New Developments in Orbital Debris Protection and Prevention

July 1, 2014
NASA / GSFC Code 592

Contacts: Scott.Hull@NASA.gov
Ivonne.M.Rodriguez@nasa.gov
Outline

• How big a problem is orbital debris?
• Protecting the spacecraft from existing debris
• Protecting the orbital environment from spacecraft (prevention of future debris)
• Removal of existing debris objects
• NASA Requirements
• Latest Developments
• Conclusions
Recent Articles

US Lawmakers Worry ‘Gravity’ Film’s Space Disaster May Really Happen

WASHINGTON—Lawmakers concerned with avoiding a space disaster from floating junk such as the one depicted in the Hollywood blockbuster "Gravity" encountered a different kind of threat at a hearing with top aerospace and academic minds today: the endless catascombs of bureaucracy.

And although members of the House Space subcommittee in both parties seemed mostly in unison, tight budgets are likely to impede some of the government’s most important safety and security initiatives.

By Matthew Lemann 
@matthemanon

Clean Up Space Junk or Risk Real-Life ‘Gravity’ Disaster, Lawmakers Say

By Denise Chow, Staff Writer | May 9, 2014 03:00pm ET

Clean Up Space Junk or Risk Real-Life ‘Gravity’ Disaster, Lawmakers Say

By Denise Chow, Staff Writer | May 9, 2014 03:00pm ET

Congress Presses NASA Chief on Domestic and Foreign Space Threats

WASHINGTON — What in another year might have been a routine hearing about NASA’s annual budget request turned into a heated—and sometimes partisan—exchange about the agency’s internal security practices and the broad state of the U.S. human spaceflight program.

In theory, the purpose of the April 9 hearing was to give the House Appropriations Committee’s subcommittee on Commerce, Justice, Science, and Related Agencies an opportunity to ask questions about the agency’s fiscal 2015 budget request. And while that was the stated purpose of the event, subcommittee chairman Rep. Dana Rohrabacher (R-CA) and ranking member Rep. Eddie Bernice Johnson (D-TX) also pressed NASA chief Charles Bolden toIncreasing the budget for space exploration.

By Dan Leone, Space News | April 09, 2014 12:30pm ET

Congress: Not Taking Out ‘Orbital’ Trash = Economy In Jeopardy | Video

Saturday, May 3rd, 2014

Congressman Dana Rohrabacher (R-CA) with the House Science, Space & Technology Subcommittee on Space conducted a hearing on how to prevent a real-life ‘Gravity’. In theory, the purpose of the April 9 hearing was to give the House Appropriations Committee’s subcommittee on Commerce, Justice, Science, and Related Agencies an opportunity to ask questions about the agency’s fiscal 2015 budget request. And while that was the stated purpose of the event, subcommittee chairman Rep. Dana Rohrabacher (R-CA) and ranking member Rep. Eddie Bernice Johnson (D-TX) also pressed NASA chief Charles Bolden to

By Dan Leone, Space News | April 09, 2014 12:30pm ET

Satellite Will Plummet From Space, Destination Unknown

Satellite Will Plummet From Space, Destination Unknown

by ABC News

Meteor Strikes Russia, Over 1,000 Believed Injured

Meteor Strikes Russia, Over 1,000 Believed Injured

by ABC News

Satellite Will Plummet From Space, Destination Unknown

by ABC News

Meteor Strikes Russia, Over 1,000 Believed Injured

by ABC News

Congress: Not Taking Out ‘Orbital’ Trash = Economy In Jeopardy | Video

Saturday, May 3rd, 2014

Congressman Dana Rohrabacher (R-CA) with the House Science, Space & Technology Subcommittee on Space conducted a hearing on how to prevent a real-life ‘Gravity’. In theory, the purpose of the April 9 hearing was to give the House Appropriations Committee’s subcommittee on Commerce, Justice, Science, and Related Agencies an opportunity to ask questions about the agency’s fiscal 2015 budget request. And while that was the stated purpose of the event, subcommittee chairman Rep. Dana Rohrabacher (R-CA) and ranking member Rep. Eddie Bernice Johnson (D-TX) also pressed NASA chief Charles Bolden to
Debris Removal Articles

Europe Explores Ideas to Clean Up Space Junk

by Elizabeth Howell, Space.com contributor | March 04, 2014 06:30am ET

Japan to Test Space Junk Cleanup Tether Soon: Report

By Miriam Kramer, Staff Writer | January 17, 2014 06:30am ET

High-Tech VASIMR Rocket Engine Could Tackle Mars Trips, Space Junk and More

By Leonard David, SPACE.com, Space Insider Columnist | November 19, 2013 07:00am ET

Space Junk Clean Up: 7 Wild Ways to Destroy Orbital Debris

by Elizabeth Howell, Space.com contributor | March 03, 2014 05:37pm ET

Scientists are making progress on an advanced space propulsion system aimed at a variety of uses, including reboosting space stations, cleaning up space junk and powering superfast journeys that could reach Mars in less than two months.

Engine work has been underway for more than 25 years, and is based on NASA and U.S. Department of Energy research and development in plasma physics and space propulsion technology. Commercializing the VASIMR electric propulsion engine is the flagship project of Ad Astra, which has been in business for nine years and has invested $30 million to date to mature the concept. [Superfast Propulsion Concepts (Images)]

With half a million pieces of space debris cluttering Earth’s orbit, according to NASA, this means there is a growing problem of cluttering up our access road to space. Several companies and entities have proposed ways to get rid of derelict satellites and other space junk.

Here are seven recent proposals, ranging from electrical currents to slingshotting to knocking debris down.

FIRST STOP: Europe’s eDeOrbit Idea
Space Fence

- New S-band radar, located near the equator
- Should be able to detect smaller objects, therefore more objects
- Designed for 5 cm detection
- Slated for operations in 2018
What did Gravity get right?*

- Great props
- Debris strikes are silent – no KABOOMs!
- Collisions and explosions produce a distribution of different size pieces
- Objects with low Area to Mass Ratio arrive first at ISS
- Different ballistic coefficients evident during reentry scene
- Debris is potentially a real problem, if we don’t do something about it

- The special feature “Collision Point” is an excellent summary of orbital debris

* the things they used ‘creative license’ to justify are staggering to many of us, and we don’t have time for that
ORBITAL DEBRIS ENVIRONMENT

How much stuff is up there?
Why is Orbital Debris a Concern?

• On-orbit Environment
  – Currently
    ~ 22,000 objects ≥10 cm in size
    ~ 500,000 objects ≥1 cm in size
    Many Millions of objects <1 mm in size
  – Growing rapidly: Already self-propagating

• Spacecraft damage potential
  – Moving at 7 km/s → ~16,000 mph!
  – \( \frac{1}{2} mv^2 \) gets to be really big, really fast

• Tracking limitations
## Recent Major Debris Events

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type</th>
<th>Date</th>
<th>Objects*</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fengyun 1C (PRC)</td>
<td>Spacecraft</td>
<td>1/11/2007</td>
<td>~2850</td>
<td>Deliberate destruction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1999-025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBERS 1 (PRC/BRZ)</td>
<td>Spacecraft</td>
<td>2/18/2007</td>
<td>~425</td>
<td>Unpassivated propellant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1999-057</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Briz – M (CIS)</td>
<td>Launch Vehicle</td>
<td>2/19/2007</td>
<td>~150</td>
<td>Unpassivated propellant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2006-006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iridium - Cosmos</td>
<td>Spacecraft x 2</td>
<td>2/10/2009</td>
<td>~1650</td>
<td>Collision</td>
</tr>
<tr>
<td>Long March 3C (PRC)</td>
<td>Launch Vehicle</td>
<td>11/1/2010</td>
<td>~50</td>
<td>Unpassivated propellant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2010-057</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Briz – M (CIS)</td>
<td>Launch Vehicle</td>
<td>10/16/2012</td>
<td>~115</td>
<td>Unpassivated propellant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2012-044</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Cataloged objects (> 10 cm)
Debris Sources

• Launch
• Spacecraft
  – Lack of proper disposal
• Collisions
  – Small collisions as well as large
• Explosions
  – Batteries
  – Pressure tanks (usually propulsion system)
• Meteoroids
  – Natural random environment
  – Meteor showers
Explosions

• Batteries
  – Overcharge can generate gas pressure
  – Ni-H₂ most susceptible, Li-ion less so
    • Only known US battery explosion was a Ni-Cd
    • Some Li-ion cells have pressure cutoff switches
    • Li-ion must never be recharged after full drain

• Pressure tanks
  – Biprop: fuel and oxidizer can mix because of a leaky valve
  – Overpressure from regulator failure
  – Small debris object impact
Long-term Growth of LEO Debris Population

- Solid lines: 1957-to-2006, no new launches beyond 2006
- Dashed lines: 1957-to-2009, no new launches beyond 2009
Collision Predictions with and without disposal efforts

Another 8-to-9 collisions are expected in the next 40 years (~1 every 5 years)
Debris Flux in the A-Train Orbit

Debris Flux (#/m² yr)

Too small to track

Tracked by JSpOC

Minor Damage

Major Damage or End of Mission

Total Destruction

Debris Diameter (m)
Reality Check
Space is still pretty big - mostly

• We’re not talking about daily major crises
  – We work to a 1% probability of a penetration that would prevent the planned disposal
    • Only about a 50/50 chance of it ever happening on a GSFC mission
    • No known case to-date of a NASA spacecraft being fatally struck
    • Benign hits might happen frequently, though, without our knowledge
    • Benign impacts might still result in shorter or reduced missions

• Daily conjunction assessments help to prevent collision with large (>10 cm) objects
• Fortunately, the cascade portrayed in Gravity wouldn’t take place nearly as fast as in the movie

The real risk is the long-term (decades) loss of access to the orbital environment
A Sample of GSFC Missions (a wealth of diversity)

• Quantity
  – Typically about 20 Space Science, 6 Earth Science, and 9 TDRS missions actively operational
  – Usually ~50 total missions, including development

• Orbits
  – Typically LEO (400 to 850km)
  – A few GEO
  – A few high eccentricity, L1 and L2
  – Lunar and Mars

• Propulsion
  – About 60% have propulsion systems

• Construction
  – Many high Z materials in detectors
  – Substantial use of Titanium
  – Glass mirrors and lenses
ORBITAL DEBRIS PROTECTION

Protecting the spacecraft from debris damage
Methods of Protection

Mission Design

Hardware Design

Shielding

Conjunction Assessment
Mission Design and Ops Considerations

• **Orbital debris needs to be considered early**

• **Orbit selection**
  – Debris peaks at ~750, 900, and 1400 km
  – Orbit selection is usually driven by science needs, but science can be difficult in a minefield

• **Operations**
  – Orbit change maneuvers to avoid predicted close approaches
  – Reorient the spacecraft during meteor showers or close approaches
  – Have plans in place to help diagnose and/or respond to potential debris hits
Hardware Design Considerations

- **Component location**
  - If possible, locate critical bus components inside the spacecraft
  - Nadir and zenith are lowest exposure
  - Ram direction and sides are highest exposure
  - Take advantage of shadowing

- **Wall thickness**

- **Add shielding**

- **Redundancy**
Shielding Considerations

• Mass
• Cost
• Complexity – mechanical effects on spacecraft design
• Multi-wall much more effective than a thicker wall
  – Depends on spacing
  – Material selection is important
• Direction of threat
• Use baffles to shield instruments in some cases
Multi-wall Shield Mechanisms

- ‘Bumper’ disruptor layer
  - Breaks up and melts projectile
  - High temperature material (Nextel does well)
- Inner stopper layer
  - Traps the slower moving secondary debris
  - High toughness material (Kevlar does well)
- Back wall
  - Usually the box wall
  - Provides the last line of defense
  - Can generate spalling from inside surface, even if not penetrated
Shield Testing

- High velocity impact guns on actual samples
  - 3 to ~7 km/sec range
    (slower than most MMOD impacts)
  - Typically >$10,000 per shot
  - 5 or 6 shots per test
- Tested across a range of velocities, sizes, impact angles, and densities
- Produces ballistic limit curves
Typical Whipple Shield Ballistic Limit Curve

“failure” occurs above curves

- Whipple \( d_{\text{crit}} \) @ 0 deg
- Monolithic \( d_{\text{crit}} \) @ 0 deg

Ballistic Limit Improvement due to Shield Standoff
\( \Delta d_{\text{Crit}} \)

Critical AI Diameter (cm)

Velocity (km/s)
ORBITAL DEBRIS PREVENTION

Protecting space from us…
Prevention Methods

• Design for Safety

• End of Mission Disposal
  – Reentry (active or passive)
  – Storage orbits

• End of Mission Passivation
  – Disconnect battery
  – Vent pressure sources
  – Essentially minimize residual stored energy
Design for Safety During and After the Mission

• Pressure tank design
  – Burst strength >2X MEOP recommended

• Battery selection
  – Usually driven by power demands
  – Ni-H₂ can be an explosion risk if overcharged
  – Li-ion less susceptible, but has strict charging considerations

• Locate pressurized components near center of spacecraft
  – Protection against debris strikes
  – Any fragmentation is more contained

• Responsible Disposal
Postmission Disposal Methods

- **Reentry**
  - Controlled or uncontrolled
  - With or without orbit lowering
  - Depends on reentry risk, orbit, propulsion capacity, guidance reliability

- **Storage orbit**
  - Can stay in LEO up to 25 years
  - 2000 km to GEO-200 km
  - Above GEO+200 km

- **Retrieval**
Power System Passivation

• Requires designing in an “off-switch” early

• Disconnect solar arrays (preferred)
  – Can be easier/safer to achieve
  – Passivates all electronic equipment at once

• Disconnect the battery from the charging circuit
  – Relays, instead of logic
  – Reducing charging rate is not enough

• Leave small loads attached to the bus
• Disable failure detection and correction modes at EOM
• Never recharge Li-ion after a deep discharge
Pressure Tank Passivation

- Requires designing in venting hardware

- Design for venting
  - Redundant valves in series on vent lines
  - Consider effects of cold gas thrust
  - Add vent lines for isolated pressurant tanks
  - Bypass around diaphragms

- Vent pressure as much as practical
  - Latching valves left open if possible
  - Very small amount often remains
ORBITAL DEBRIS REMOVAL

Taking out the trash
Challenges to Debris Removal

• Cost
  – Value of removing a rocket body ~$3.7M
  – Cost of removing a rocket body ~10X value
  – Ignores the less tangible value of access to the orbit

• Legal Aspects
  – Salvage rights
  – Removal responsibility
  – Could be viewed as an attack
  – No international jurisdiction or agreements

• Target Selection

• Technology
Target Selection for Debris Removal
What should we remove?

• Orbit selection
  – LEO: highest density, mostly science missions (government funding)
  – GEO: lower density, mostly commercial missions (industry funding)

• Debris size selection
  – 1 mm to 1 cm: high quantity, low damage
  – 1 cm to 10 cm: moderate quantity, moderate damage, not trackable
  – >10 cm: low quantity, catastrophic damage, trackable
  – Rocket Bodies: can produce most smaller debris due to collisions
Technology Challenges for Debris Removal

• Each different approach is suited to a specific set of orbit and size conditions
• Cost varies widely
• Most techniques have yet to be demonstrated
  – Tethers have been used for electric generation, but not necessarily drag or propulsion
  – Some spacecraft retrieval and on-orbit servicing experience
• No single solution will work for all applications and orbits
• Rendezvous and capture is a common challenge for most removal methods
Examples of Removal Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Target Size</th>
<th>Orbit Range</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Based Lasers</td>
<td>1 cm to 10 cm</td>
<td>All of LEO</td>
<td>$$</td>
</tr>
<tr>
<td>Drag Enhancement</td>
<td>10 cm to 5 m</td>
<td>LEO &lt;700 km</td>
<td>$$$</td>
</tr>
<tr>
<td>Sweepers</td>
<td>&lt; 10 cm</td>
<td>LEO</td>
<td>$</td>
</tr>
<tr>
<td>Space Tugs (ADR)</td>
<td>1 m to 5 m</td>
<td>LEO through GEO</td>
<td>$$$$$</td>
</tr>
</tbody>
</table>
NASA ORBITAL DEBRIS REQUIREMENTS

Coloring inside the lines
Section 4.3 (2)  Operational Debris
Section 4.4 (4)  Explosions, Passivation, Intentional Break-up
Section 4.5 (2)  Collisions
Section 4.6 (4)  Postmission Disposal
Section 4.7 (1)  Reentry Risk
Section 4.8 (1)  Tethers

15  Total
Requirement Group 4.4
Accidental Explosions

Req. 4.4-1: Risk of Accidental Explosions During the Mission
– Need to assess and report a **quantitative** estimate for explosion risk
– < 0.001 probability for all credible failure modes

Req. 4.4-2: Risk of Accidental Postmission Explosions
– “Deplete all onboard sources of stored energy”
– Also referred to as **passivation**
– Disconnect battery from charging circuit
– Vent pressure
  
- **The concern is the risk to other spacecraft, and to the long-term orbital environment**
Collision with Small Debris

- Spacecraft only; not launch vehicle
- Projectile size based on spacecraft component robustness
- Function of vulnerable component area, inherent shielding, nominal mission lifetime, and object flux
- **Each** disposal-critical component must be examined from **ALL** directions
- \( \leq 0.01 \) probability of preventing disposal
- DAS 2.0.2 used for the first evaluation
- Results can be refined using Bumper 3
<table>
<thead>
<tr>
<th><strong>Large Objects</strong></th>
<th><strong>Small Objects</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic impact</td>
<td>Prevents disposal</td>
</tr>
<tr>
<td>$\geq 10 \text{ cm}$</td>
<td>Based on design (typically 1-3 mm)</td>
</tr>
<tr>
<td>Spacecraft average area</td>
<td>Critical component area</td>
</tr>
<tr>
<td>$\leq 0.001 \ (1 \text{ in } 1000)$</td>
<td>$\leq 0.01 \ (1 \text{ in } 100)$</td>
</tr>
<tr>
<td>Shielding ineffective</td>
<td>Shielding can be effective</td>
</tr>
</tbody>
</table>
Disposal from LEO orbits (choose one)

6-1 a. Atmospheric reentry
- Orbit decay within 25 years after end of mission
- No more than 30 years total orbital lifetime
- Can be Uncontrolled Reentry or Controlled Reentry

6-1 b. Maneuver to a storage orbit
- Perigee > 2000 km, Apogee < GEO – 500km

6-1 c. Direct retrieval
Available Storage Orbits

- Super GEO Storage Orbit: 35,986 km
- GEO: 35,286 km
- High Altitude Storage Orbit: 20,700 km
- 12 Hour Orbits: 19,200 km
- Low Altitude Storage Orbit: 2000 km
- LEO: ~300 km

Not to Scale
Risk of Human Casualty

- For objects with impact energy >15J
- Risk ≤ 0.0001 (1 in 10,000)
- For controlled reentry:
  - Uncontrolled Risk X Pf ≤ 0.0001
  - No object closer than 370km to foreign landmass, or 50km to US landmass of Antarctica
- Hazardous materials must now be reported and considered
Debris Casualty Area (DCA)

When an object survives, a 0.3 m “person-border” is essentially added to the circumference of the object.

\[
\begin{align*}
A_{\text{ref}} &= 0.01 \text{ m}^2 \\
DCA &= 0.49 \text{ m}^2 \\
A_{\text{ref}} &= 0.16 \text{ m}^2 \\
DCA &= 1.0 \text{ m}^2 \\
A_{\text{ref}} &= 1.0 \text{ m}^2 \\
DCA &= 2.6 \text{ m}^2
\end{align*}
\]
LATEST DEVELOPMENTS
What’s New?

- ORDEM 3.0 Released
- John Lyver & Nick Johnson retired
- Sue Aleman is the new MMOD Program Executive
- J.-C. Liou is the new Chief Scientist for OD
- NPR 8715.6B going to NODIS review soon
- New tools in GSFC OD Group
  - Bumper 3.0
  - ORDEM 3.0
  - MEMR2
  - 42
NPR 8715.6B Overview (as of latest proposed draft)

- Updates to reflect organizational changes
  - New US Space Policy
  - New NASA top level organization (SOMD → HEOMD)
- Removes obsolete NSS 1740.14 references
- Greatly streamlines the ODAR and EOMP process
  - Most interim drafts approved at the Center level
  - HQ only signs prelaunch and final versions
- Chief/SMA now accepts risks (versus the AA/SMD)
- Generously streamlines the document
- Reduces the number of “shall” statements
Recent ‘Perfect Storm’ #1
Potential Collision Concern

- 28 3U Commercial CubeSats
- Time to Catalog Each Spacecraft
- CubeSat Launch/Deployment Delayed
- Potential for Collision with a Major Asset
- GPM Launching
- GPM Prop takes 5-10 days to activate
Recent ‘Perfect Storm’ #2
JPSS-1 Small Object Collision Assessment

- 824 km orbit very high flux
- Many Components on the outside
- 10 Year mission lifetime goal
- New ORDEM 3.0 debris model
- $P_F$ much higher than 1%
Conclusions (1 of 2)

• The accumulation of debris in operational orbits is a real and growing concern.

• Collisions will dominate the generation of additional debris in the future.

• There are design techniques for protecting most spacecraft and instruments from the effects of orbital debris.
While it is presently impractical to remove derelict objects from orbit, there are agreements and requirements in place to limit the addition of more debris.

Disposal and passivation planning are critical to limiting the long-term rate of debris growth.

Code 592 and JSC/ODPO can assist with design optimization as well as documentation.
Resources

• Email the GSFC team any time for assistance:
  – Scott.Hull@nasa.gov 6-7597
  – Ivonne.M.Rodriguez@nasa.gov 6-5837

• Online Resources
  – http://orbitaldebris.jsc.nasa.gov/