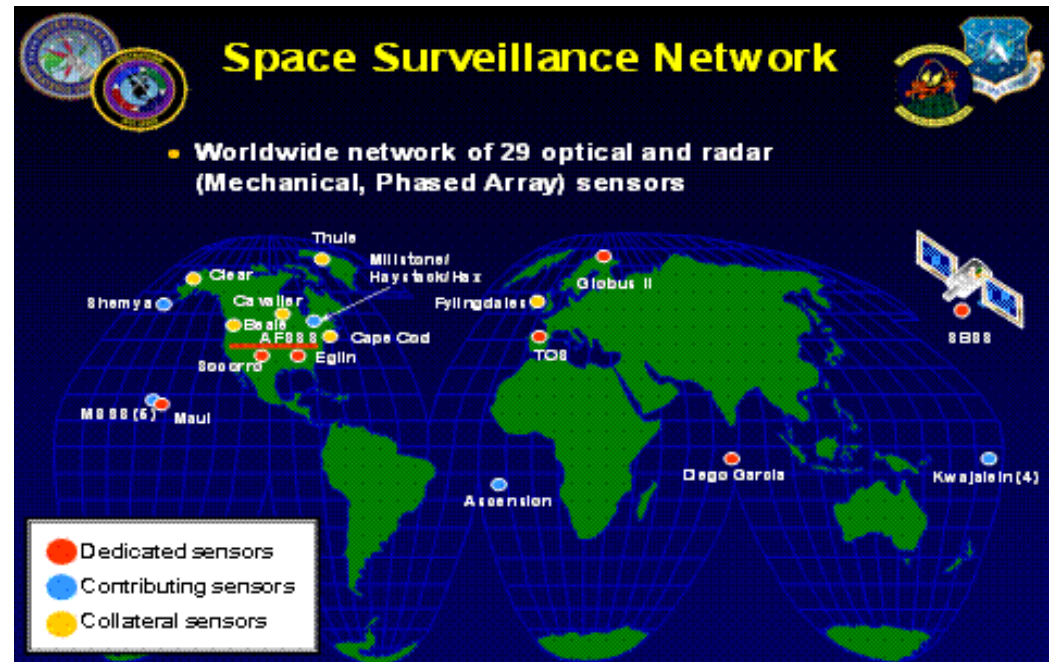


http://www.stratcom.mil/factsheets/11/Space_Control_and_Space_Surveillance/

# Checkpoint #1

- ***Learning from Yesterday:*** *On-orbit collision is a real and increasing mission risk*
  - *On-orbit collisions have occurred and the risk increases with debris population increase*
  - *Demand for the space environment not going away*
  - *Debris production continues and is expected to accelerate*
- ***Where we are Today:*** *Collision risk management requires more than just predicting close approaches*

- ***Looking to Tomorrow:*** *What challenges do we anticipate in the future*

# CA is the First Step

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

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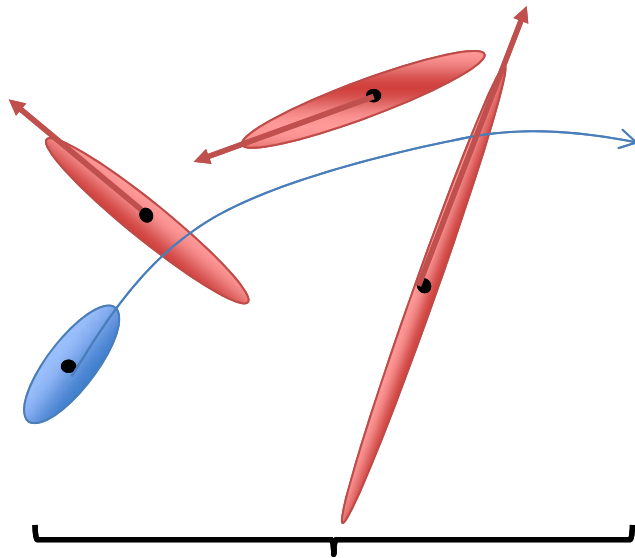
**Conjunction Assessment (CA)** is the process of identifying close approaches between two orbiting objects; sometimes called conjunction "screening"

The **CARA detachment** at the **Joint Space Operations Center (JSpOC)** screens CARA-supported assets against the catalog, assists with OD and tasking for identified conjunctions, and generates close approach data
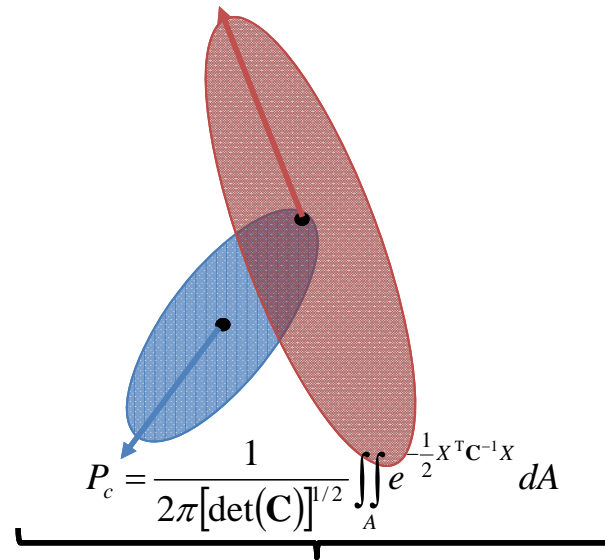
**CA Risk Analysis (CARA)** is the process of assessing collision risk and assisting with maneuver planning to mitigate that risk, if warranted
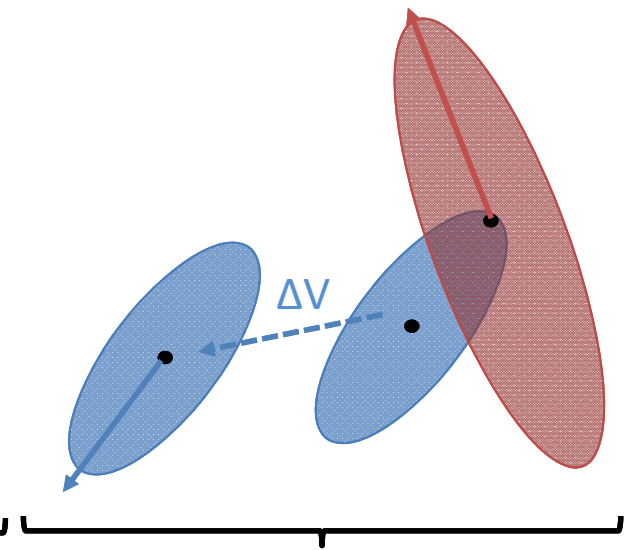
The **CARA** Team at NASA-GSFC provides CARA for all NASA operational robotic satellites, as well as a service provider for some other external agency/organizations

**Collision Avoidance (COLA)** is the process of executing mitigation actions, 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

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# Are they going to hit or not?
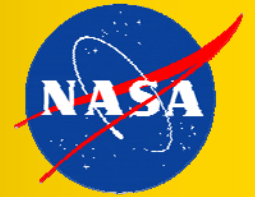
- A typical CA process produces necessary but not sufficient information for determining whether to maneuver a satellite
  - Typically receive the state and state uncertainty (covariance) of both objects at time of closes approach (TCA)
  - Data provides directly the miss distance and indirectly the uncertainty of that prediction
- This information can be used to calculate the primary risk metric, the Probability of Collision (Pc)
  - In addition to states and covariance, also need estimate for the sizes of the objects (the hard-body radius, HBR)

$$P_c = \frac{1}{2\pi[\det(\mathbf{C})]^{1/2}} \iint\limits_A e^{-\frac{1}{2}X^{\mathrm{T}}\mathbf{C}^{-1}X} \, dA$$

- What the Pc tells you …
  - *Given the uncertainty in the predicted object states (as described by the covariance), the Pc is likelihood that the actual miss distance is less than what would cause physical contact (as described by the HBR)*

# Risk Management isn't just Pc

- So, CA + Pc = collision risk management?  Wrong.
- What the Pc *doesn't* tell you …
  - Do I believe the mean estimates of the objects' positions?
  - Do I believe the uncertainty estimates about those means?
  - How likely are the current state estimates and uncertainties to change significantly?
  - Is the conjunction likely to be substantially affected by atmospheric density mismodeling?
  - Is a risk mitigation maneuver necessary?
  - Which direction should I maneuver and what magnitude?
  - Will this maneuver create high-risk situations with other objects?

# NASA's Process: CARA
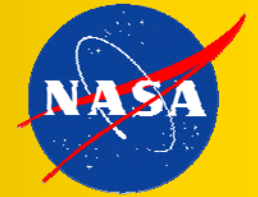
- In 2005, NASA established Agency-wide policy for performing CA and reacting to close approaches
  - Required for all operational robotic (unmanned) NASA satellites
  - Similar effort for protecting human spaceflight (Shuttle, ISS) since early 1990s
- The Conjunction Assessment Risk Analysis (CARA) was stood up to offer this service to all NASA robotic satellites
  - Currently provides service to ~70 operational satellites

# CARA's Operational Pedigree

- Has processed over 1,000,000 close approach messages and assisted with about 100 avoidance maneuvers

# CARA Still Evolving



**Apr 2005** First collision avoidance maneuver for a NASA robotic mission performed (Terra)

**Oct 2007** CARA begins providing CA support to GEO missions (TDRSS)

**2006** CARA hosts special session on CA at Astrodynamics Specialist Conference in Keystone, CO, including a paper establishing a formal conjunction risk assessment process at NASA-GSFC

**Oct 2010** CARA provides service to 1SOPS/SBSS after launch; continues to provide support today

**Dec 2011** CARA promotes Conjunction Assessment System (CAS) Release 7.0 to operations. CAS 7.0 leverages a Service-Oriented Architecture framework featuring GMSEC technologies.

**2012** CARA provides support to the NOAA POES and DoD DMSP

**Oct 2013** First operational support to non-elliptical orbit (Juno Earth Flyby)

**Jun 2008** Highest Pc observed in CARA history – 1 in 2 (Aura)

**Aug 2011** CARA hosts special session on CA at the Astrodynamics Specialist Conference in Girdwood, AK, a 5-year anniversary after hosting it previously
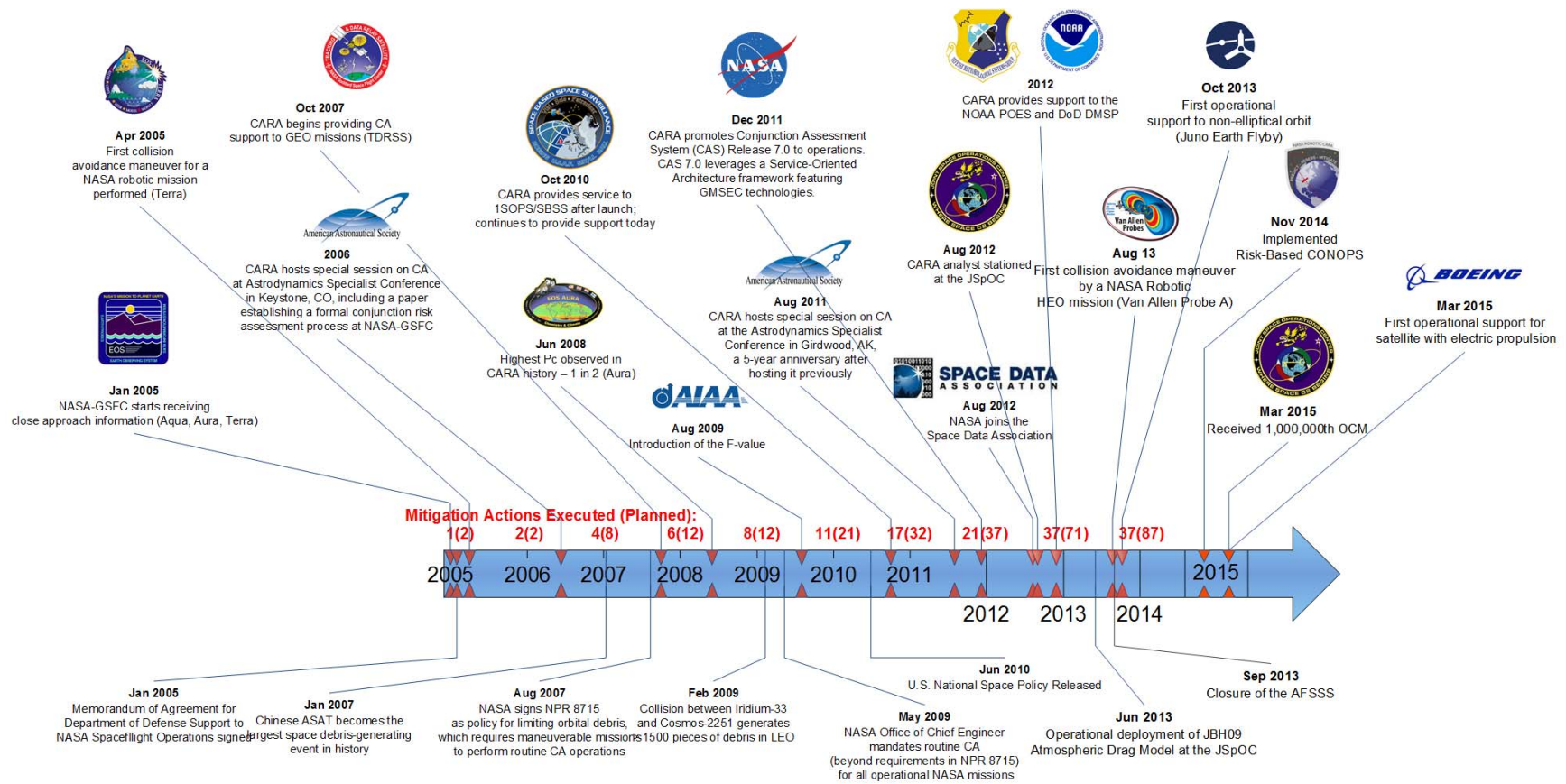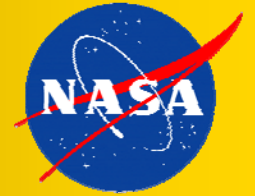
**Aug 2012** CARA analyst stationed at the JSpOC

**Aug 13** First collision avoidance maneuver by a NASA Robotic HEO mission (Van Allen Probe A)

**Nov 2014** Implemented Risk-Based CONOPS

**Jan 2005** NASA-GSFC starts receiving close approach information (Aqua, Aura, Terra)

**Aug 2009** Introduction of the F-value

**Aug 2012** NASA joins the Space Data Association

**Mar 2015** Received 1,000,000th OCM

**Mar 2015** First operational support for satellite with electric propulsion

**Mitigation Actions Executed (Planned):**
1(2)   2(2)   4(8)   6(12)   8(12)   11(21)   17(32)   21(37)   37(71)   37(87)

2005   2006   2007   2008   2009   2010   2011   |   2015

2012   2013   2014

**Jan 2005** Memorandum of Agreement for Department of Defense Support to NASA Spaceflight Operations signed

**Jan 2007** Chinese ASAT becomes the largest space debris-generating event in history

**Aug 2007** NASA signs NPR 8715 as policy for limiting orbital debris, which requires maneuverable missions to perform routine CA operations

**Feb 2009** Collision between Iridium-33 and Cosmos-2251 generates 1500 pieces of debris in LEO

**May 2009** NASA Office of Chief Engineer mandates routine CA (beyond requirements in NPR 8715) for all operational NASA missions

**Jun 2010** U.S. National Space Policy Released

**Jun 2013** Operational deployment of JBH09 Atmospheric Drag Model at the JSpOC

**Sep 2013** Closure of the AFSSS

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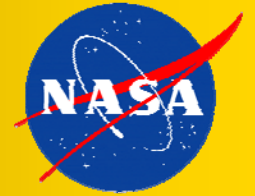**NASA • USGS • NOAA**

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# Centralizing Expertise

- Use combined resources in cost-constrained environment to:
  - Keep up with policy changes
  - Maintain single interfaces with other cost-constrained organizations
  - Stay abreast of advances and initiatives within community
  - Perform R&D to advance state of the art
  - Bring more capability than available to one O/O individually
  - Build operations experience more quickly, learning from operational situations
  - Maintain corporate knowledge despite launch manifest ebbs and flows
  - Identify industry-wide trends extracted from very large database of CA information

# Checkpoint #2

- ***Learning from Yesterday:*** *On-orbit collisions is a real and increasing mission risk*


- ***Where we are Today:*** *Collision risk management requires more than just predicting close approaches*
  - *Responding to collision risk is more than just data*
  - *Requires understanding of predicting close approaches and capabilities/limitations of missions*
  - *NASA CARA process stood up to help Agency but still evolving*
  - *Centralizing expertise creates efficiencies*
- ***Looking to Tomorrow:*** *What challenges do we anticipate in the future*
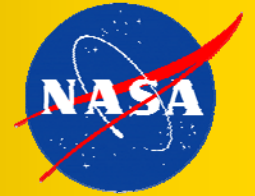
# Substantially Expanded Catalog
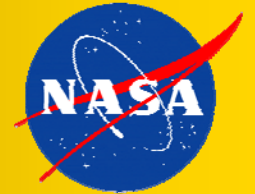
- The planned S-band Space Fence will significantly improve the SSN's ability to track smaller debris objects
  - Currently estimated to increase space catalog by order of magnitude
- Currently we analyze, and if necessary remediate, each close approach discretely
- With substantially larger catalog, individual analysis of discrete events no longer possible
- R&D effort to determinate alternative approaches
  - Analysis and remediation based on grouped data and aggregated Pc values
  - Direct modeling of satellite to reduce HBR sizes
  - Better mapping of uncertainties through entire process

# To Maneuver or Not to Maneuver
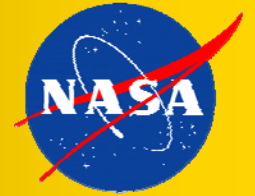
- Not all satellites are equipped with conventional propulsion systems, and many with no propulsion systems at all
- Having no impulsive orbital maneuverability limits mitigation actions
- Other options do exist
  - Reducing cross-sectional area presentation to incoming object
  - Affecting orbit through drag profile modifications
  - Turning off or varying electric propulsion continuous thrust
    - Whether this will be effective in most operational situations is an open question

# CubeSats

- Smallsats are becoming more and more popular due to relatively low launch and operating costs
    - Can be built "from a kit" and operated by novice users
    - Can be co-hosted on launch vehicles or deployed from ISS
- CubeSats present CA challenges
    - Often deployed in "clusters," with long separation times
    - Some cubesats are too small to be tracked reliably, and O/Os often do not produce high-fidelity predicted ephemerides
    - Deployment to high-drag orbit regimes only compounds position prediction problem
    - Often have no propulsion capability and thus no ability to remediate conjunctions
    - Amateur operators may lack ability or impetus to take CA seriously

# Collocation
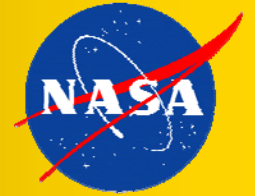
- Spacecraft collocation and systematic conjunctions are special breed of close approach
  - Potential for repeated and long-term recurrence
- Many systematic conjunctions can be avoided
  - Such scenarios can be predicted and therefore avoided during mission design
    - More of a coordination and management effort than technical
- Proposed concepts such as an Orbital Registry could affect this
  - Would function like the International Telecommunication Union (ITU) but would apply to all orbit regimes
  - Would examine proposed orbits for repeating conjunction vulnerability and recommend alternatives
  - Concept floated but remains paper-ware
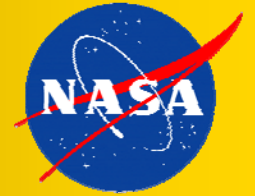
# Predicting the Sun
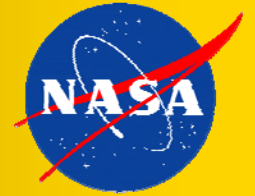
- Many different atmospheric density models exist, but all are empirical
  - Employ semi-analytic approaches and curve-fitting
- New atmospheric density model (JBH09) deployed recently at JSpOC
  - Past densities extracted from calibration satellite orbits
  - Future densities predicted from 11 solar EUV indices
  - Solar storm active compensation capability
- Despite improved functionality, still is an empirical model, which will limit its predictive power
  - Imposes limit to fidelity of CA solutions in many situations
- Only method for substantial improvement is physics-based model, which attempts to model the actual processes of atmospheric heating
  - Several efforts attempted in past, but none have come to fruition

# Checkpoint #3
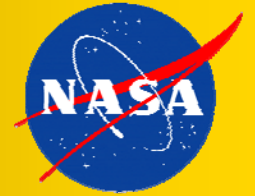
- ***Learning from Yesterday:*** *On-orbit collisions is a real and increasing mission risk*

- ***Where we are Today:*** *Collision risk management requires more than just predicting close approaches*

- ***Looking to Tomorrow:*** *What challenges do we anticipate in the future*
  - *Large-scale catalog growth*
  - *CubeSats*
  - *Collocation and Systematic conjunctions*
  - *Physics-based solar model*

# **Conclusion**

- Orbital Debris is an international problem
  - Affects safety of flight for all operators
  - Collaboration and data sharing are essential to addressing the issue