The Space Debris Environment
Its Current State & Future Evolution

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by May 2013, 4935 successful launches led to 3690 satellites, 1908 orbital stages, 1,155 mission-related objects, and 10,160 break-up and release debris in the US SSN Catalog (sizes > 10cm)

the total current mass in orbit is on the order of 7,000 tonnes
Recent Effects on the US SSN Catalog

- effect of recent collisions on the orbital environment (status May 2013):
  - FengYun 1C (11-Jan-2007) → 3,064 catalog objects (of 3,383)
  - Iridium-33/C-2251 (10-Feb-2009) → 1,783 catalog objects (of 2,204)
  - USA-193 (21-Feb-2008) → no objects remaining on orbit (of 173)

- collision fragments will dominate the future orbital debris environment
“space debris are all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional” (IADC definition)

sources of \(\sim 17,000 \ (\sim 23,000)\) tracked space objects:

- 60% explosion & collision fragments (\(\sim 250\) events) ➔ break-up avoidance
- 6% active satellites + 16% retired satellites ➔ end-of-mission disposal
- 11% spent orbital stages + 7% mission related objects ➔ fewer mission-related objects

only 6% (\(\sim 1,000\)) of all tracked objects are operational satellites
intacts & debris of d ≥ 10cm (May 2009, ESA MASTER Model):
• total number ≈ 29,000; total mass ≈ 6,500 t
• highest concentration of objects in low Earth orbits (LEO)
debris of $d \geq 1 \text{ cm}$ (May 2009, ESA MASTER Model):
- total number $\approx 740,000$ ($+2,600\%$); total mass $\approx 6,550$ t ($+0.8\%$)
- more uniform spatial distribution as compared to 10cm objects
Distribution of the Space Debris Population

- Intacts & debris of \( d \geq 10\text{cm} \):
  - Cause catastrophic break-ups
  - Total number \( \approx 29,000 \)
  - Total mass \( \approx 6,500 \text{ t} \)

- LEO (0.3% of the volume) \( \Rightarrow \) 75% of objects >10cm, 36.5% of the mass

- Relative catastrophic collision flux \( \text{LEO/GEO} \Rightarrow \approx 1,000/1 \)

- Debris of 10cm > \( d \geq 1\text{cm} \):
  - Cause mission termination
  - Number increase \( \approx +670,000 \)
  - Mass increase \( \approx +50 \text{ t} \)
Space Debris – Why be Concerned?

- 1 cm Al-sphere at 10 km/s = mid-size car of 1.5 tonnes at 50 km/h = explosion of a hand grenade

- 1 gram impactor at 2 km/s → 1 gram TNT (at 16 km/s → 64 grams TNT)
- 1 mm objects (≈ 170,000,000) → can damage satellite sub-systems
- 1 cm objects (≈ 740,000) → likely to disable satellites; limit of ISS shielding capabilities for its manned modules
- 10 cm objects (≈ 29,000) → likely to cause catastrophic satellite break-ups; limit of operational tracking capabilities of surveillance networks
**Space Debris Mitigation**

- **Finding:** to mitigate the space debris growth, reduce the release and dwell-time of critical-size objects in densely populated orbits regions (only applicable to functional objects as part of the mission planning)

- **Internationally agreed debris mitigation measures:**
  - Limit the number of mission-related objects during mission deployment (now causing 7% of all catalog objects)
  - Limit the post-mission on-orbit dwell time of spacecraft and orbital stages (now causing 33% of all catalog objects), in particular in the “protected” LEO and GEO regions
  - Avoid on-orbit break-ups (now causing 60% of all catalog objects)

- **Examples of debris mitigation measures:**
  - Passivation of spacecraft and orbital stages at end-of-life, and collision avoidance for operational spacecraft
  - Re-orbiting of GEO spacecraft at end-of-life
  - De-orbiting of LEO spacecraft and orbital stages at end-of-life (direct, controlled or within 25 years, uncontrolled)
IADC study participants: ASI, ESA, ISRO, JAXA, NASA and UK; prediction time span: 200 years; presented at UNCOPUOS/STSC in 2013

assumptions: initial MASTER-2009 population for d>10 cm; replicate of 8-year launch traffic; 90% post-mission disposal success

results: one catastrophic collision every 5 to 10 years; highest collision probabilities near 800km and 950km altitude
"Limiting Case" of Debris Environment Forecast

- **assumption:** no further launches → "best case" mitigation scenario

- **result:** collisional cascading starts within ~20 years ("Kessler syndrome")

  → debris mitigation alone cannot stabilize the environment
finding: space debris mitigation is a necessary but insufficient stabilization measure; it must be complemented by space debris environment remediation (also applicable to non-cooperative targets)

debris environment remediation measures:
- short-term risk reduction (ST): removal of large numbers of objects at sub-catalog sizes (fewer mission-terminating collisions)
- long-term risk reduction (LT): removal of large, intact objects at rates of 10 ± 5 LEO objects/year (fewer catastrophic collisions)
- remediation measures should focus on LEO and start soon

eamples of debris environment remediation techniques:
- space tugs to de-orbit from LEO or to re-orbit from GEO ➔ LT
- conductive tethers, drag augmentation, solar sails, or thruster plume impingement to reduce the orbit lifetime of LEO objects ➔ LT
- momentum-exchange tethers, or propulsion unit attachments to de-orbit or re-orbit ➔ LT
- ground-based lasers, or on-orbit momentum-retarding surfaces to de-orbit/remove sub-catalog objects ➔ ST
Debris Concentration in GEO

- characteristics of the GEO debris environment:
  - 1.3% of the useful volume of the Earth orbit environment
  - 36% of the on-orbit mass (≈ 2,500 t), with up to 790 t per bin of [50 km altitude] x [2° inclination] in the operational GEO ring
  - 7% of the catalog population, with up to 240 objects per bin of [50 km altitude] x [2° inclination] in the operational GEO ring
Example: GEO Mass Removal via Space Tug

- **principle**: deploy a tethered capture device (net or grapple fixture); tug the compound to a disposal orbit; cut tethered attachment; perform the next rendez-vous with a GEO object (“ROGER” concept)

- **pro**: effective for large (GEO) objects; multi-target capability (≈20)

- **con**: complex rendez-vous and capture operations; more difficult for non-GEO orbits, and for rotating or tumbling target objects
characteristics of the LEO debris environment:

- 0.3% of the useful volume of the Earth orbit environment
- 36.5% of the on-orbit mass ($\approx 2,500$ t), with up to 300 t per bin of [50 km altitude] x [2° inclination] at $H \approx 900$ km and $i \approx 82^\circ$
- 75% of the catalog population, with up to 800 objects per bin of [50 km altitude] x [2° inclination] at $H \approx 900$ km and $i \approx 98^\circ$
Example: LEO Mass Removal via Tethers

- **concept:** attachment & deployment of a conductive tether at a target object; orbit decay is enabled through a retarding Lorentz force

- **pro:** effective also for large objects on high LEO orbits (\(~1/r^3\) )

- **con:** complex rendez-vous and deployment operations; tethers are susceptible to severing impacts by debris and meteoroids; de-orbits through conductive tethers lead to uncontrolled re-entries
risk metric #1: [catastrophic collision rate]  
\[= [10cm \text{ flux}] \times [\text{target cross-section}]\]  
- mean rate of catastrophic collisions ≈ 0.2/year (45% S/C, 55% R/B)  
- 22% contribution from a single 2° x 50km bin at 87±1° and 775±25km  
- this bin contains 80 intact objects, 73 thereof Iridium S/C, each with a mass of 660kg and a cross-section of 22m²

risk metric #2: [short-term catastrophic collision risk]  
\[= [10cm \text{ flux}] \times [\text{target cross-section}] \times [\text{target mass}]\]  
- 28% contribution from a single 2° x 50km bin at 71±1° and 825±25km  
- this bin contains 16 Zenith-2 2\textsuperscript{nd} stages, each with a mass of 8900kg and a cross-section of 32m², and 15 Cosmos S/C of 3200kg and 6m²  
- removing the Zenith-2 stages would reduced risk metric #2 by 27%

risk metric #3: [long-term catastrophic collision risk]  
\[= [10cm \text{ flux}] \times [\text{target cross-section}] \times [\text{target mass}] \times [\text{time on orbit}]\]  
- 42% contribution resulting from the same orbit bin as for metric #2  
- removing the Zenith-2 stages would reduced risk metric #3 by 24%
Conclusions

- Space debris are a global space environment problem requiring ...
  - Fast reaction to maintain/re-gain control ("Kessler Syndrome")
  - Strict implementation of space debris mitigation measures
  - Removal of 10±5 large objects per year to reach a "zero growth rate"
  - International consensus to enable an effective environment control

- Open issues:
  - Solution concepts are technically demanding and potentially costly; they must, however, be seen in context with a possible degradation or even loss of parts of the existing space infrastructure
  - Mass removal operations must be backed by a legal framework and by political support at the international level

- Categorical imperative of space operations (J.P. Loftus/NASA, 1990s):
  - "Space operations should comply with a general rule of the National Park Service: what you take in you must take out"