SPACE DOMAIN

How Vulnerable are Space Activities?

1 O’clock Space Lectures
Bentham House, 11 December 2019

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11/12/2019

Outline

- Indispensable space.
- Assets and threats.
- Space debris.
- Space cyber.
- Space weather.
- Space as a new defence theatre.
- UN COPUOS guidelines.
- Challenges ahead.

The pervasiveness of space 1/2

Space is now an esential part of the way we understand and influence our surroundings and shape our way of living, wether the focus is on Earth, the solar system or the distant universe.

Space technologies have become an important part of everyday life and lifestyle through:

Earth Observation	Telecom & Broadcasting	PNT	Science & Exploration
• Meteorology • Remote sensing • Reconnaissance • Early warning • Surveying • Environment monitoring • Global change • Disaster management • Agriculture, forest and Fisheries • Shipping routes	• Direct TV • Communication/ trunk roads • Internet • Commercial and financial transactions • Insurance • Telemedicine • Distance learning • Entertainment • Other tele-activities	• Positioning • Navigation • Synchronisation of networks/Timing • Transportation of people and goods • Air traffic control • Maritime traffic • UAVs	• Understanding the Earth system • Exploring Earth's immediate vicinity • Exploring the solar system with human and robotic means • Exploring the universe with space based instruments • Space tourism

The pervasiveness of space 2/2

- At least 7 % of world GDP is tied to usage of space assets.
- Increasingly dense, diverse, and multi-stakeholder ecosystem of space activities.
- Basically transmitting information generated from the ground (EO, Weather, environment, Earth surface, telecom and broadcast,…), or from space (positioning, navigation, timing, exploration/astronomy).
- Space fed applications are pervasive throughout society and impact our daily lives:
  - 40 % apps require space-based information.
  - >50 % parameters needed to monitor climate change only obtained via measurements made from space.
- Turning off all the satellites (1h, 1 day, 1 week, 1 month or 1 year) would give a good estimate of such dependency.

Space Assets vs Threats

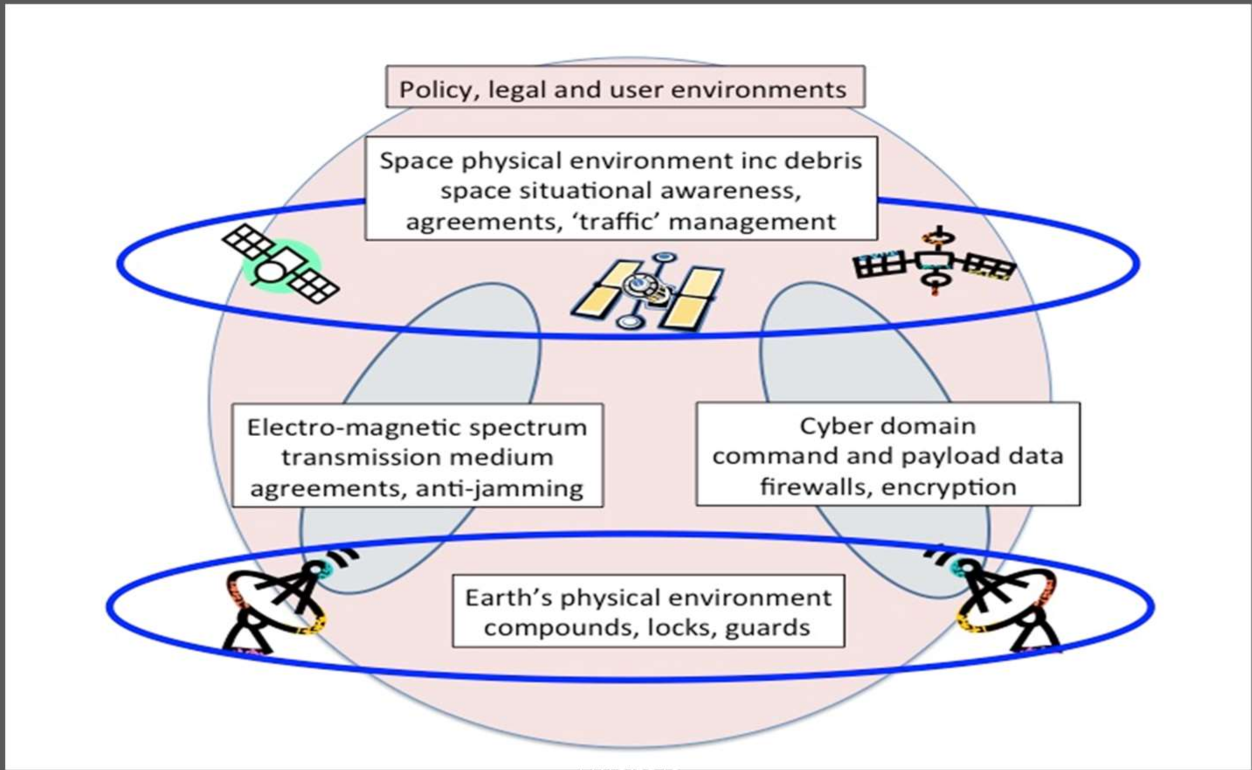
Assets

- Orbiting assets.
- Ground stations.
- Command and Control.
- Users.
- Information.

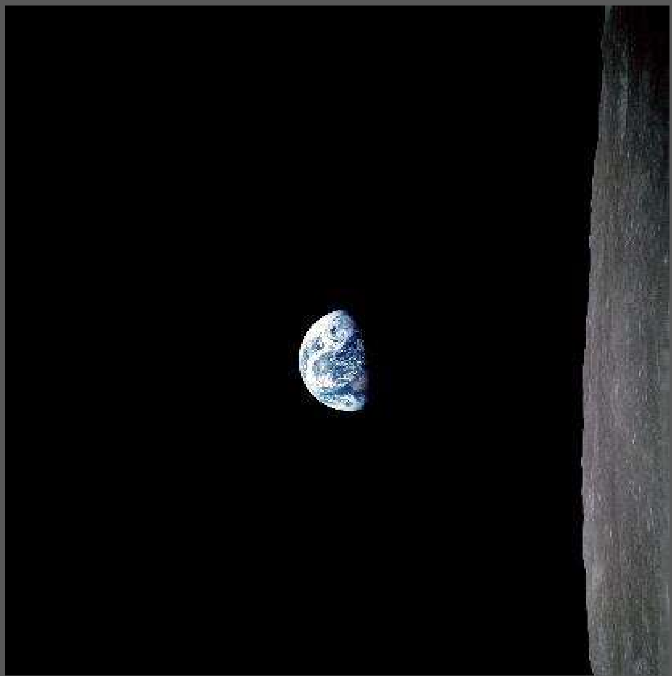
Threats (unintentional / intentional)

- Space debris.
- Electromagnetic.
- Cyber.
- Space weather storms.
- Kinetic.
- Radiative.

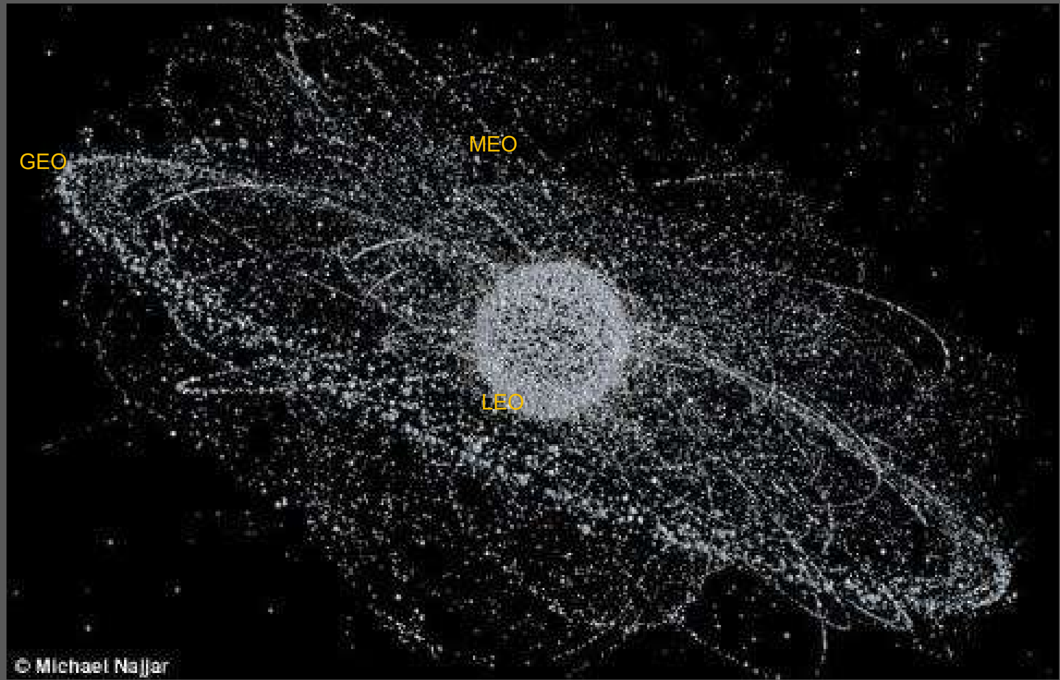
The Space Security System



Space Debris 1/2



3rd October 1957

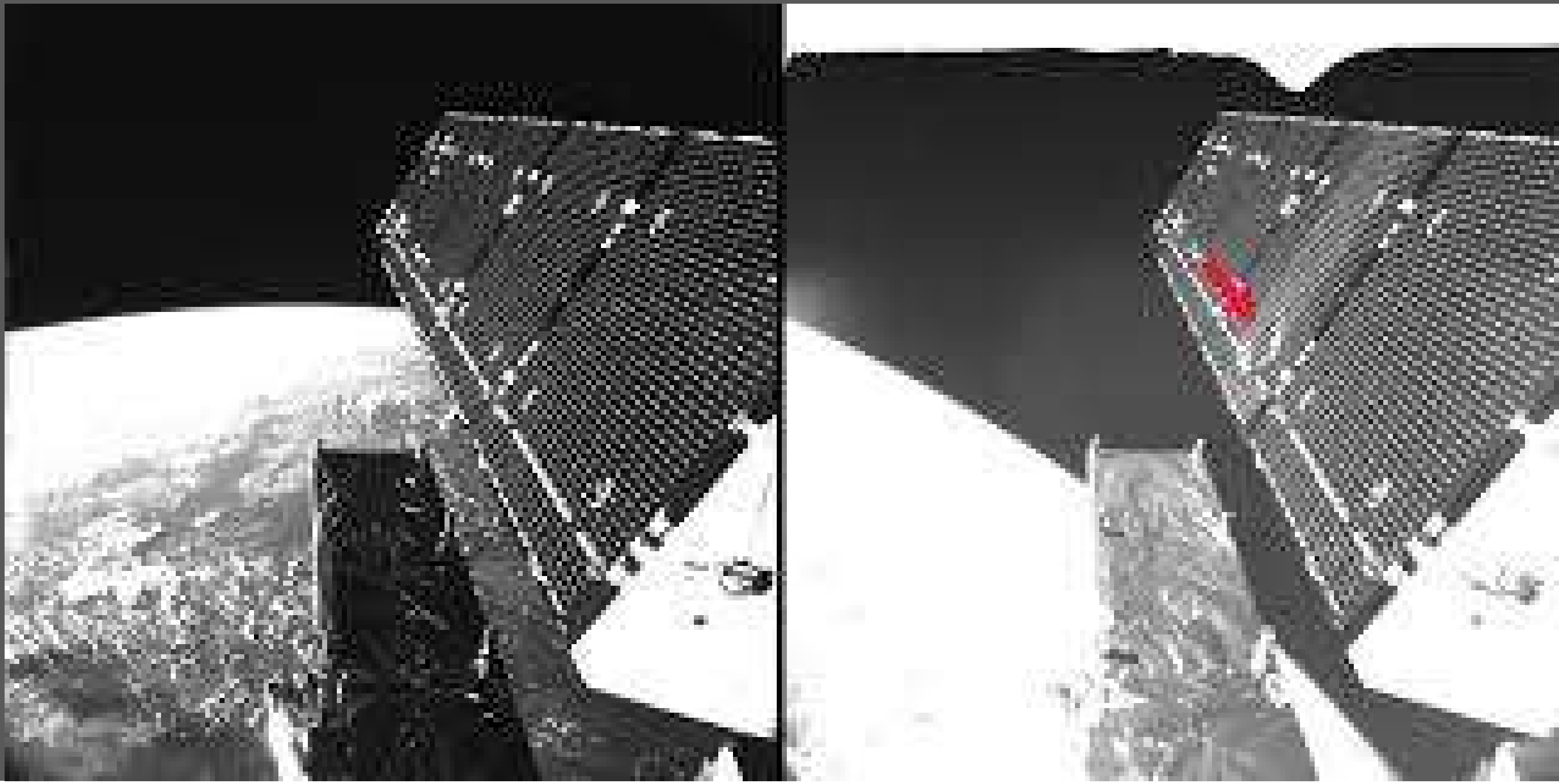


Today

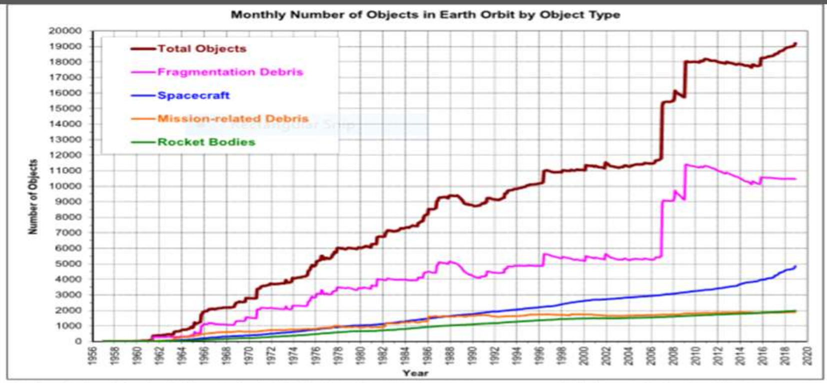
Space Debris 2/2

- Definition: all the inactive, manmade objects, including fragments, that are orbiting Earth or re-entering the atmosphere (ESA Space Debris Brochure 2017).
- 4800 satellites in space, about 1800 active and increasing.
- 23 000 objects tracked by USSSN and 18 000 maintained in their catalogue.
- 8000 tons orbiting the Earth, about Eiffel Tower's mass.
- 29 000 objects > 10 cm.
- 1 cm < 750 000 objects < 10 cm.
- 1 mm < 166 10^6 objects < 1 cm.
- Kessler Syndrome, analogue to nuclear chain reaction → may be a source of exponential production of debris.

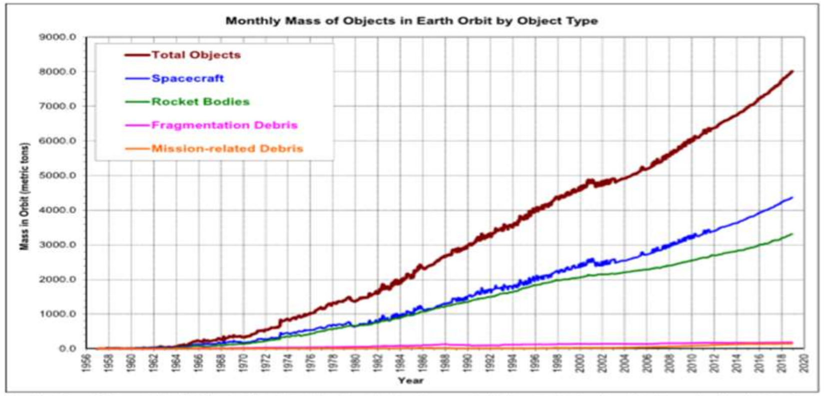
Debris Impact on ESA's Sentinel-1A (2016)



Space Debris Population and Mass Evolution

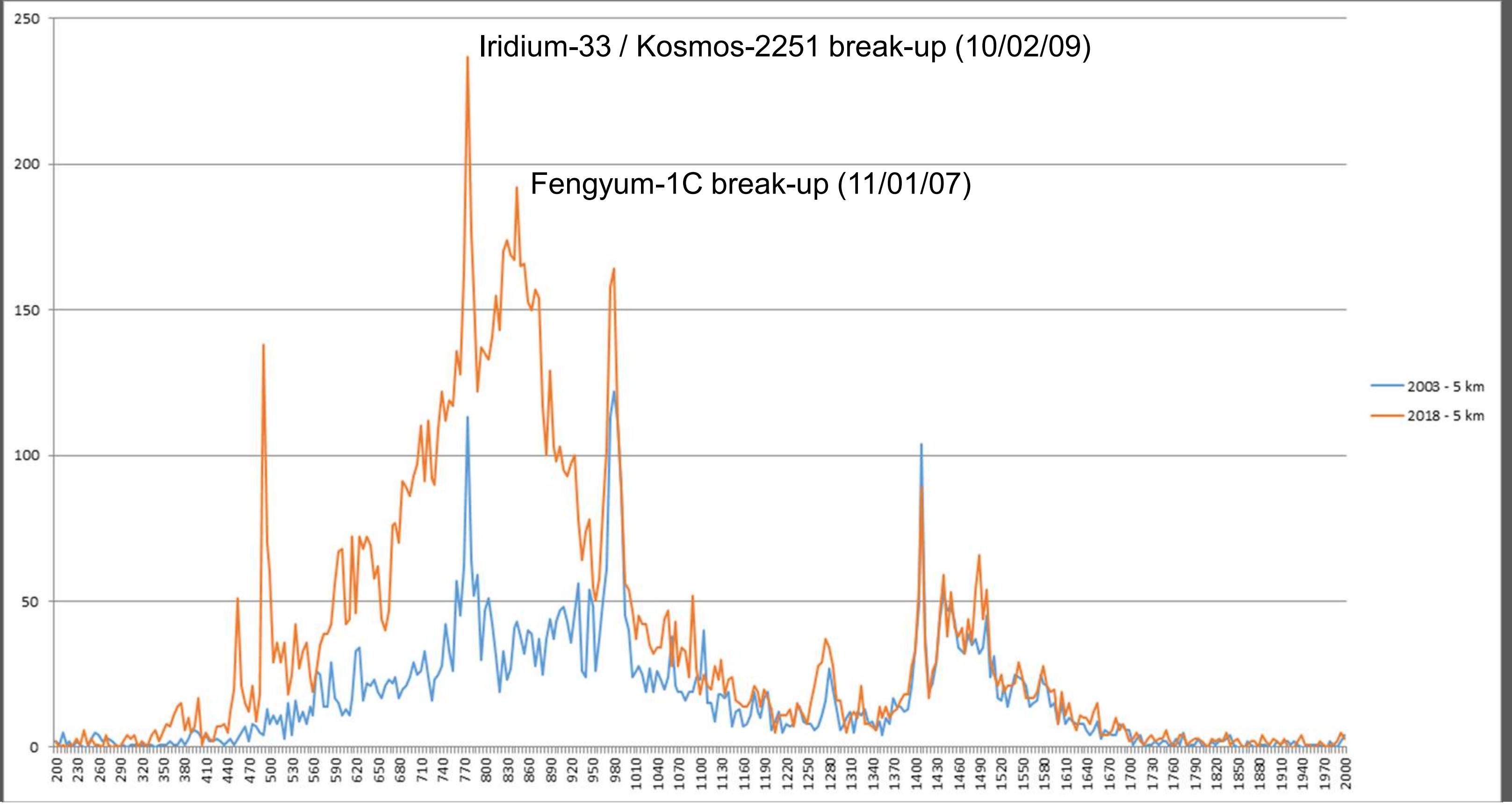


Monthly Number of Cataloged Objects in Earth Orbit by Object Type. This chart displays a summary of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris"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

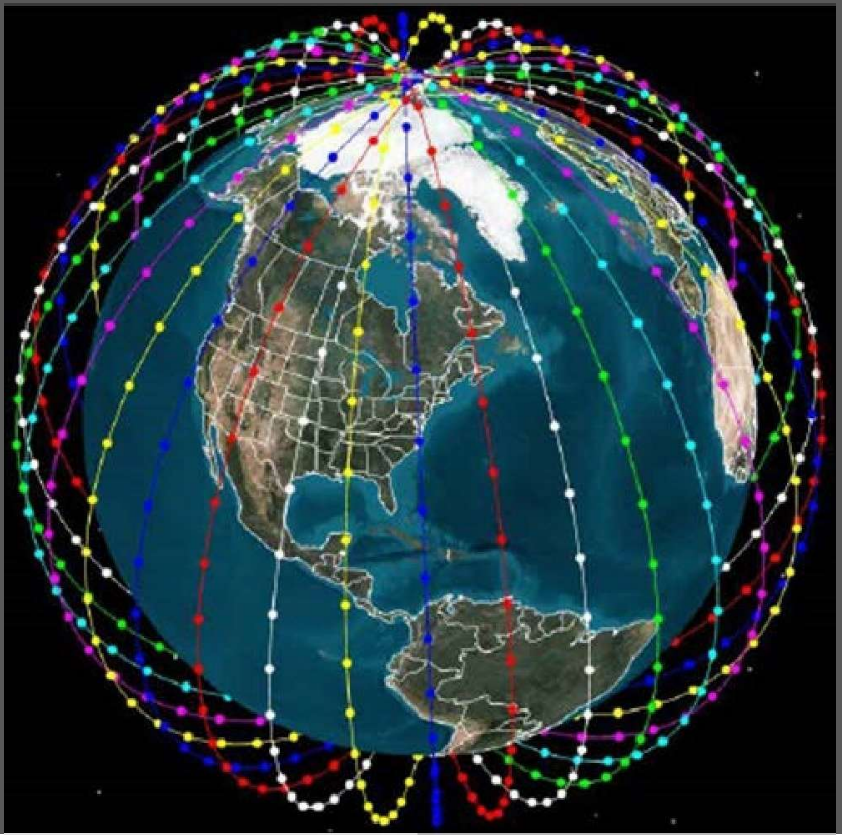


Monthly Mass of Objects in Earth Orbit by Object Type. This chart displays the mass of all objects in Earth orbit officially cataloged by the U.S. Space Surveillance Network.

Evolution of LEO Debris Population



Large LEO Constellations and Space Debris



Space Debris Prevention/Mitigation

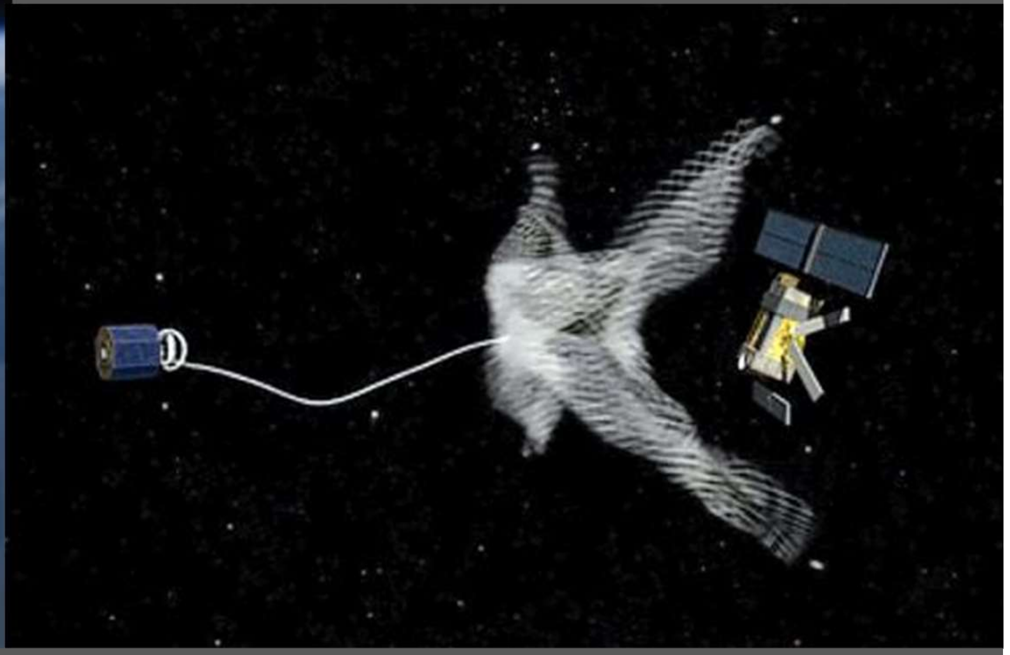
Prevention

- Outer Space Treaty (OST) 1967, governing activities of States in the exploration & use of OS.
- Convention on international liability for damage caused by space objects (1972).
- UN Space Debris Mitigation Guidelines (2007).
- PPWT (2008), Sino-Russian initiative.
- ICoC (2008), then EU PREBOS (2017).
- LTSSA/ UN COPUOS: 1st set of guidelines, June 2018.
- National Space laws.

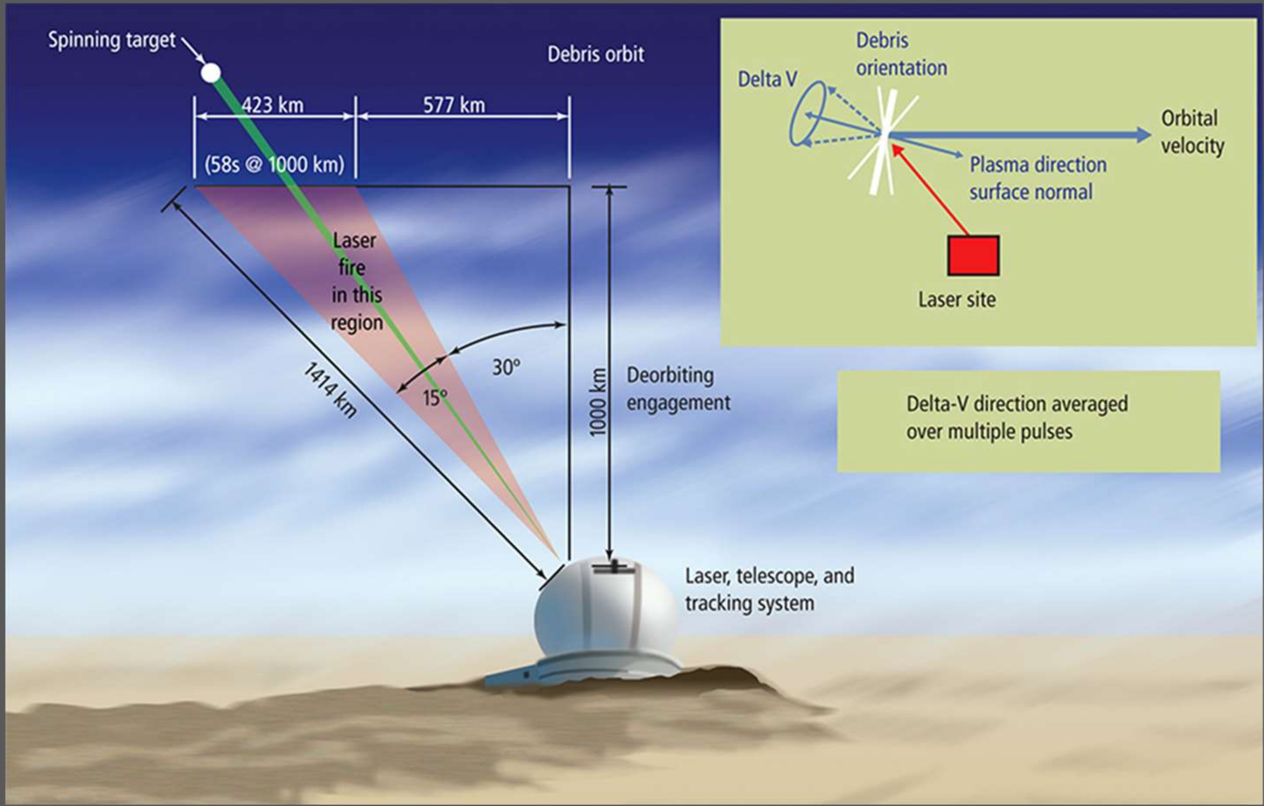
Mitigation

- Active Debris Removal (ADR):
  - Tug satellites.
  - Electro dynamic tethers.
  - Laser brooms.
  - Solar sails.
  - Space nets and collectors.
- Global assessment
  - Space Surveillance and Tracking (SST).
  - Space Situational Awareness (SSA).
  - Space Traffic Management (STM).

Passive & Active Removal



ADR via Clean up Laser Broom



UN Space Mitigation Guidelines

- Limit debris released during normal operations (spacecraft / orbital stages).
- Minimize the potential for break-up during operational phases.
- Limit the probability of accidental collision in orbit.
- Avoid intentional destruction and other harmful activities.
- Minimize potential for post-mission break-ups resulting from stored energy.
- Limit the long-term presence of spacecraft and launch vehicle orbital stages in the LEO region after the end of their mission (IADC recommended 25 years).
- Limit the long-term presence of spacecraft and launch vehicle orbital stages in the GEO region after the end of their mission (IADC recommended graveyard orbit 200 km higher).

Space Cyber 1/2

- Cyber (Cybercrime - DHS March 2010):

Any identified effort towards access to, exfiltration of, manipulation of, or impairment to the integrity, confidentiality, security or availability of data, an application, or a federal system, without lawful authority.

- Degradation, disruption or denial of transportation, banking, power, telecommunications, Air, Sea and Land navigation, distress detection, GPS timing.

Slide 17

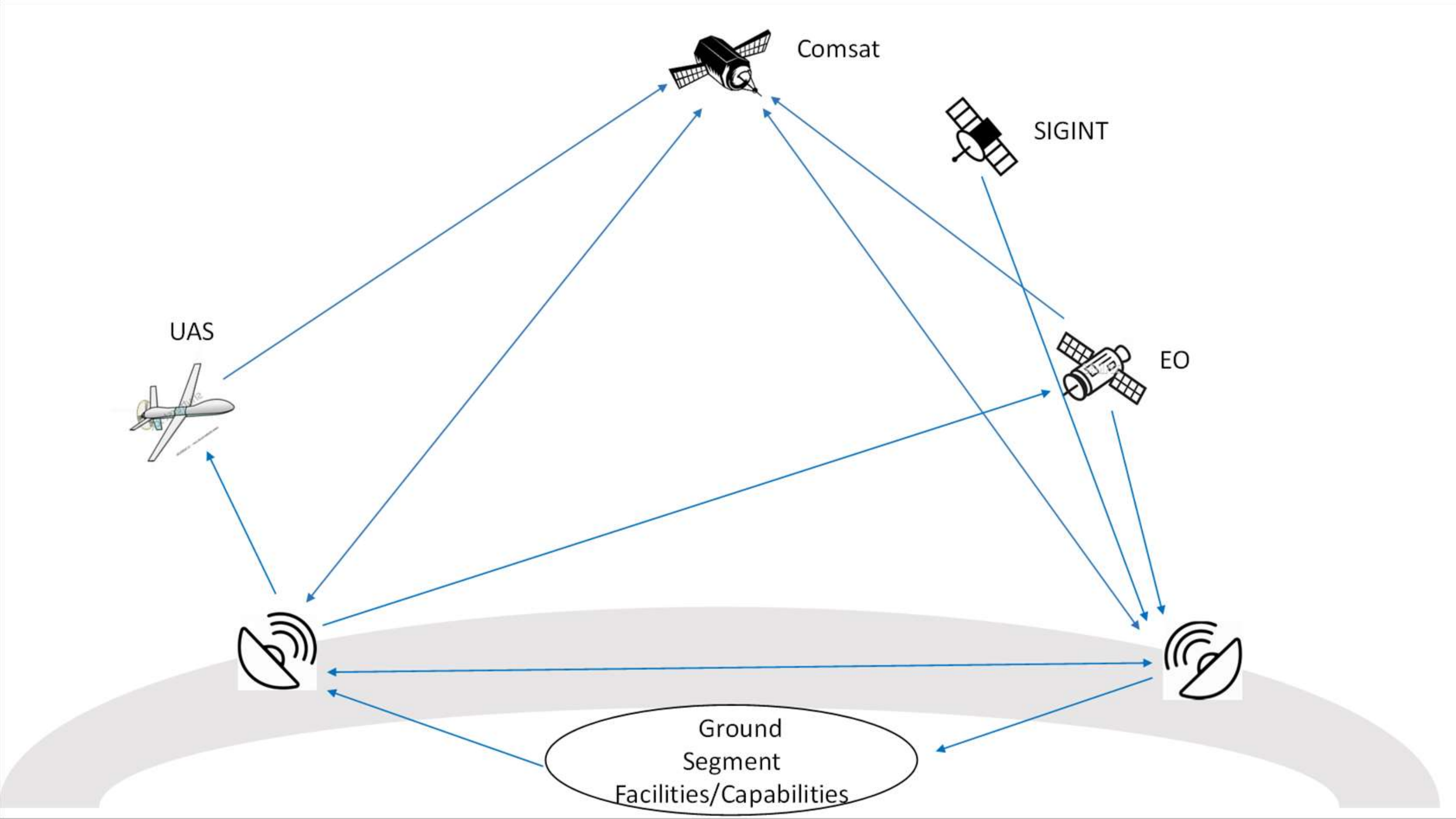
SP2 Serge Plattard, 09/12/2019

Space Cyber 2/2

Some open source space incidents:

-1998 US-German ROSAT disabled.
-2003 Telstar 12 jammed.
-2005 2 satcoms jammed.
-2007 Successful Chinese ASAT test.
-2009 Homemade setup equip used to hijack UHF frequencies.
-2010 Satellites broadcasts jammed.
-2011 Terra EOS & Landsat 7 experienced cyber interference: hackers achieved required steps to assume C&C.
-2011 Intelsat ONE identified 300 000 denial-of-service attacks.
-2014 US National Oceanographic and Atmospheric Information denied for 48 hours.

Info-Cyber Space System

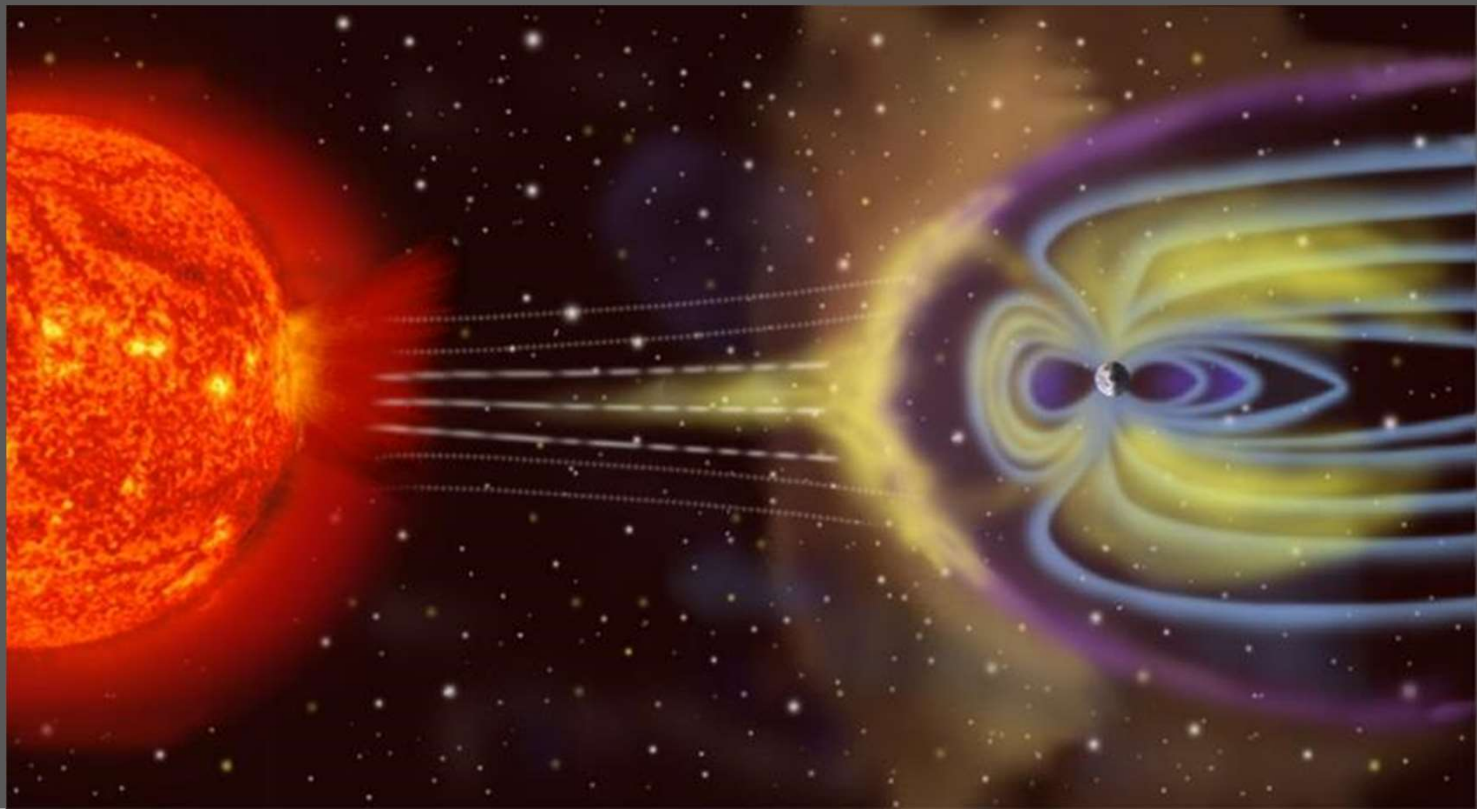


Solar Storms and Superstorms

- Massive solar flares, called coronal mass ejections (CME) send high velocity particles in the solar system.
- Earth is reached in a couple of days.
- The magnetic field carried by this plasma connects with the Earth magnetic field driving a huge amount of particles into the ionosphere and the Earth magnetosphere.
- Such rapid magnetic field changes induce electric current on conductors such as grid cables, transformers, telecommunication cables.
- 1859 Carrington event: should it occur today, cost for the US alone to be

  about $0.6-2.6 trillion…
- The power grid may then experience uncontrolled overloads leading to a local blackout, if not an extended one (Quebec, March 1989).
- Solar flares also can hit and incapacitate satellites.

Solar Storm Mechanism



The Solar Storm Issues 1/2

- Solar storms are global, essentially unpredictable, with intensity generally unknown *ex ante.*
- Sun erratic activity bears full responsibility.
- Super geomagnetic storm: about one in a century. Could affect a number of economic sectors for days, weeks, or even months, posing some civil security problems, including civil aviation.
- Terrestrial and space assets would be hit.
- Electrical power grids.
- Pipelines, transoceanic communication cables.
- *Satellites, including GNSS constellations.*
- Aircraft passengers and crew.
- *Avionics and ground systems.*
- Radio communication systems.

The Solar Storm Issues 2/2

- Consequences can be severe → advanced preparedness, mitigation actions and contingency plans have to be drawn early on.
- Avoid relying on a crisis management scenario. International cooperation is to be promoted and put into operational phase.
- Decision makers to be briefed and updated regularly.
- Damages due to charged particles bombardments. Electrons (electrostatic charging, cumulative effects → ageing effects. Protons (crystalline structure of components damaged).
- Satellite lifetimes affected.
- Mobile satellite communications using L-band might be unavailable due to superstorm scintillation.
- Better hardening of components is mandatory.
- Fleet management to be adapted to extreme circumstances.

Space as a New Defence Theatre

- Space is already a force multiplier.
- US Space Policy clearly states the necessity to have the right of passage, including for its allies, into space and operate freely in space without interference. Purposeful interference to be considered an infringement of a nation’s rights.
- Space assets have become critical for conducting ground operations of very diverse nature → need to be protected.
- Some space objects have the capability to deter, deny, damage, disable, destroy space assets considered as unfriendly .
- NATO members endorsed space, at its December 2019 Summit in London, as a new operational domain alike land, sea, air, and cyber.

UN COPUOS LTSSA Working Group

- WG established in 2010. Four categories of guidelines.
- A. Policy & regulatory framework for space activities (5/9 adopted).
- B. Safety of space operations (10/15 adopted).
- C. International cooperation, capacity building & awareness (4/4 adopted).
- D. Scientific & technical R&D (2/4 adopted).

UN COPUOS LTSSA Guidelines 1/4

- A. Policy and Regulatory framework for space activities.
- A.1 Adopt, revise and amend, as necessary, national regulatory frameworks for OS activities.
- A.2 Consider a number of elements when developing, revising or amending, national regulatory frameworks for OS activities.
- A.3 Supervise national space activities.
- A.4 Ensure the equitable, rational and efficient use of radio frequency spectrum and the various orbital regions used by satellites.
- A.5 Enhance the practice of registering space objects.

- B. Safety of Space Operations.
- B.1 Provide updated contact information and share information on space objects and orbital events.
- B.2 Improve accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects.
- B.3 Promote the collection, sharing and dissemination of space debris monitoring information.

UN COPUOS LTSSA Guidelines 2/4

- B.4 Perform conjunction assessment during all orbital phases of controlled flight.
- B.5 Develop practical approaches for pre-launch conjunction assessment.
- B.6 Share operational space weather data forecasts.
- B.7 Develop space weather models and tools and collect established practices on the mitigation of space weather effects.
- B.8 Design and operation of space objects regardless of their physical and operational characteristics.
- B.9 Take measures to assess risks associated with the uncontrolled re-entry of space objects.
- B.10 Observe measures of precaution when using sources of laser beams passing through OS.

UN COPUOS LTSSA Guidelines 3/4

- C. International cooperation, capacity-building and awareness.
- C.1 Promote and facilitate international cooperation in support of the long-term sustainability of OS activities.
- C.2 Share experience related to the long-term sustainability of OS activities and develop new procedures, as appropriate, for information exchange.
- C.3 Promote and support capacity-building.
- C.4 Raise awareness of space activities.

- D. Scientific and technical research and development.
- D.1 Promote and support research into and the development of ways to support sustainable exploration and use of OS.
- D.2 Investigate and consider new measures to manage the space debris population in the long term.

UN COPUOS LTSSA Guidelines 4/4

Guidelines for which no agreement could be reached:

- Commitment to carrying out space activities solely for peaceful purposes.
- Preclusion of interference with the operation of foreign space objects.
- Operational and technological self-restraints to forestall adverse developments in space.
- Prevention of dangerous alternations to the space environment.
- Development of criteria for safe ADR operations.
- Modalities for the safe conduct, in extreme cases, of operations to destroy orbital space objects.
- Development of common understanding and safe practices for removal or destruction of unregistered space objects.
- Ensuring the safety & security of ground infrastructure.
- Establishment of frameworks for implementation, promotion and review of the LTS guidelines.

Pending Chalenges Ahead 1/2

Legal-binding basis

Russia-China 2008 proposal to a UN Conference on Disarmament of a draft treaty on the Prevention of Placement of Weapons in Outer Space, the Threat of Use of Force against Outer Space Objects (PPWT). Leading to nowhere so far (insufficient means of verification, ground-based threats improperly addressed).

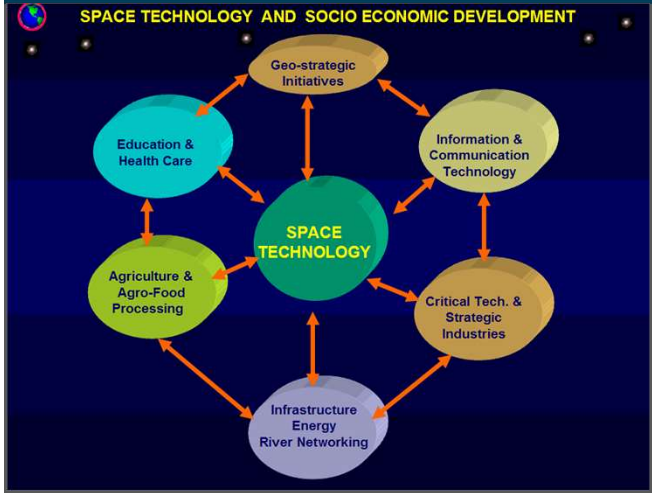
Voluntary basis

- UN Governmental Group of Experts (GGE) recommendations on TCBMs endorsed by the UNGA in 2013. Just a procedural implementation so far.
- UN COPUOS WG on LTSSA compendium of a set of 21 guidelines adopted in June 2018 during the COPUOS session. Hard points still need to be addressed.
- Discussions on a draft of an International Code of Conduct (ICoC), released by the EU in 2008 have stalled in July 2015. Rescue attempt with the PREBOS initiative in 2017.

Pending Challenges Ahead 2/2

- Technical side
  - US decision to modernize its SST means to bring a tracking capability up to 250 000 objects by 2025 (US Space Fence).
  - IADC space debris mitigation guidelines (2007) are now in force.
  - Is there a need for new guidelines to cope with the coming LEO large constellations made up of small satellites, and the booming population of LEO nanosats?
  - Operational and accepted ADR tools and procedures: still to be worked out (responsibility, liability, dual use)

SPACE DOMAIN



Thank you!

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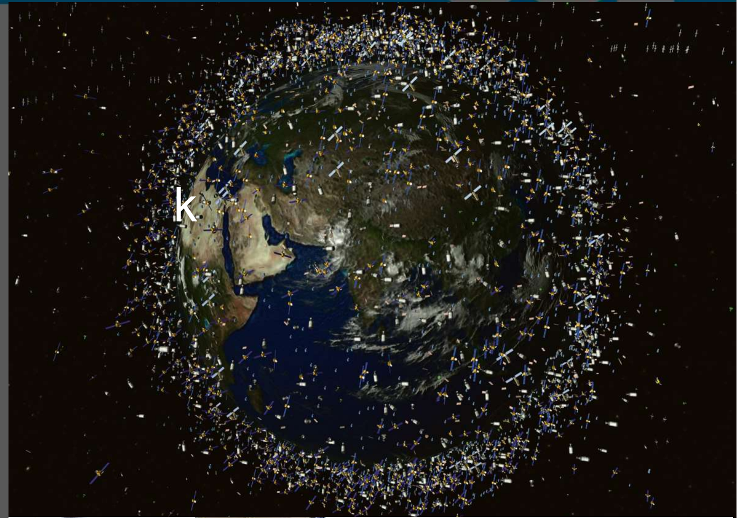

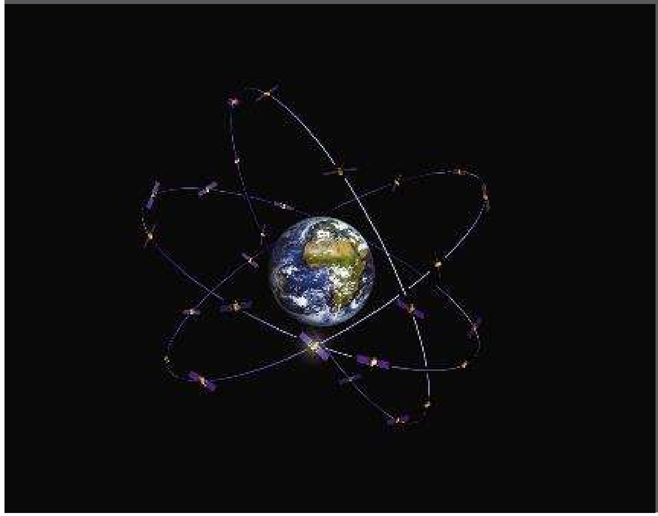

Some Reading Material

Space Debris Mitigation Guidelines of the UN COPUOS:
http://www.unoosa.org/pdf/publications/st_space_49E.pdf

UN COPUOS Resolutions and documents database:
http://www.unoosa.org/oosa/documents-and-resolutions/search.jspx

Studies and position papers of the International Academy of Astronautics (IAA).
https://iaaweb.org/content/view/229/356

Security in space: Should space traffic management also concern payloads management? Serge Plattard, Space Policy 33 (2015) 56-62.
http://dx.doir.org.10.1016/j.spacepol.2015.02.005

Debating proposals on common principle to ensure outer space activity.
https://www.un.org/press/en/2016/gadis3557.doc.htm

Stronger rules that must guarantee that outer space remains conflict-free.
https://www.un.org.press/en/2017/gadis3583.doc.htm

Challenges to security in space, Report of the US Defense Intelligence Agency, January 2019.
http://www.dia/mil/Portals/27/Documents/News/Military%20Power%20Publications/Space_Threat_Threats_V14_020119_sm.pdf

SPACE
SAFETY
COALITION

"Best Practices for the Sustainability of Space Operations"

Date: 16 September 2019

Since the first orbital launch in 1957, the number of artificial objects in Earth orbit has been growing. The corresponding increase in close approaches and collision risk to active space objects from collisions [1, 2] may lead to interruption of crucial space services [3]. Orbital debris population modeling indicates the potential for further increases in collision risk [4, 5, 6, 7, 8]; some of these studies indicate that even in the absence of new space traffic, orbital debris mitigation measures may be insufficient and debris removal remediation may be necessary. Accordingly, mitigation measures are needed to minimize orbital debris and preserve safe access to space in the future. Space industry stakeholders are well aware of these challenges and have achieved key milestones to address them.

In 2002, the Inter-Agency Space Debris Coordination Committee (IADC) assembled a set of guidelines for international space debris mitigation [9], aimed at limiting the generation of debris in the environment in the short-term – through measures typically related to spacecraft design and operation – and the growth of the debris population over the longer-term, by limiting time spent in the low Earth orbit (LEO) region after the end of mission to 25 years. The IADC updated these Space Debris Mitigation Guidelines in 2007 as Revision 1 [10]. The IADC also issued a statement on issues and concerns relevant to planned large LEO constellations [11].

The United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS), drawing largely upon the IADC's initial set of orbital debris mitigation guidelines, developed its own reduced set of consensus Space Debris Mitigation Guidelines [12]. The UN General Assembly endorsed these guidelines in its resolution 62/217.

The International Organization for Standardization (ISO) develops international standards that address space debris mitigation. ISO's top-level space debris mitigation standard is ISO-24113, "Space Systems — Space Debris Mitigation" [13]. This standard and its derivative standards to include [14, 15, 16, 17, 18, 19, 20], incorporate IADC and UN guidelines as well as commercial best practices and expected norms of behavior.

The Consultative Committee for Space Data Systems (CCSDS) is comprised of the major space agencies of the world and develops communications and data systems standards for spaceflight. CCSDS seeks to enhance governmental and commercial interoperability and cross-support, while also reduces risk, development time and project costs, by developing, publishing and freely distributing international standards [21]. The CCSDS international standards for the exchange of orbit, attitude, conjunction, reentry, and event data are particularly relevant to exchanging space data to facilitate safety of flight.

Some spacefaring nations have set up a licensing scheme or national regulatory framework for the space operators in their country. In general, such national regulation reflects a combination of the UN, IADC, and/or ISO-24113, which generally refer to common mitigation measures [22].

Plans to increase our space population with more CubeSats and other small satellites, as well as new, large constellations of satellites, were not envisioned when the above-mentioned guidelines and standards were established. These new planned spacecraft and constellations, coupled with improvements in space situational awareness, space operations, and spacecraft design, all provide an opportunity to expand upon established space operations and orbital debris mitigation guidelines and best practices.

In developing the following best practices, it was recognized that future efforts may be warranted to:

1) Adopt an existing forum or establish new forum(s) to create conditions favorable to the sharing of relevant space information and operator-to-operator coordination of space activities.
2) Address maneuver prioritization in the event that two spacecraft with maneuver capability conjunct. In the meantime, spacecraft operator communications and data sharing will remain the best strategy for avoiding collisions.
3) Address coordination between new large constellation satellite missions and operators existing in the targeted new mission orbit as early as possible to prevent unnecessary co-location or repeating conjunctions once on-orbit.
4) Collaborate with spacecraft manufacturers, governments, and intergovernmental agencies to strive to deorbit all spacecraft after their operational life to achieve ultimate sustainability of the space environment. In particular, relevant facets include the creation of conditions favorable for the development of deorbit servicers, the development of international standards for servicer interfaces and operations, evolution of spacecraft designs to be servicer-friendly, and striving to avoid any spacecraft from becoming derelict in an orbit which will not passively decay to reentry within 25 years, and which is not a seldom- used (i.e., graveyard) orbit.

The undersigned space industry stakeholders hereby endorse, and will promote and strive to implement within their respective organizations, the best practices identified and described herein as a valuable advancement towards the sustainability of space operations:

Logo	Organization	Endorsed on
AMOS by Spacecom MAKING SPACE FEEL	**AMOS by Spacecom**	**18 Sep 2019**
AGI	**Analytical Graphics, Inc.**	**18 Sep 2019**
Astroscale	**Astroscale Holdings**	**18 Sep 2019**
AXA XL	**AXA XL**	**18 Sep 2019**
centauri	**Centauri**	**18 Sep 2019**
D-ORBIT	**D-Orbit**	**18 Sep 2019**
Geeks without frontiers	**Geeks Without Frontiers**	**18 Sep 2019**
sat	**Hellas Sat**	**18 Sep 2019**
inmarsat The mobile satellite company	**Inmarsat**	**18 Sep 2019**
INTELSAT	**Intelsat S.A.**	**18 Sep 2019**
iridium	**Iridium Communications Inc.**	**18 Sep 2019**
Loverro Consulting	**Loverro Consulting LLC**	**18 Sep 2019**
	Maxar Technologies	**18 Sep 2019**

OneWeb	**OneWeb**	**18 Sep 2019**
planet.	**Planet Inc.**	**18 Sep 2019**
PAC PROVIDENCE ACCESS COMPANY	**Providence Access Company**	**18 Sep 2019**
SECURE WORLD FOUNDATION	**Secure World Foundation**	**18 Sep 2019**
SES	**SES S. A.**	**18 Sep 2019**
SAS	**Sky and Space Global**	**18 Sep 2019**
SPACE DATA ASSOCIATION	**Space Data Association Ltd.**	**18 Sep 2019**
Virgin ORBIT	**Virgin Orbit**	**18 Sep 2019**
XTAR	**XTAR LLC**	**18 Sep 2019**

Best Practices for Sustainability of Space Operations

Respecting,

The 2007 IADC Space Debris Mitigation Guidelines, the 2007 UN COPUOS Space Debris Mitigation Guidelines, and the ISO-24113 "Space Systems — Space Debris Mitigation" standard;

Recalling,

IADC guidelines for international space debris mitigation are designed to limit the generation of debris in all orbital regimes in the short-term and the growth of the debris population over the longer-term, through measures typically related to spacecraft design and operation [23]. These guidelines and other industry best practices were then codified and expanded in ISO's 24113 top-level orbital debris mitigation standard.

Noting,

Most spacefaring nations have established regulations for the space activities of the space operators in their country [22]. In most cases, the national regulation reflects or incorporates the UN, IADC and/or ISO-24113 guidelines.

Recognizing,

That technological innovation and market demands have led to a profusion of pioneering space projects and new systems to provide space services and services from space. This includes innovation in commercial projects that leverage space, spacecraft design and operational advancements, and a number of projects being planned that would deploy large numbers of spacecraft in non-geostationary orbits (NGSOs) to provide broadband connectivity, Earth observation, and other services.

Further Noting,

The IADC and UN guidelines and ISO-24113 standardized practices were formulated on the basis of future space-traffic envisaged at the time they were created. As such, they are not necessarily sufficient in light of recent scenarios that incorporate step increases in commercial space activities, such as the deployment of NGSO constellations with larger numbers of spacecraft than those deployed in previous decades.

Concerned,

About the ability to preserve a safe space environment for future exploration and innovation and the need to limit the creation of new space debris, maximize the information available on both debris and spacecraft, and encourage the development of and adherence to community-wide best practices for all space industry stakeholders.

Urge,

All space actors to promote and adhere to the best practices herein to ensure the safety of current and future space activities, and to preserve the space environment.

The undersigned space industry stakeholders hereby endorse, and will promote and strive to implement within their respective organizations, existing standards and guidelines as published by the IADC [10], UN COPUOS [12] and ISO [13].

In addition, the undersigned space industry stakeholders hereby endorse, and will promote and strive to implement within their respective organizations, the following best practices. These best practices are generally applicable to all spacecraft regardless of physical size, orbital regime or constellation size, and they directly address many aspects of the twenty-one consensus Long-Term Sustainability (LTS) guidelines approved by the United Nations Committee for the Peaceful Use of Outer Space (UN COPUOS) in June 2019.

1. **Spacecraft owners, operators and stakeholders should exchange information relevant to safety-of-flight and collision avoidance.**
   a. Such information should include, at a minimum, operator points-of-contact, ephemerides, ability to maneuver, and maneuver plans.
   b. Typical interfaces include direct operator-to-operator coordination and use of Space Situational Awareness and/or Space Traffic Management entities.
   c. Such exchanges should respect owner/operator intellectual property and proprietary information.
   d. Space industry stakeholders should be protected from legal liability associated with the good faith sharing of information relevant to safety-of-flight
   e. Such exchanges should be in accordance with each operator's country export regulations.

2. **In selecting launch service providers, space operators should consider the sustainability of the space environment.**
   a. Spacecraft operators should include requirements in their launch contracts for LEO missions that upon completion, the launch vehicle upper stages are deorbited through a controlled reentry.
   b. Spacecraft operators should include requirements in their launch contracts for GEO missions that upon completion, the launch vehicle upper stage should be disposed of in such a way that long-term perturbation forces do not cause it to enter the GEO protected region within 100 years of its end of life.
   c. Spacecraft operators should utilize launch vehicle stages for launching their spacecraft that are designed to ensure launch vehicle stage post mission disposal reliability, with a minimum success rate of 90% , and a goal of even higher success rate as technology permits.

d. Spacecraft operators should utilize launch vehicle stages for launching their spacecraft that are designed to ensure launch vehicle stage post mission passivation reliability, with a minimum success rate of 90%, and a goal of even higher success rate as technology permits.

e. Spacecraft operators should utilize launch providers who take steps to preclude collisions between deployed spacecraft and any other object that may be within the vicinity of the deployed orbit, including stages of the launch vehicle, active space objects, and inactive space objects, throughout the deployment phase.

3. **Mission and constellation designers and spacecraft operators should make space safety a priority when designing architectures and operations concepts for individual spacecraft, constellations and/or fleets of spacecraft.**

   a. Constellation architectures should include a safety-by-design approach:

      i. Adequate radial separation between large constellations should be maintained to assure a margin of safety under both nominal and anomalous operational conditions.

      ii. Constellation designers should limit the need for active control to mitigate collision risk between their own spacecraft.

      iii. Constellation designers should favor constellation designs which increase the time available to detect a failed spacecraft within their constellation and avoid colliding with it.

   b. Precautions should be taken to safeguard the environment from dead-on-arrival (DOA) deployments, particularly when launching spacecraft based on a new design*. Such precautions should include one or more of the following:

      i. Rigorous ground-based environmental acceptance testing based upon established acceptance test standards and procedures to include [24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41].

      ii. Qualification-level testing of all protoflight [42] spacecraft, until all critical systems (including those required for maintain spacecraft control and perform active collision avoidance) have been demonstrated on-orbit.

      iii. Launch into and initial operation in orbits that comply with a natural orbit lifetime of less than 25 years;

      iv. Launch into and initial operation in orbits at seldom-used altitudes (see definition of "seldom-used altitude").

4. **Spacecraft designers and operators should design spacecraft that meet the following best practices:**

* i.e., spacecraft that include elements critical to initial acquisition and control that do not have sufficient heritage to provide confidence in a successful LEOPS campaign.

a. Spacecraft should strive for a disposal process providing a probability of successful disposal of 95%.

b. Specific criteria for initiating the disposal of a spacecraft should be developed, included in a disposal plan, evaluated during the mission and, if met, consequent actions should be executed.

c. Spacecraft in orbits with apogee altitude above 400 km should be designed to be capable of performing timely and effective collision avoidance maneuvers sufficient to reduce the probability of collision per conjunction to less than 0.0001.

d. Designers of spacecraft disposed of through atmospheric re-entry should strive to reduce residual casualty risk to less than 1:10,000 per spacecraft and additionally should evaluate casualty risk on a system-wide, annual basis.

e. Spacecraft designers should consider means to improve the reliability of passivation functions, including the ability to complete passivation even after loss of command or loss of contact. Enabling this capability should be at the discretion of the spacecraft operator, i.e., later in mission life, or once the deorbit phase has been initiated.

f. Spacecraft designs should consider including technologies and features that facilitate capture and deorbit in the event that the spacecraft becomes derelict.

g. In order to facilitate the possibility of future servicing and/or removal by an in-orbit service provider, spacecraft operators and designers should maintain information on their spacecraft's inertia tensors, array positioning and other associated spacecraft characteristics.

h. Spacecraft should be designed to be reliably trackable from the ground using passive tracking means (e.g., radar, optical and passive RF). Spacecraft with limited observability should include features that enhance visibility (e.g., laser retro-reflectors and/or radar-cross-section enhancements).

i. Spacecraft operators and designers should consider using methods (e.g., encryption) in spacecraft command and control to maintain positive control of, and avoid unauthorized access to, space asset flight command functions.

5. Spacecraft operators should adopt space operations concepts that enhance sustainability of the space environment.

a. Operators of spacecraft in orbits with apogee altitude above 400 km should conduct active collision avoidance to reduce the probability of collision per conjunction to less than 0.0001, so long as it remains possible for the spacecraft to do so (i.e., until the spacecraft fails or has been passivated).

b. Collision avoidance maneuvers should be coordinated with the other spacecraft operator(s) and implemented as applicable.

c. The condition of a spacecraft should be monitored periodically during its operation to detect and mitigate any anomalies that could either lead to an accidental break-up or prevent successful disposal.

d. In case of mission extension, the capability of a spacecraft (including any mission extension servicer) to perform successful disposal should be reassessed considering the status of the spacecraft (including any mission extension servicer) at the beginning of the mission extension.

e. A spacecraft operating in the GEO protected region with a periodic presence should be disposed of in such a way that long-term perturbation forces do not cause it to enter the GEO protected region within 100 years of its end of life.

f. IADC and ISO guidance is to passivate as soon as is practical. However, with shorter deorbit durations this is not necessarily the best practice. The timing of post mission spacecraft passivation should be based on a tradeoff between the risk of debris generation due to self-break-up versus that due to collision with orbital debris over the passive deorbit period:

   i. GEO spacecraft should be moved into a GEO disposal orbit and should be passivated as soon as practical after the end of its in-service life and completion of its active disposal maneuver.

   ii. LEO spacecraft with long passive deorbit durations (greater than 5 years) should be passivated as soon as practical after the end of its in-service life and completion of its active deorbit maneuvers (if any). Prior to passivation, operators deorbiting LEO spacecraft should strive to place them into a final configuration that maximizes average (uncontrolled) cross-sectional area.

   iii. Spacecraft with short passive deorbit durations (i.e., less than 5 years) should be passivated as late as practical so they may continue to perform collision avoidance maneuvers. Retaining the collision avoidance maneuver capability reduces the risk of collision with orbital debris, and diminishes the need for in-service spacecraft to maneuver.

   iv. Hazardous fluids that are expected to survive reentry should be vented prior to reentry.

g. LEO spacecraft should be disposed of by means of atmospheric re-entry.

h. Operators of spacecraft that use chemical or electric propulsion to deorbit should strive to complete the deorbit phase within 5 years of end-of-mission.

i. Operators of passively deorbited spacecraft that require longer deorbit periods should strive to deorbit their spacecraft as soon as possible after the end of the service life of the spacecraft.

j. Spacecraft operators should strive to maintain current and 48h-predicted positional knowledge of their assets to within 500 m (two-sigma). This accuracy pertains to predicted ephemerides provided under Best Practice 1.(a) above. It is recognized that during orbital maneuvering periods, positional knowledge may be degraded.

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Glossary

For the purposes of this endorsement of best practices document, the following terms and definitions apply:

active collision avoidance
positive action such as an orbital maneuver (through propulsive, differential drag, or other means that is executed in order to reduce the probability of collision with another spacecraft or with orbital debris.

active phase of deorbit
the phase of deorbit during which the spacecraft is performing maneuvers to re-enter the atmosphere more quickly or to relocate it to a seldom-used altitude (e.g., GEO disposal orbit).

break-up
event that completely or partially destroys a space object and generates fragments.

casualty
person who is killed or seriously injured.

NOTE 1 to entry: The medical profession has defined a number of different injury scoring systems to distinguish the severity of an injury. Broadly, a serious injury is one of such severity that hospitalization is required.

casualty risk
probability that one or more casualties occur as a consequence of an event.

NOTE 1 to entry: The re-entry of a spacecraft is an example of an event.

controlled re-entry
type of re-entry where the time of re-entry is sufficiently controlled so that the impact of any surviving debris on the surface of the Earth is confined to a designated area (e.g., an uninhabited region such as an ocean).

derelict spacecraft
a spacecraft that has been abandoned, neglected, or has become nonfunctional but remains in an orbit of any kind in space.

disposal
actions taken by a spacecraft or launch vehicle orbital stage to achieve its required long-term clearance of the protected regions and to permanently reduce the chance that it will fragment.

disposal maneuver
action of moving a spacecraft or launch vehicle orbital stage to a different orbit as part of its disposal.

disposal orbit
orbit in which a spacecraft or launch vehicle orbital stage resides following the completion of its disposal maneuvers.

disposal phase
interval during which a spacecraft or launch vehicle orbital stage completes its disposal.

end of life (EOL)
instant when a spacecraft or launch vehicle orbital stage is permanently turned off, nominally as it completes its disposal phase, or when it re-enters, or when the operator can no longer control it.

end of mission
instant when a spacecraft or launch vehicle orbital stage completes the tasks or functions for which it has been designed, other than its disposal, or when it becomes non-functional or permanently halted because of a failure or because of a voluntary decision.

Geosynchronous Earth orbit (GEO)
Earth orbit whose orbital period is equal to the Earth's sidereal rotation period.

Geostationary Earth orbit (GSO)
Earth orbit having zero inclination and zero eccentricity, whose orbital period is equal to the Earth's sidereal rotation period.

hazardous fluids
Gasses and/or liquids that are generally considered detrimental to the environment, animals and/or humans.

launch vehicle
system designed to transport one or more payloads from the surface of the Earth to outer space.

launch vehicle orbital stage
complete element of a launch vehicle that is designed to deliver a defined thrust during a dedicated phase of the launch vehicle's operation and achieve orbit.

Low Earth Orbit (LEO)
Earth orbit occupying orbit altitudes below 2000 km.

maneuver
To intentionally steer or manipulate (via either propulsive effects or induced perturbations) a spacecraft's subsequent position.

mission extension servicer
A spacecraft servicing vehicle designed to extend a spacecraft's mission duration.

Non-Geostationary Orbit (NGSO)
Earth orbit that is not a geostationary Earth orbit (as defined above).

orbit lifetime
elapsed time from when an orbiting space object is at an initial or reference position to when it re-enters the lower atmosphere.

passivation
act of permanently depleting, irreversibly deactivating, or making safe all on-board sources of stored energy, capable of causing an accidental break-up.

NOTE 1 to entry: Passivation is necessary to reduce the chance of an accidental explosion that could generate space debris and the chance of hazardous materials surviving re-entry.

NOTE 2 to entry: Residual propellants, batteries, high-pressure vessels, self-destruct devices, flywheels and momentum wheels are examples of on-board sources of stored energy potentially capable of causing an accidental break-up.

probability of successful disposal
probability that a spacecraft or launch vehicle orbital stage is able to complete all of the actions associated with its disposal.

NOTE 1 to entry: This probability is calculated from the reliabilities of those subsystems that are necessary to enable the disposal. The probability also includes consideration of uncertainties in the availability of resources (e.g., propellant required for the disposal), the probability that the nominal mission will be completed, and considering the probability that the disposal will be precluded by predictable external causes.

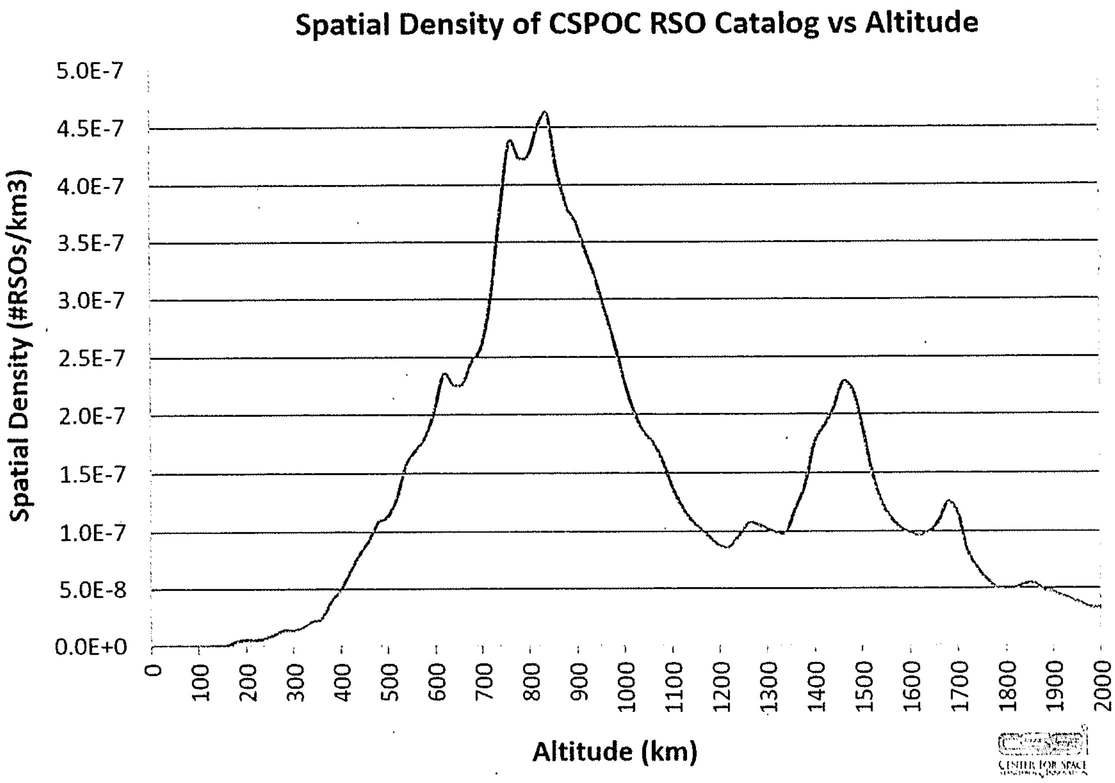
propulsion
the action of driving or pushing forward.

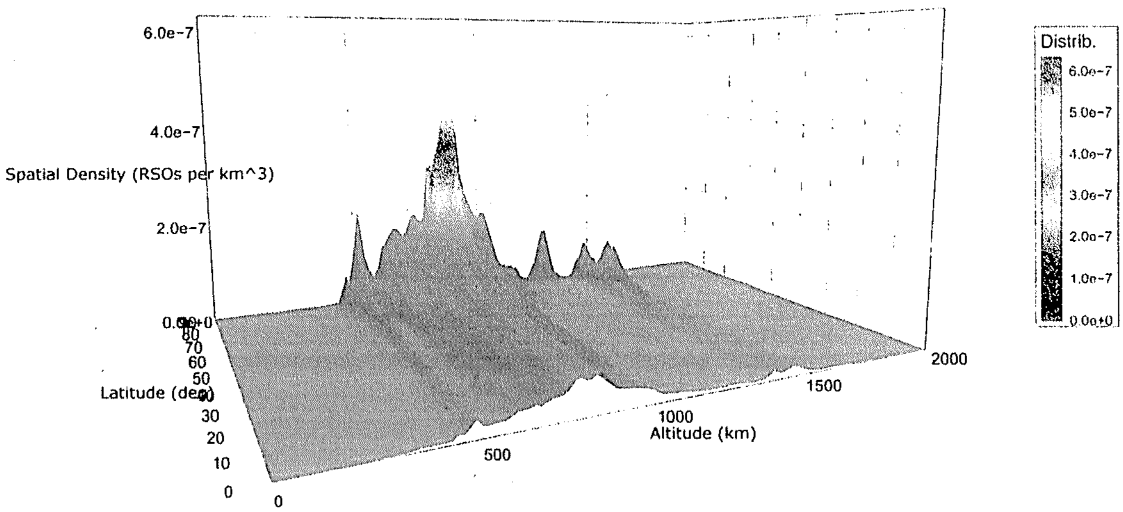
protected region
region in outer space that is protected with regard to the generation of space debris to ensure its safe and sustainable use in the future.

protoflight
As defined by NASA Technical Standard NASA-STD-7002B [42], protoflight refers to flight hardware of a new design which is subject to a qualification test program that combines elements of prototype and flight acceptance verification. A protoflight payload is built, serves to qualify the design and is also the flight article.

re-entry
return of a space object into the Earth's atmosphere.

seldom-used altitude
an altitude that is not an orbit altitude of special significance (e.g. GSO) and that is relatively unpopulated as compared to heavily-used operational spacecraft altitudes and/or crowded debris fragment altitudes (see one-dimensional and two-dimensional depictions below, based upon public space catalog data from 18 July 2018 and 8 September 2017, respectively).





should
something that is seen as being advisable to do but is not binding or mandatory.

space debris (equivalently, orbital debris)
man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional.

space object
man-made object which has reached outer space.

spacecraft
system designed to perform specific tasks or functions in outer space, excluding launch vehicles.

SSA
Space Situational Awareness - Comprehensive knowledge and understanding of the space and terrestrial environment, factors, and conditions, to include the status of other space objects, ground and/or space transmitters, and weather, that enables timely, relevant, decision-quality and accurate assessments, in order to successfully protect space assets and properly execute the function(s) for which a spacecraft is designed. (Oltrogge, D., Johnson, T. and D'Uva, A.R., "Sample Evaluation Criteria For Space Traffic Management Systems," 1st IAA Conference on Space Situational Awareness (ICSSA), 13-15 November 2017, Orlando, FL, USA).

STM
Space Traffic Management, defined as the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference (Schrogl, K.U., Jorgenson, C., Robinson, J., and Soucek, A., "The IAA Cosmic Study on Space Traffic Management).

uncontrolled re-entry
type of re-entry where the time and location of re-entry are not controlled.

18SPCS
The United States Air Force 18th Space Control Squadron.