“Best Practices for the Sustainability of Space Operations”

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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 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], 2020 (Revision 2) (no online presence found), and 2021 (Revision 3) [11]. The IADC also issued a statement on issues and concerns relevant to planned large LEO constellations [12].

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 [13]. 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" [14]. This standard and its derivative standards to include [15, 16, 17, 18, 19], 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 reducing risk, development time, and project costs by developing, publishing and freely distributing international standards [20]. 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 [21].

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 abovementioned 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. Spacecraft operator communications and data sharing will remain the best strategy for avoiding collisions.
2) 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.
3) Collaborate with spacecraft manufacturers, governments, and intergovernmental agencies to deorbit all spacecraft after their operational life to achieve ultimate sustainability of the space environment. Create conditions for the development of deorbit servicers, international standards for servicer interfaces and operations, and servicer-friendly spacecraft designs, while not leaving a derelict spacecraft in an orbit that will not passively decay within 5 years, or which is not a seldom-used or designated 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. Endorsing entities are categorized by type as follows:

A=Association/Foundation	C=Consulting/Analytical Serv.	D=Disposal services
F=Flight safety/SSA/STM	G=Govt Operator	I=Insurer
L=Launch provider	M=Manufacturer of spacecraft	N=Network
O=Operator (commercial)	P=Part/comp manufacturer	R=RPO/OOS services
S=Security	T=Systems/Tools supplier	

Logo	Organization	Type	Endorsed on
ABS AGILITY BEYOND SPACE	**ABS Global Ltd.**	**O**	**4 Apr 2023**
AEROSPACE	**The Aerospace Corporation**	**F C G O R T**	**4 Apr 2023**
AIRBUS	**Airbus SKYNET Operations Team**	**G**	**4 Apr 2023**
AMOS by Spacecom MAKING SPACE FEEL CLOSER	**AMOS by Spacecom**	**O**	**4 Apr 2023**
Ansys GOVERNMENT INITIATIVES (AGI)	**Analytical Graphics, Inc.**	**T F**	**4 Apr 2023**
AstroDynamic	**Astro Dynamic Ltd**	**O S A**	**11 May 2023**
Astroscale	**Astroscale Holdings**	**O D**	**4 Apr 2023**
AVANTI	**Avanti Communications, Ltd.**	**O**	**4 Apr 2023**
BENCHMARK space systems	**Benchmark Space Systems**	**F P R D T**	**5 Apr 2023**
COMSPOC	**COMSPOC Corporation**	**F C R O T**	**4 Apr 2023**
D-ORBIT NEW SPACE SOLUTIONS	**D-Orbit**	**D L M O P R T**	**7 Apr 2023**

Logo	Organization	Type	Endorsed on
	Digantara Research and Technologies Private Limited	**F T C**	**22 May 2024**
	ENPULSION GmbH	**P**	**4 Apr 2023**
	Exo Launch GmbH	**L O T**	**4 Apr 2023**
	GMV	**C F T**	**4 Apr 2023**
	Hellas Sat	**O**	**4 Apr 2023**
	Inmarsat	**O**	**4 Apr 2023**
	Intelsat S.A.	**O**	**4 Apr 2023**
	International Association for the Advancement of Space Safety	**A**	**4 Apr 2023**
	Iridium Communications Inc.	**O**	**4 Apr 2023**
	Kall Morris Inc.	**C R D**	**4 Apr 2023**
	Kayhan Space	**C, F, R, T**	**24 Apr 2023**
	LeoLabs, Inc.	**C F**	**4 Apr 2023**
	Mars Planet Technologies	**C, O**	**17 May 2023**
	Maxar Technologies	**P M R O**	**6 Apr 2023**

Logo	Organization	Type	Endorsed on
	NetFoundry, Inc.	N S	28 Aug 2023
	NorthStar Earth and Space Inc.	M O	7 Apr 2023
	OKAPI: Orbits GmbH	C F T	6 Jun 2023
	Planet Inc.	M O	4 Apr 2023
	Providence Access Company	C	4 Apr 2023
	Rogue Space Systems Corporation	R	4 Apr 2023
	Secure World Foundation	A	4 Apr 2023
	SES SA	O	4 Apr 2023
	Share my space	F	28 Jul 2023
	Slingshot Aerospace, Inc.	C F R T	4 Apr 2023
	Rockdrill Resolve Inc. DBA Space Cowboy ADR	F, O, S, M, D, R	28 Sep 2023
	Space Data Association Ltd.	A F	4 Apr 2023

Logo	Organization	Type	Endorsed on
	Space Domain Awareness, Inc.	**F P C**	**4 Apr 2023**
	SpaceTug	**D**	**15 Feb 2024**
	Society of Satellite Professionals, Intl.	**A**	**12 Apr 2023**
	Vestigo Aerospace, Inc.	**D**	**10 May 2023**
	Vyoma GmbH	**F T**	**4 Apr 2023**

Best Practices for Sustainability of Space Operations

Respecting,

The 2021 IADC Space Debris Mitigation Guidelines, the 2007 UN COPUOS Space Debris Mitigation Guidelines, and the ISO-24113:2019 “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 [22]. These guidelines and other industry best practices were then codified and expanded in ISO’s 24113:2019 top-level orbital debris mitigation standard.

Noting,

Most spacefaring nations have established regulations for the space activities of the space operators in their country [21]. 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 the deployment of large numbers of spacecraft (large constellations) 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 based on future space traffic envisaged at the time they were created. As such, they are not necessarily sufficient considering 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 [13] and ISO [14].

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 except where specifically noted, 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 stakeholders should avoid intentional space object fragmentations or intentional collisions with other objects that place other nations' interests, satellites, or crew at risk.**

NOTE: Freedom of navigation in space is crucial to the expansive use of space to benefit humanity. Spacecraft operators, spacefaring nations, and stakeholders have a shared responsibility to promote and ensure space flight safety. Intentionally fragmenting a space object may cause harm to the space environment and endanger humans in space, threatening the security and sustainability of the spacecraft operating environment.

2. **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 should include direct operator-to-operator coordination and interchange with Space Situational Awareness and/or Space Traffic Management entities.
   c. Operators should consider widespread adoption of CCSDS Navigation Working Group standards* for conveyance of orbit, attitude, reentry, tracking, launch, fragmentation, and event data.
   d. Orbit solutions exchanged with others should maintain accurate positional knowledge, both predicted forward for flight safety purposes and historically for the purposes of anomaly resolution, machine learning, and close approach analyses.

* Current versions of these freely-available standards are posted at https://public.ccsds.org/Publications/MOIMS.aspx with supporting normative content provided at https://sanaregistry.org/r/navigation_standard_registries

e. Exchange of operator predictive ephemerides is preferred over the exchange of orbital state vector or Two-Line Element (TLE) data, in that it provides a more accurate, time-varying conveyance of positional knowledge:

   i. Operators should incorporate planned maneuvers and known/modeled perturbations into predictive ephemerides.

   ii. Operators should provide orbital knowledge that is valid for at least four days in LEO and seven days in GEO.

   iii. Provided ephemerides should use a sufficiently small step size to ensure accurate ephemeris interpolation.

   iv. Provided ephemerides should be accompanied by realistic position covariance where available and shareable.

f. Such exchanges should respect owner/operator intellectual property and proprietary information.

g. Space industry stakeholders should engage with domestic regulatory authorities and contribute their perspectives to public rulemaking proceedings on methods to lessen legal liability issues associated with good faith sharing of information relevant to safety-of-flight.

h. Such exchanges should be in accordance with each operator's country export regulations.

3. 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 stages are deorbited in a manner that ensures a casualty risk below one in ten thousand.

b. Spacecraft operators should consider the use of launch system providers that seek to minimize the overall impact of their launch systems on the space environment (e.g., use of reusability, eco-friendly fuel alternatives).

c. Spacecraft operators should include requirements in their launch contracts for GEO missions that upon completion, the launch vehicle stage(s) 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.

d. 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.

e. Spacecraft operators should include requirements in their launch contracts for LEO missions that upon completion, the launch vehicle stage(s) and any payload adapter should be disposed of in a manner that keeps them outside of the LEO and GEO protected regions for 100 years upon completion of the launch vehicle stage's mission.

f. Where launch vehicle stages are used which do not directly reenter the atmosphere following completion of their mission, spacecraft operators should utilize launch vehicle stages 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.

g. 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.

4. 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 [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40].

   ii. Qualification-level testing of all protoflight [41] spacecraft, until all critical systems (including those required for maintain spacecraft control and perform active collision avoidance) have been demonstrated on orbit.

   iii. Launch to and initial operation in orbits that comply with a natural orbit lifetime of less than 25 years or launch to and initial operation in orbits at seldom-used altitudes (as an example, see 1200 km altitude in plot accompanying the definition of "seldom-used altitude").

[†] 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.

5. **Spacecraft should be designed to meet the following best practices:**

   a. Spacecraft should enact a disposal process providing a probability of successful disposal after end-of-mission within the period shown in the table below. Spacecraft operators in all orbit regimes are encouraged to incorporate probability of successful disposal as a component of their reliability analysis.

   NOTE: Current ISO standards and IADC guidelines specify 90% probability of successful disposal.

	GEO PMD‡	LEO PMD w/in 5 yrs	LEO PMD w/in 25 yrs
PMD	95%	95%	99%

   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 for all identified conjunctions consistent with section 8.j.

   d. Designers of spacecraft disposed of through atmospheric re-entry should reduce residual casualty risk to less than 0.0001 per spacecraft and additionally should evaluate casualty risk on a system-wide, annual basis.

   e. Propulsion systems should be designed to ensure that fluids and gases can be vented apart from static and dynamic residuals which will remain onboard.

   f. Power systems should be designed to allow all power system components to be isolated, preventing battery recharging.

   g. Designers should consider means to further 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.

   h. Spacecraft should be designed to be reliably trackable from the ground using passive tracking means (e.g., radar, optical, and passive RF).

   i. Spacecraft with limited observability should include features that enhance visibility (e.g., laser retroreflectors and/or radar-cross-section enhancements) or improve track association (e.g., beacon emitters or RFID interrogation systems).

6. **Spacecraft designers and operators should consider mission- and component-level design and operations that prepare current and future spacecraft in both controlled and derelict modes for services such as inspection, refueling, and timely post-mission disposal, to include:**

‡ Per IADC guidelines, disposal shall leave GEO satellite in an orbit that will not conflict with GEO protected region for at least 100 years.

a. Interfaces and physical features to enable rendezvous and proximity navigation operations and docking (RPOD), such as features for grappling, docking, and/or berthing, closeouts or coverings over serviceable interfaces that enable on-orbit robotic access, sensor calibration or guidance markers, and other Cooperative Servicing Aids (CoSA).

b. Features to improve the ability for spacecraft to be uniquely identified and reliably tracked once deployed, such as beacons.

c. Modular spacecraft design features that facilitate the replacement or upgrade of failed or degraded components.

d. The creation, retention, and preservation, to the maximum practical extent, of detailed and up-to-date internal documentation of both spacecraft designs and status for as long as possible beyond end of mission, such as: inertia tensors, array positioning, interface control documents, 'digital twin' models or simulations, photos and documentation of serviceable areas of spacecraft, and telemetry of the current state of spacecraft systems, subsystems, and components.

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

a. Operators of non-geosynchronous orbit spacecraft in orbits with apogee altitude above 400 km should conduct active collision avoidance by maneuvering whenever the estimated probability of collision exceeds 0.0001, thereby reducing collision probability to less than 0.00001 per conjunction, so long as it remains possible for the spacecraft to do so (i.e., until the spacecraft fails or has been passivated).

b. 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.

c. Spacecraft operators should, to the best of their ability, ascertain the root cause of a satellite anomaly or failure to determine and implement those corrective actions deemed necessary to reduce the number of failed satellites in orbit. Root cause investigations are often complicated by limited instrumentation and data rates on most spacecraft telemetry systems to capture evidence of causative factors (e.g., accelerations, electrical transients, etc.) and the dynamic/uncertain space environment.

NOTE: A root cause anomaly investigation for a space incident investigation could include the following aspects:

i. Establish an unambiguous timeline of events.

ii. Compare all spacecraft events with historical data to identify outliers.

iii. Maintain all hypothetical failure mechanisms throughout the entire investigative process (to avoid confirmation bias).

iv. Share anomaly and root cause information to the extent allowed by law.

v. Neither ignore the space environment nor attribute the anomaly to space weather without identifying an established mechanism that fits the facts.

vi. Accept that multiple events and associated equipment may have contributed to the anomaly.

vii. Focus on the lowest possible level of hardware and software (e.g., solar array actuator motor rather than simply the power system).

viii. Maintain detailed manufacturing and test data and photographic evidence, especially for hardware rework, repair, or changes throughout the spacecraft lifecycle until the spacecraft is retired.

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

g. Operators should also consider employing other methods to achieve disposal (e.g., on a timescale consistent with clause 7.h).

h. Spacecraft passivation (including propulsion system passivation, battery passivation, and the shut-down sequence) should occur once a spacecraft is no longer intended to be controlled or able to conduct active collision avoidance. 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 mission and completion of its active disposal maneuver.

ii. LEO spacecraft should be passivated as soon as practical, with the exception that if the operator is able to conduct reliable collision avoidance maneuvers for a period of up to five years following initiation of the deorbit and disposal phase, such collision avoidance should occur and passivation should be deferred until the spacecraft nears reentry or when 5 years have elapsed, whichever is sooner.

iii. As part of the passivation process, operators should place spacecraft into a final configuration that maximizes the average (uncontrolled) drag-facing cross-sectional area (in LEO) and minimizes solar array input after the spacecraft reaches it natural spin rate and attitude.

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

NOTE: IADC and ISO guidance is to passivate as soon as is practical. However, with shorter deorbit durations this is not necessarily the best practice.

i. Operators of LEO spacecraft that use chemical or electric propulsion to deorbit should complete the deorbit phase as soon as possible, but no more than 5 years after end-of-mission.

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

k. Spacecraft operators should seek to maintain current and 48h-predicted positional knowledge of their assets to within 500 m (two-sigma) in both LEO, MEO, and GEO regimes. This accuracy pertains to predicted ephemerides provided under Best Practice 2.e above. It is recognized that during orbital maneuvering periods, positional knowledge may be degraded.

NOTE: Achieving these accuracies will likely require regular, on-going calibration of the sensor network.

l. Spacecraft operators and Space Situational Awareness (SSA) systems should perform regular, on-going assessments of the realism of positional error (or covariance) characterizations for spacecraft. This should be done using one or more covariance realism tests as shown in [42]. Where covariance information is not realistic within a scale factor, operators and SSA service providers should account for these mischaracterizations by examining the variability on covariance realism to determine the distribution and peak collision risk for a given encounter.

8. Rules of the Road (RotR) and Maneuver Prioritization.

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

b. Spacecraft may fall into five maneuverability categories:

i. Nonmaneuverable: Total inability to effect flight safety-relevant orbital changes.

ii. Minimally Maneuverable Robotic: Only able to perturb one's orbit to a very small degree, e.g., using low duty cycle low-thrust maneuvers or differential drag perturbations.

iii. Manually maneuverable Robotic: Able to easily alter, on a short reaction time, the spacecraft course to mitigate the threat of collision.

iv. Automated collision avoidance (COLA) maneuvering capability (i.e., the decision to conduct an avoidance maneuver is made without human confirmation or intervention): In this case, operators should publish information with peer review on how the automation system works and coordinate with other operators (to include establishment of bilateral agreements) to ensure that maneuvers are properly taking place to effectively eliminate the risk.

v. Crewed (presumed maneuverable): A crewed spacecraft, able to alter their orbit to avoid collision.

c. The following general maneuver rules are suggested:

	Nonmaneuverable	Minimally Maneuverable	Maneuverable	Automated collision avoidance	Crewed
Nonmaneuverable	N/A	Minimally maneuverable S/C moves	Maneuverable S/C moves	Automated COLA S/C moves	Crewed vehicle moves
Minimally Maneuverable		Satellites moving into or out of their designated mission orbit should yield to satellites in their mission orbit. Otherwise, decided in bilateral discussion.	Maneuverable S/C Moves	Automated COLA S/C moves	Crewed vehicle moves, unless other arrangements are in place
Maneuverable			Satellites moving into or out of their designated mission orbit should yield to satellites in their mission orbit. Otherwise, (or in cases where both satellites are moving into or out of their mission orbits), decided in bilateral discussion.	Automated COLA S/C moves	Crewed vehicle moves, unless other arrangements are in place
Automated collision avoidance				Established via pre-coordinated agreement	Crewed vehicle moves, unless other arrangements are in place
Crewed					Bilateral discussion to determine who maneuvers.

d. Exceptions to the above RotR default assignments are:

i. Cases where the above is preempted by an established operator-to-operator bilateral (or multilateral) agreement between both (or all) parties.

ii. Cases where both spacecraft belong to the same operator and that operator chooses the opposite decision.

iii. Negotiated cases where other operational or resourcing considerations that may justify overriding RotR defaults.

e. Operators of non-crewed maneuverable spacecraft should give a wide berth to crewed vehicles whenever feasible and possible.

f. Operators of crewed vehicles should communicate their risk tolerance metrics and thresholds publicly.

g. During the period leading up to a mutually acknowledged high-risk conjunction between maneuverable non-crewed and crewed spacecraft, operators of the uncrewed spacecraft should only maneuver (a) if a prior agreement is in place (e.g., NASA/SpaceX agreement[§]) authorizing such a maneuver; or (b) when negotiated between both operators.

NOTE: Because human safety is of paramount importance, crewed spacecraft often prefer to ***"give way" (meaning to take evasive maneuvering action)***, preferring to retain the highest levels of support and control over threat mitigation scenarios.

h. In the presence of a high-risk conjunction between maneuverable non-crewed and crewed spacecraft, if after repeated attempts an operator is unable to establish contact with the other, that operator should execute an avoidance maneuver that satisfies the more stringent of (a) its own risk tolerance target levels, and (b) those of the other operator (when such levels are known).

i. Communication of status and avoidance actions: Operators should communicate their interpretation of RotR maneuver rules, their planned avoidance maneuvers, and notification of achieved maneuvers with all spacecraft operators of active spacecraft involved in the conjunction for all predicted close approaches, even if the other spacecraft is/are un-maneuverable or minimally maneuverable.

j. Close approach avoidance maneuver planning should be conducted for predicted encounters having an estimated probability of collision or miss distance thresholds specified in the following table, unless SSA product positional accuracy necessitates the use of more conservative (larger) keep out thresholds.

	GEO	**LEO**

§ "NONREIMBURSABLE SPACE ACT AGREEMENT BETWEEN THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION AND SPACE EXPLORATION TECHNOLOGIES CORP FOR FLIGHT SAFETY COORDINATION WITH NASA ASSETS", accessed 1 Sep 2022 at https://www.nasa.gov/sites/default/files/atoms/files/nasa-spacex_starlink_agreement_final.pdf

Screening threshold(s):	Pc > 1/10,000 or miss distance < 5 km	Pc > 1/10,000

k. Collision probability target should be reduced by a factor of at least 1.5 orders of magnitude upon completion of the maneuver, as recommended in [43] and [44] or a miss distance of 5 km for GEO.

9. Security to Prevent Unauthorized Access.

Spacecraft operators and designers should adhere to relevant international standards related to Information Technology and 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. Cybersecurity should be proactively integrated into spacecraft hardware, ground infrastructure, and operations, based upon sound systems engineering approaches and existing standards:

a. ISO 27001: Information technology - Security techniques - Information security management systems – Requirements.

b. CCSDS 352.0-B-2: Cryptographic Algorithms, and CCSDS 355.0-B-1: Space Data Link Security Protocol and associated NIST cybersecurity requirements for space systems[**] and U.S. Space Policy Directive-5[††]).

c. Where possible spacecraft should employ cyber protection functions through software and firmware update verification of cryptographic signatures using either hardware or software cryptographic solutions [45].

d. Spacecraft owners should consider employing Defense in Depth for more robust protection of space assets through multiple layers of security [45].

    i. Spacecraft developers should ensure the ground infrastructure is protected from cyber-attack and the Command-and-Control link is protected from spoofing, jamming, command replay, hardware backdoor commands.

    ii. Spacecraft should employ a robust intrusion detection system including continuous monitoring of telemetry, command sequences, command receiver status, shared bus traffic and flight software configurations and operating states [45], [46], [47].

    iii. Spacecraft communication buses that bridge critical and noncritical spacecraft systems should either be separated or explicitly protected using encryption, authentication, and anti-babble protection. [45], [48], [49], [50], [51].

[**] NISTIR 8270 (Draft), Introduction to Cybersecurity for Commercial Satellite Operations (2nd Draft), 25 Feb 2022, accessed at https://csrc.nist.gov/publications/detail/nistir/8270/draft

[††] Space Policy Directive–5, Cybersecurity Principles for Space Systems, 4 Sep 2020, accessed at https://www.govinfo.gov/content/pkg/FR-2020-09-10/pdf/2020-20150.pdf

References

[1] D.L. Oltrogge and S. Alfano, "Collision Risk in Low Earth Orbit," IAC-16,A6,2,1,x32763, 67th International Astronautical Congress, Guadalajara, Mexico, 26-30 September 2016.

[2] D.L. Oltrogge, S. Alfano, C. Law, A. Cacioni, T.S. Kelso, "A comprehensive assessment of collision likelihood in Geosynchronous Earth Orbit," Acta Astronautica (2018), doi:10.1016/j.actaastro.2018.03.017.

[3] Satellite-derived Time and Position: A Study of Critical Dependencies, Government Office for Science, www.gov.uk, 30 January 2018.

[4] D. J. Kessler and B. G Cour-Palais. Collision frequency of artificial satellites: The creation of a debris belt. Journal of Geophysical Research, page 2637–2646, 1978.

[5] Peterson, G.E., et al, "Implications of proposed small satellite constellations on space traffic management and Long-Term Debris Growth in Near-Earth Environment," IAC-16,A6,7,8,x32388, 67th International Astronautical Congress, Guadalajara, Mexico, 26-30 September 2016.

[6] IADC "Stability of the Future LEO Environment, IADC-12-08, Revision 1, January 2013, iadc-online.org

[7] Bastida Virgili, B., et al, "Mega-constellations, small satellites and their impact on the space debris environment," IAC-16,A6.2,4,x34551, 67th International Astronautical Congress, Guadalajara, Mexico, 26-30 September 2016.

[8] "Space Debris Situation Report" by the International Academy of Astronautics Space Debris Committee (IAASDC), freely downloadable as https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/sg514finalreport.pdf.

[9] IADC "Report on the IADC activities in particular with regard to the IADC Mitigation Guidelines," 39th Session of the Scientific and Technical Subcommittee, United Nations' Committee on the Peaceful Uses of Outer Space, Vienna, 25 February – 8 March 2002.

[10] IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, September 2007, https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf.

[11] IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 3, 23 June 2021, https://iadc-home.org/documents_public/view/id/172.

[12] IADC-15-03, IADC Statement on Large Constellations in Low Earth Orbit", issued in September 2017, downloadable from the IADC website https://www.iadc-home.org/documents_public/view/id/174

[13] Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, A/RES/62/217, 2007, available at http://www.unoosa.org/pdf/publications/st_space_49E.pdf.

[14] International Standards Organisation. Space Systems - Space Debris Mitigation, ISO TC 20/SC 14 N 24113, 2019.

[15] ISO 27852: "Space systems — Estimation of orbit lifetime," available at https://www.iso.org/committee/46614/x/catalogue/ .

[16] ISO 16126: "Space systems — Assessment of survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful post-mission disposal," available at https://www.iso.org/committee/46614/x/catalogue/ .

[17] ISO 16127: "Space systems — Prevention of break-up of unmanned spacecraft," available at https://www.iso.org/committee/46614/x/catalogue/ .

[18] ISO 20893: "Space systems — Detailed space debris mitigation requirements for launch vehicle orbital stages," available at https://www.iso.org/committee/46614/x/catalogue/.

[19] ISO 23312: "Space systems — Detailed space debris mitigation requirements for spacecraft," available at https://www.iso.org/committee/46614/x/catalogue/ .
[20] Official web site of the Consultative Committee for Space Data Systems, https://public.ccsds.org/default.aspx.
[21] Compendium of space debris mitigation standards adopted by States and international organizations, http://www.unoosa.org/oosa/en/ourwork/topics/space-debris/compendium.html.
[22] "Support to the IADC Space Debris Mitigation Guidelines," IADC-04-06, Revision 5.8, June 2021, https://www.iadc-home.org/documents_public/view/id/173.
[23] ISO 11227: "Space systems — Test procedures to evaluate spacecraft material ejecta upon hypervelocity impact," available at https://www.iso.org/committee/46614/x/catalogue/ .
[24] ISO 10786: "Space Systems — Structural components and assemblies," available at https://www.iso.org/committee/46614/x/catalogue/ .
[25] ISO 14302: "Space systems — Electromagnetic compatibility requirements," available at https://www.iso.org/committee/46614/x/catalogue/ .
[26] ISO 14622: "Space systems — Structural design — Loads and induced environment," available at https://www.iso.org/committee/46614/x/catalogue/ .
[27] ISO 14623: "Space systems — Pressure vessels and pressurized structures — Design and operation," available at https://www.iso.org/committee/46614/x/catalogue/ .
[28] ISO 15864: "Space systems — General test methods for spacecraft, subsystems, and units," available at https://www.iso.org/committee/46614/x/catalogue/ .
[29] ISO 16454: "Space systems — Structural design — Stress analysis requirements," available at https://www.iso.org/committee/46614/x/catalogue/ .
[30] ISO 16781: "Space systems — Simulation requirements for control system," available at https://www.iso.org/committee/46614/x/catalogue/ .
[31] ISO 17566: "Space systems — General test documentation," available at https://www.iso.org/committee/46614/x/catalogue/ .
[32] ISO 19683: "Space systems — Design qualification and acceptance tests of small spacecraft and units," available at https://www.iso.org/committee/46614/x/catalogue/ .
[33] ISO 19924: "Space systems — Acoustic testing," available at https://www.iso.org/committee/46614/x/catalogue/ .
[34] ISO 19933: "Space systems — Format for spacecraft launch environmental test report," available at https://www.iso.org/committee/46614/x/catalogue/ .
[35] ISO 21648: "Space systems — Flywheel module design and test," available at https://www.iso.org/committee/46614/x/catalogue/ .
[36] ISO 23038: "Space systems — Space solar cells — Electron and proton irradiation test methods," available at https://www.iso.org/committee/46614/x/catalogue/ .
[37] ISO 24637: "Space systems — Electromagnetic interference (EMI) test reporting requirements," available at https://www.iso.org/committee/46614/x/catalogue/ .
[38] ISO 24638: "Space systems — Pressure components and pressure system integration," available at https://www.iso.org/committee/46614/x/catalogue/ .
[39] ISO 26871: "Space systems — Explosive systems and devices," available at https://www.iso.org/committee/46614/x/catalogue/ .
[40] NASA General Environmental Verification Standard, available at https://standards.nasa.gov/standard/gsfc/gsfc-std-7000
[41] NASA-STD-7002B, "Payload Test Requirements," available at https://standards.nasa.gov/sites/default/files/standards/NASA/B/0/nasa-std-7002b.pdf.
[42] Oltrogge, D.L., Wauthier, P., Vallado, D.V., Alfano, S., and Kelso, T.S., "Results Of Comprehensive STCM Data Fusion Experiment," Proc. 8th European Conference on Space

Debris (virtual), Darmstadt, Germany, 20-23 April 2021, https://conference.sdo.esoc.esa.int/proceedings/sdc8/paper/263/SDC8-paper263.pdf (accessed 30 September 2021).
[43] NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook, accessed 5 Aug 2022 at https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf.
[44] Hall, D.T. 2019a. “Determining Appropriate Risk Remediation Thresholds from Empirical Conjunction Data using Survival Probability Methods.” 2019 AAS Astrodynamics Specialist Conference (Paper #19-631), Portland ME, August 2019.
[45] Brandon Bailey, Ryan J. Speelman, et al, “Defending Spacecraft in the Cyber Domain,” Aerospace Corporation Center for Space Policy and Strategy article, November 2019, https://csps.aerospace.org/papers/defending-spacecraft-cyber-domain
[46] Martin, Jon; Satellite Telemetry Indicators for Identifying Potential Cyber Attacks, Aerospace TOR-2019-02178, The Aerospace Corporation, El Segundo, California (August 16, 2019). Approved for Public Release, Distribution Unlimited.
[47] Scarfone, K; Mell, P; Guide to Intrusion Detection and Prevention Systems, February 2007, page 2-4, https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-94.pdf.
[48] Holzmann, G; The Power of Ten – Rules for Developing Safety Critical Code, June 2006, http://spinroot.com/gerard/pdf/P10.pdf.
[49] “SEI CERT Coding Standards,” Software Engineering Institute, last modified February 5, 2019, https://wiki.sei.cmu.edu/confluence/display/seccode.
[50] Center for Assured Software National Security Agency; CAS Static Analysis Tool Study – Methodology, December 2011, page 24, https://samate.nist.gov/docs/CAS_2011_SA_Tool_Method.pdf.
[51] Glaessgen, E; Stargel, D; The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles April 2012, page 1-2, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120008178.pdf.

Glossary

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

access control
the process of granting or denying specific requests: 1) for obtaining and using information and related information processing services; and 2) to enter specific physical facilities (e.g., Federal buildings, military establishments, and border crossing entrances). Source: FIPS PUB 201-1 (adapted).

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).

authentication
1. Verifying the identity of a user, process, or device, often as a prerequisite to allowing access to resources in an information system. Source: FIPS PUB 200; NIST SP 800-27 Rev A.

2. A security measure designed to protect a communications system against acceptance of fraudulent transmission or simulation by establishing the validity of a transmission, message, originator, or a means of verifying an individual's eligibility to receive specific categories of information. Source: CNSSI No. 4005 (COMSEC); NSA/CSS Manual Number 3-16 (COMSEC).

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

casualty
person who is killed or seriously injured.

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

collision risk
Collision risk is the product of the likelihood and consequence of space object collision, either for a single close approach event, or in total (aggregated over multiple close approach events).
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).

cryptography
1. Art or science concerning the principles, means, and methods for rendering plain information unintelligible and for restoring encrypted information to intelligible form. Source: NSA/CSS Manual Number 3-16 (COMSEC).

2. The discipline that embodies the principles, means, and methods for the transformation of data to hide their semantic content, prevent their unauthorized use, or prevent their undetected modification. Source: NIST SP 800-59.

3. The discipline that embodies the principles, means, and methods for the providing information security, including confidentiality, data integrity, non-repudiation, and authenticity. Source: NIST SP 800-21 2nd edition.

cybersecurity
prevention of damage to, protection of, and restoration of computers, electronic communications systems, electronic communications services, wire communication, and electronic communication, including information contained therein, to ensure its availability, integrity, authentication, confidentiality, and nonrepudiation. Source: NSPD-54/HSPD-23.

defense in depth
information security strategy integrating people, technology, and operations capabilities to establish variable barriers across multiple layers and missions of the organization. Source: NIST SP 800-53 Rev 4.

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 successful 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.

give way
A spacecraft that "gives way" takes evasive maneuvering action to avoid another space object.

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

intrusion detection system
software that automates the intrusion detection process. Source: NIST SP 800-94.

intrusion prevention system
software that has all the capabilities of an intrusion detection system and can also attempt to stop possible incidents. Source: NIST SP 800-94.

Large Constellation
A single constellation or system of constellations containing from several hundreds to thousands or more spacecraft.

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.

Long-Term Sustainability (LTS)
Long-Term Sustainability (LTS) is "the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations."

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, unfired [or unused] pyro 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.

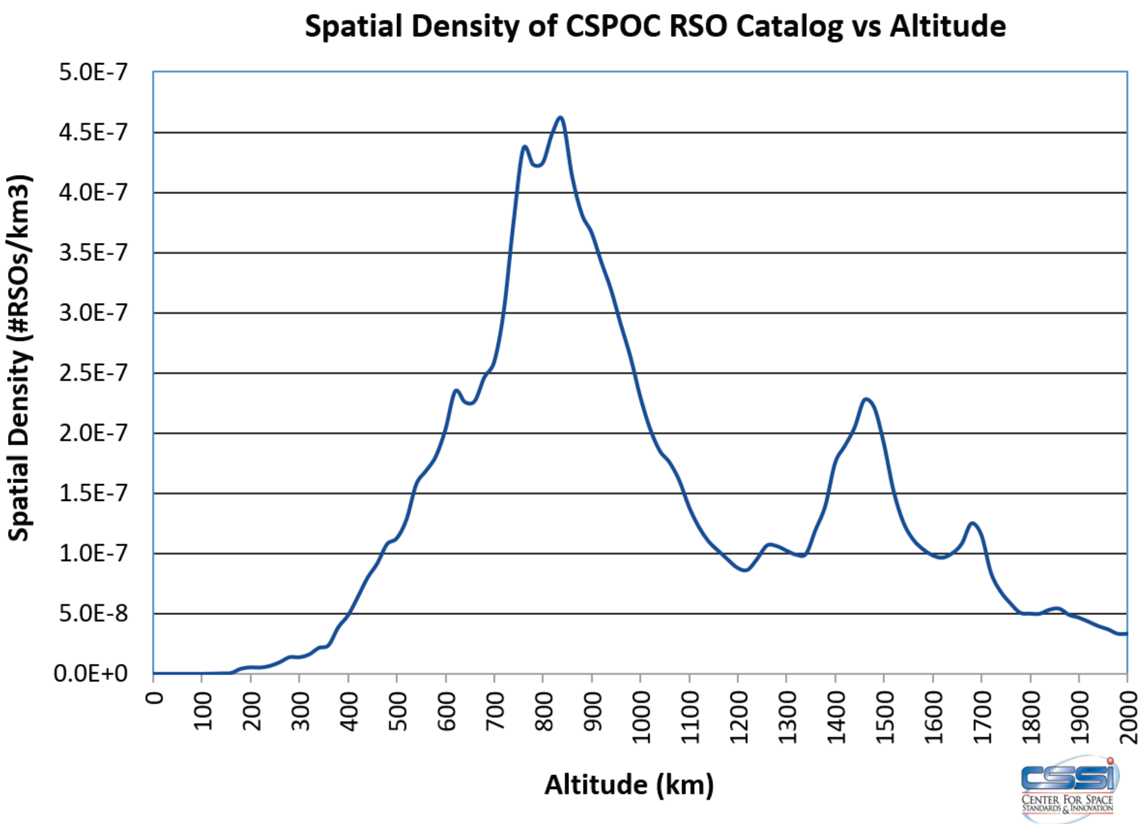
propulsion
the action of driving or pushing forward.

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.

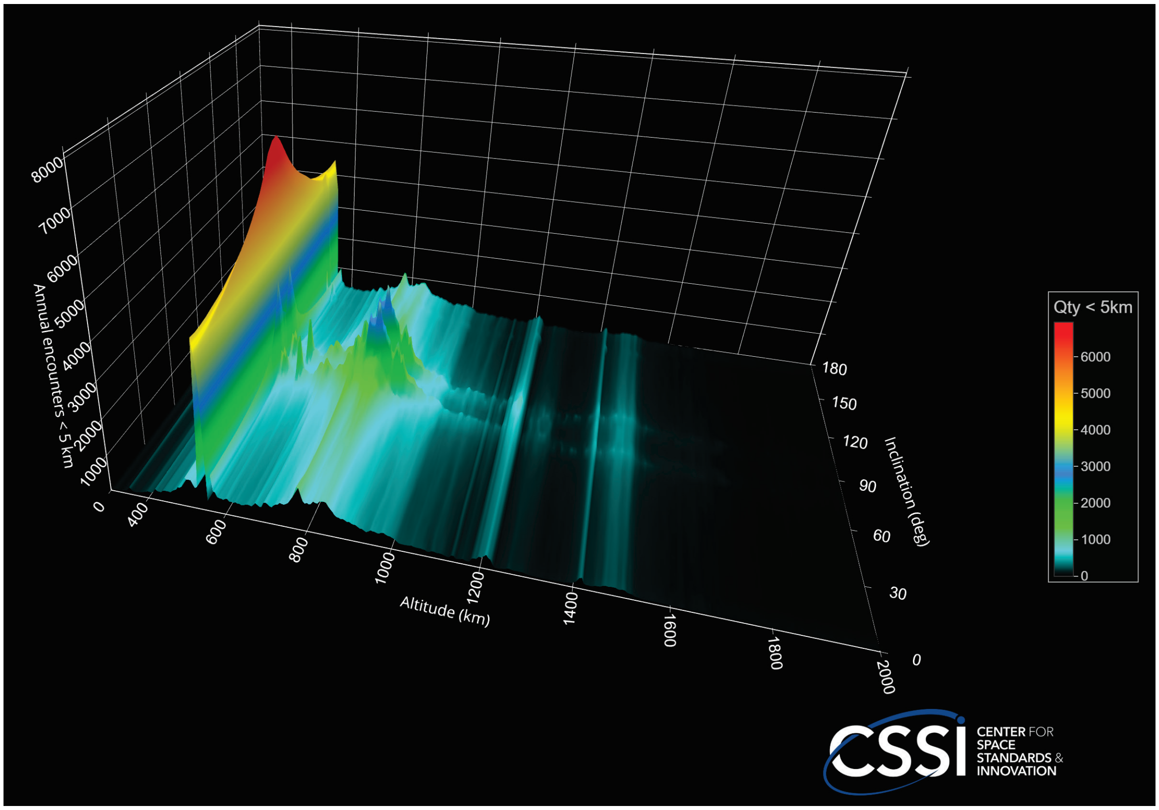
protoflight
As defined by NASA Technical Standard NASA-STD-7002B [41], protoflight refers to flight hardware of a new design which is subject to a qualification test program that combines elements of prototype and flight acceptance verification. A protoflight payload is built, serves to qualify the design 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 1 July, 2022, respectively).



SPACE SAFETY COALITION



Rate of annual close approach encounters between a newly-introduced satellite and the Jan 2023 public tracked space catalog.

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

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

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

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

Space Domain Awareness (SDA)
Space Domain Awareness (SDA) is the effective identification, characterization, and understanding of any factor, passive or active, associated with the space domain (the area surrounding the Earth at altitudes equal to, or greater than, 100 km) that could affect

space operations and thereby impact the security, safety, economy, or environment of a nation.

Space Environment Preservation (SEP)
Space Environment Preservation (SEP) is the activity of preserving and sustaining the space operations environment, accomplished by space debris mitigation (adherence to post-mission lifetime and disposal guidelines and rules, prevention of release of mission-related debris, and collision avoidance) and remediation (derelict object removal, relocation, and collision prevention).

Space Situational Awareness (SSA)
Space Situational Awareness (SSA) is "the understanding, knowledge, characterization, and maintained awareness of the space environment: artificial space objects, including spacecraft, rocket bodies, mission-related objects and fragments; natural objects such as asteroids (including Near Earth Objects or NEOs), comets and meteoroids, effects from space weather, including solar activity and radiation; and potential risks to persons and property in space, on the ground and in air space, due to accidental or intentional re-entries, on-orbit explosions and release events, on-orbit collisions, radio frequency interference, and occurrences that could disrupt missions and services."

Space Surveillance and Tracking (SST) is "the detection, tracking, monitoring, cataloguing and prediction of the movement of space objects, and the identification and alerting of derived risks. It is comprised of the operation of ground-based or space-based sensors (radar, optical, passive RF) to survey, track and catalogue space objects, and the processing and analysis of orbital data to provide information and services such conjunction analysis, analysis of space object re-entries and analysis of space object fragmentations."

Space Traffic Coordination (STC)
Space Traffic Coordination (STC) is the cooperative planning, coordination, data and information sharing, and on-orbit synchronization of space activities.

Space Traffic Management (STM)
Space Traffic Management (STM) is the assurance value chain that contributes to a safe and sustainable space operations environment, composed of Space Traffic Coordination (STC) and Regulation & Licensing, and dependent upon a foundation of continuous Space Situational Awareness (SSA).

supply chain
a system of organizations, people, activities, information, and resources, possibly international in scope, that provides products or services to consumers. (CNSSI No. 4009 Glossary April 6, 2015).

threat
any circumstance or event with the potential to adversely impact organizational operations (including mission, functions, image, or reputation), organizational assets, individuals, other organizations, or the Nation through an information system via

unauthorized access, destruction, disclosure, modification of information, and/or denial of service. Source: NIST SP 800-30 Rev 1.

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

vulnerability
weakness in an information system, system security procedures, internal controls, or implementation that could be exploited by a threat source.
Source: NIST SP 800-30 Rev 1.

18SDS
The United States Space Force 18th Space Defense Squadron, formerly known as 18th Space Control Squadron (18SPCS).