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Challenges in Assessing Orbital Debris Impact Risk: IDA Support from the Columbia Failure Investigation to Today

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Executive Summary

This presentation will be part of the planned "IDA Forum on Orbital Debris Risks and Challenges," to be held in September 2020 for IDA attendees and selected government officials from the Executive Branch. It summarizes the orbital debris risk assessment process as developed and employed by NASA. It also describes IDA research and support in various orbital debris risk assessment tasks performed for NASA and other organizations, from the Columbia disaster in 2003 to the present.

Challenges in Assessing Orbital Debris Impact Risk:

IDA Support from the Columbia Failure Investigation to Today

Dr. Joel Williamsen

Operational Evaluation Division

Institute for Defense Analyses

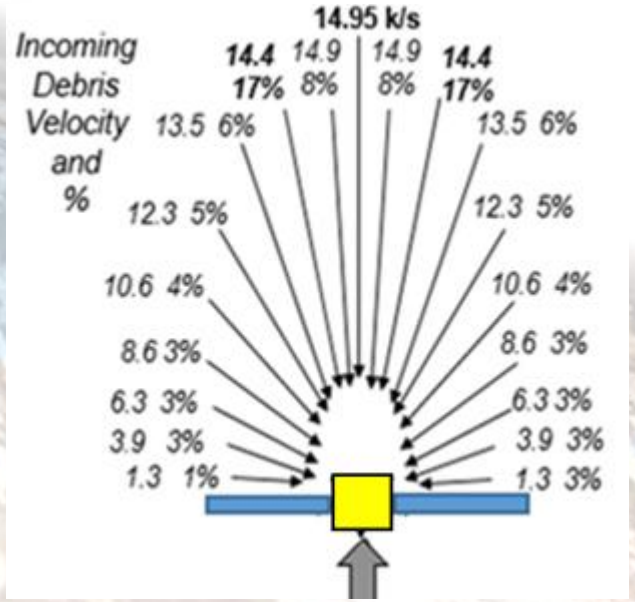
July 20, 2020

Untracked Orbital Debris Poses a Great Risk to Active Satellites

Without warning, small untracked orbital debris from 1mm to 5mm can kill satellites in low earth orbit (LEO), where rapid satellite population growth is taking place

Untracked debris is a much higher risk than tracked debris to active satellites

Debris Velocities at 800 km Orbit

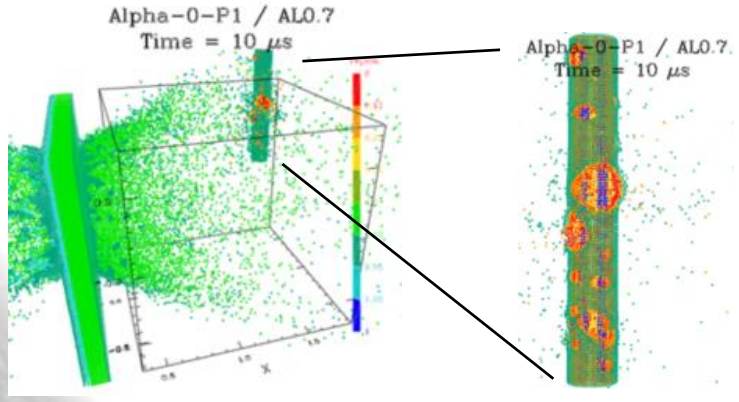


Most debris approaches "front" of spacecraft – and is the highest velocity

High impact velocities drive potential spacecraft damage

Orbital Debris Impact Energies at 14 km/s

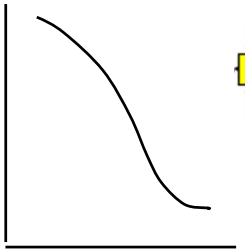
Alum Sphere	1mm (.0015g)	3mm (.039 g)	1 cm (1.5 g)
Energy (j)	192	4992	192,000
TNT (g)	0.45	1.19	45.9
Other Equiv.	.22 bullet	.30-06 bullet	Mark 2 grenade

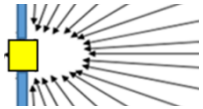


IDA high-speed impact simulation against NISAR spacecraft wiring harness-- 0.7 mm AL particle impacting multi-layer insulation over Kapton covered wires

NASA's Critical M/OD (Meteoroid/Orbital Debris) Risk Assessment Process

Failure Criteria



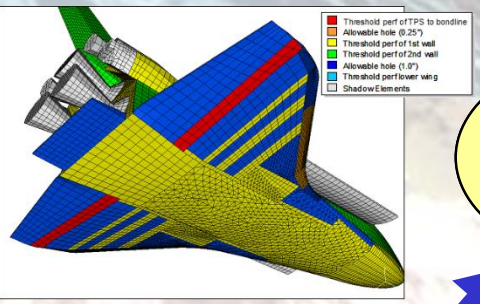


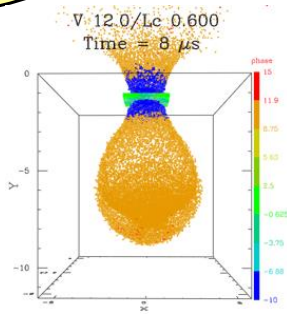
Directionality

Meteoroid and Orbital Debris Environment Model

Spacecraft Geometry

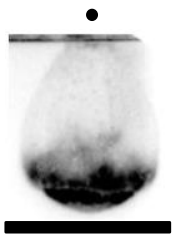
BUMPER M/OD Assessment Probability of No Critical Failure





Spacecraft Operating Plan

Damage Prediction Tests and Hydrocode Analysis



NO

YES

Meet Risk Criteria?

Proceed to Flight

Once a design is finalized, change in attitude, altitude, duration are only measures of risk reduction.

Note: BUMPER (no acronym) is also a term for the outer shield that breaks up M/OD following impact.

Two Decades of IDA Meteoroid and Orbital Debris (M/OD) Risk Assessments

2003-2004	Space Shuttle Columbia Investigation
2007-2008	Orion Spacecraft M/OD Design Evaluation
2009-2010	Deep Impact "EPOXI" Mission Support
2011-2012	International Space Station M/OD Investigation
2014	Briefings on M/OD Protection to National Science Foundation
2015-2016	Joint Polar Satellite System Design Evaluation and Review
2016-2017	Evaluation of Orbital Debris Risk Predictions With Available On-Orbit Assets
2018-2019	NASA Support for M/OD Effects on NISAR Spacecraft Wire Harness Design
2019-2020	NASA ORDEM 3.1 Orbital Debris Environment Review

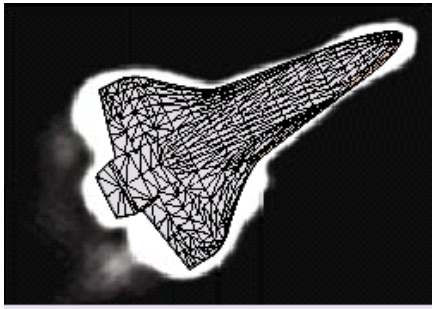
IDA supported many of these studies through the NASA Engineering and Safety Center (NESC), which brings experts from within and outside NASA to provide ongoing independent safety assessments.

The Loss of Columbia
Orbital Debris Strike Was a Primary Suspect

On February 1, 2003, Space Shuttle *Columbia* was destroyed in a disaster that claimed the lives of all seven of its crew.

The Columbia Accident Investigation Board was established within two hours of the loss of signal from the returning spacecraft.

One of the potential causes of the loss was a **meteoroid/orbital debris (M/OD) strike** on Columbia's thermal protection system (TPS) while in orbit, causing failure of the orbiter during re-entry.



IDA Supported the CAIB and NASA "Independent Assessment"

Columbia Accident Investigation Board (CAIB)
Chair: Adm. Gehman

Aim: To conduct **"**not only an investigation of what happened to *Columbia*, but also – to determine the conditions that allowed the accident to occur – **a safety evaluation of the entire Space Shuttle Program."**

Examined:

- **Launch Debris from ET Foam**
- **Meteoroid/Orbital Debris Strike**
- Willful Damage/Security
- SRB Bolt Catchers
- Kapton Wiring (Arcing)
- Hypergolic Fuel Spill
- Space Weather
- "Rough" Left Wing
- Training and On-orbit Performance
- Payload Malfunction
- Foreign Object Damage

Report August 2003

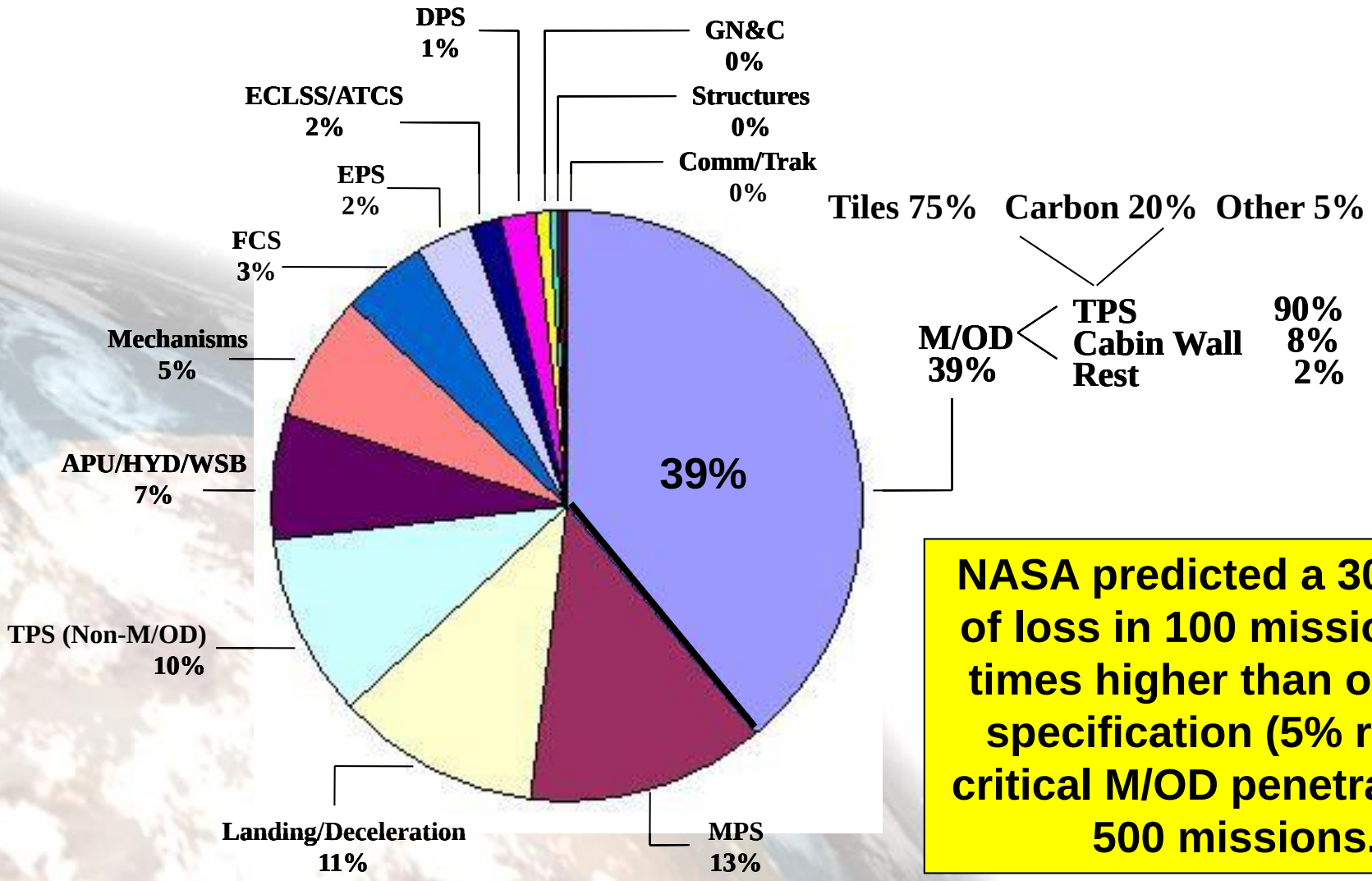
NASA Support (IDA's Direct Client)
JSC Office of Safety and Mission Assurance
Independent Assessment – Hugh Baker

- **On-orbit anomalies** — **JSC Mission Ops**
- **"Day 2" RADAR Object** — **NORAD**
- **M/OD Risk Assessment** — **IDA**
  - **What is the risk of an M/OD penetration?**
  - **How does NASA compute the risk for each flight? How does it reduce risk?**
  - **How can this process be improved?**

M/OD was a Major Candidate for Causing Columbia Loss

Finding: Risk Far Exceeded Original Specification

"A Priori" Estimate of M/OD Risk vs. Other Orbiter Risks



NASA predicted a 30% risk of loss in 100 missions, 30 times higher than original specification (5% risk of critical M/OD penetration in 500 missions.

CAIB Study Found Inaccuracies in Debris Models and their Prediction Uncertainties

- **Meteoroid Environment was Wrong (*fixed, increased risk*)**
- **NASA Needs a Tool to Quantify Its Prediction Uncertainties (*added, not normally used*)**
- **OD Environment and Penetration Model Needs Improvement (*still does*). Model approximates debris as spheres, which over predicts their mass and risk.**

An IDA theme over many studies: Equating "characteristic length" with a spherically shaped particle adds unneeded spacecraft shielding.

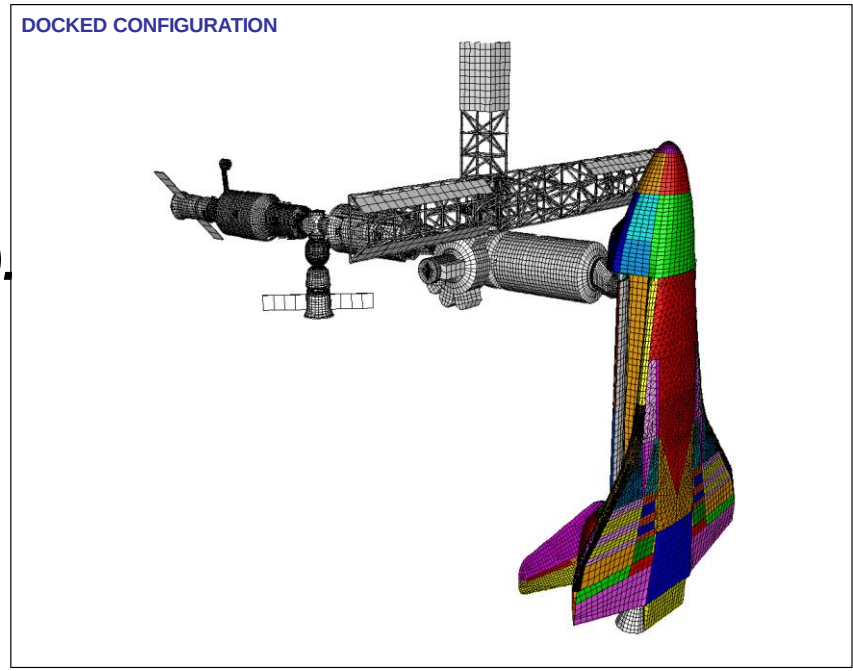
Typical debris from a satellite breakup (DoD SOCIT Tests, 1993).

Where are the spheres?

The good news…hypervelocity impact modelling has improved in speed and accuracy. This allows formation of OD models that include shape prediction.

SOCIT: Satellite Orbital Debris Characterization Impact Test

CAIB Study Led to Some Reform, but More is Needed



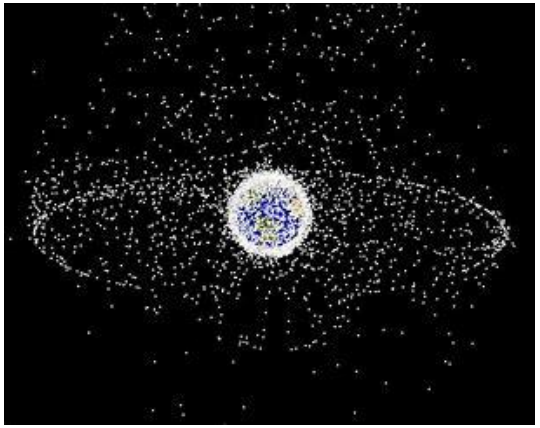
- **Independent M/OD safety assessment…isn't (happening).**
  Added NASA Engineering and Safety Center—outside oversight (like DOT&E).

- **The shuttle and station are linked…but not in M/OD analysis.**
  Started linking them immediately

- **XYO (Examine Your Organization)!**
  Threat characterization and risk assessment shouldn't mix

- **This wasn't the first time they'd heard this…**Recommendations from the **1997 National Research Council Committee on Space Shuttle Meteoroid/Orbital Debris Risk Assessment** are still valid. Notably: **"NASA should reconsider conducting on-orbit surveys of the orbiter exterior to detect impact damage and repair it if necessary."**

Does NASA Overestimate Orbital Debris Risk? Recent IDA-Supported NASA Study Results

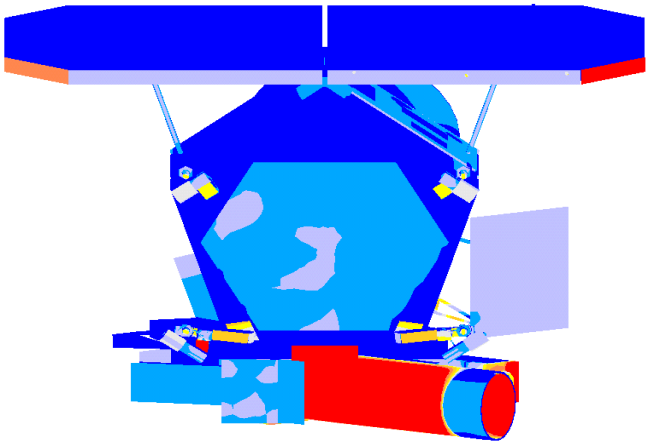


- Considering over 100 LEO satellites over 20 years, **NASA over predicted the number of satellite failures by a factor of ~5** (8 to 11 failures predicted vs. two actual).*
- **NASA and Boeing calculated the number of expected radiator leaks aboard the ISS as between 1.6 and 3.1 perforations, but none occurred (**driven by **~1.5 mm** orbital debris particles penetrating vulnerable tubing).
- A well-known satellite constellation reported **only seven movements of > 3 m dMSA.** IDA predicted that **> 10 times more movements of these magnitudes should have occurred if NASA's OD model is accurate.**
- The mismatch in expected versus actual failures could be due to either:
  - Conservative orbital debris environment models (use of spheres vs. flakes, etc.)
  - Conservative penetration model assumptions
  - Anomaly underreporting (not likely based on narrow failure modes focused on)
  - Or, a combination of these factors.

* Squire, M., et al. "Evaluation of Micrometeoroid and Orbital Debris (MMOD) Risk Predictions with Available On-Orbit Assets" (NESC-RP-14-01000). Hampton, VA: NASA Engineering and Safety Center, September 1, 2017.

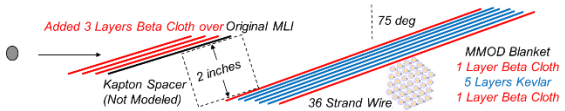
IDA Has Contributed to Numerous Other Spacecraft Risk Assessment Projects

Deep Impact Flyby Spacecraft Expected Element Penetrations: Comets Temple I and Hartley

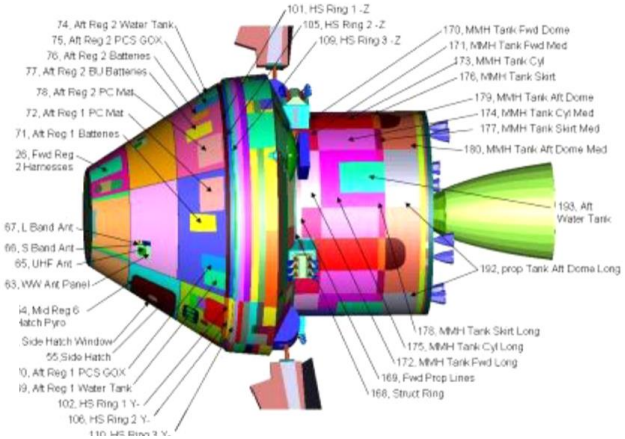


Damage Prediction Models

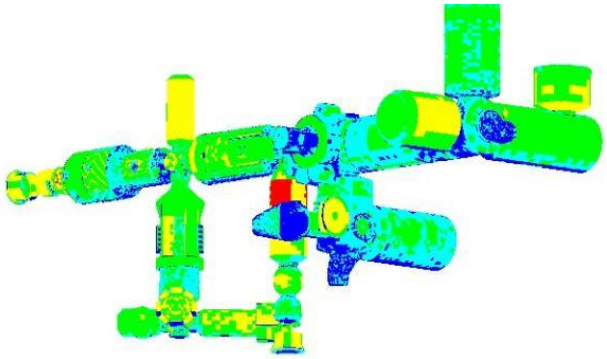
Joint Polar Satellite Shielding



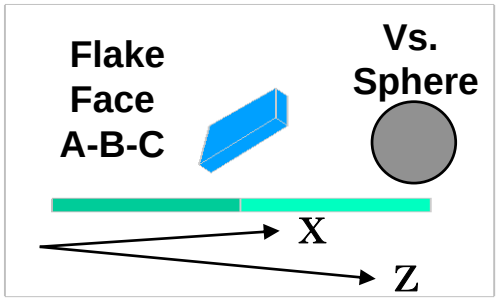
Orion Thermal Protection Design

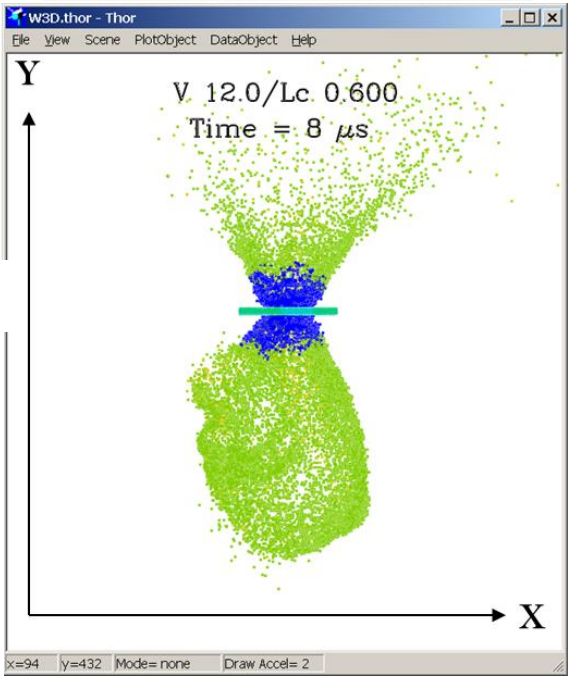


Space Station Protection



Effect of a "Flake" OD Shape Model on Space Station Risk: Cuts Risk in Half





IDA Continues to Support Spacecraft Risk Assessment

- Continued assistance to NASA Engineering and Safety Center
- Assistance to Commerce Department and NASA
  - Establishing orbital debris data repository
  - Trusted agent for protecting data
  - Potential risk reductions possible
- Support to Office of Science and Technology Policy
  - Identify R&D needs
  - Point to potential FCC risk assessment process improvements
- Assistance to DOT&E and larger DoD – military satellite risk assessment support
  - Meteoroid/orbital debris risks
  - Anti-satellite risk assessment

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