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Space systems — Design, testing and operation of a large constellation of spacecraft

Systèmes spatiaux — Conception, essais et manœuvre d'une grande constellation d'engins spatiaux

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Foreword

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

More than a dozen large constellations of spacecraft are planned to be launched in the next several years. While large constellations can provide societal benefits to humanity, they can also put pressure on the orbital and electro-magnetic environments, introducing mission design, hardware design, launch, operations and disposal challenges to other operating space assets and the long-term sustainability of space activities.

This document provides a set of standard practices throughout the large constellation life cycle to promote safety on the ground from re-entry hazard and long-term sustainability of space operations.

In developing this document, the practices of the existing large constellation programs, consensus in the Space Safety Coalition, "Best Practices for the Sustainability of Space Operations,"[1], the "Statement on Large Constellations"[2] of the "Inter-Agency Space Debris Coordination Committee (IADC)", ISO 24113, which specifies space debris mitigation requirements, the "Guidelines for the Long-term Sustainability of Outer Space Activities" COPUOOS June 2021[3] and other effective documents were consulted.

Space systems — Design, testing and operation of a large constellation of spacecraft

1 Scope

This document provides requirements that are either unique or particularly relevant to large constellations of spacecraft operating in the LEO protected region throughout their life cycle, including planning, designing, testing, operating and disposal activities.

The requirements in this document are applicable to large constellation owners. While some are directly applicable to the constellation owners, others are allocated to the manufactures or operators under the responsibility of the constellation owners.

2 Normative reference

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19389[1)], *Space data and information transfer systems — Conjunction data message*

ISO 24113, *Space systems — Space debris mitigation requirements*

ISO 26900[2)], *Space data and information transfer systems — Orbit data messages*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
large constellation of spacecraft
large constellation
system of a hundred or more spacecraft working together

Note 1 to entry: While providing a specific quantity of spacecraft, the size, mass, complexity and function of the spacecraft also have a bearing.

3.2
latitude range
band of geocentric latitude that spacecraft in two constellations may simultaneously occupy

3.3
radial separation
distance between constellation orbits in the radial direction within a common *latitude range* (3.2), irrespective of right ascension of ascending node and timing (nodal regression and in-track motion)

1) Adoption from CCSDS 508.0-B-1.

2) Adoption from CCSDS 502.0-B-2.

4 Abbreviated terms

CCSDS Consultative Committee for Space Data System

DoA dead-on-arrival

ITU International Telecommunication Union

LED light emitting diode

LEO low Earth orbit

RCS reaction control system

RFI radio frequency interference

SSA space situational awareness

5 Requirements

5.1 Mission design

5.1.1 Orbit selection of constellation and maintenance to minimise collision risk

5.1.1.1 Selection of orbit of constellation considering collision risk

The orbit of constellation shall be selected to minimise the probability of collision with other space objects.

5.1.1.2 Selection of orbit of constellation considering collision risk with neighbouring constellations

The constellations shall be designed and operated to avoid interaction with neighbouring large constellations to assure safe operations under both nominal and anomalous vehicle operating conditions.

NOTE Maintaining an adequate radial separation from other large constellations is an effective way to minimize collision risk.

5.1.2 Intra-constellation collision avoidance

5.1.2.1 Allocation of orbit of member spacecraft to minimise collision risk

Constellations shall be configured to mitigate collision risk between constellation spacecraft according to the threshold defined by approving agent.

5.1.2.2 Allocation of orbit considering the contingencies

Constellations shall be configured such that constituent failures do not significantly elevate intra-constellation collision risk (e.g. by separating the orbit planes and radial profiles to avoid intersection points).

5.1.2.3 Orbit control of spacecraft during operation

Spacecraft insertion, operational and disposal orbits shall be chosen considering collision risk and post-mission orbital lifetime, commensurate with mission objectives and constraints.

5.1.3 Space debris mitigation

A large constellation shall satisfy the space debris mitigation requirements in ISO 24113, except where stricter versions of the requirements are specified elsewhere in this document.

5.1.4 Selection of launch service providers

The launch service provider shall be selected from those that conform to the space debris mitigation requirements in ISO 24113.

5.1.5 Assessment on the long-term evolution of debris environment

When planning to apply a large constellation, an assessment of the aggregate risk to space operations sustainability posed by the mission and constellation design, the individual spacecraft design, operations, and launch services shall be made and approved by the responsible authority.

NOTE 1 Commonly used metrics include risks placed on other operators, expected levels of space debris, likelihood of triggering a Kessler syndrome, etc.

NOTE 2 Such a risk assessment can identify increased levels for post-mission success rate and/or reduced disposal lifetime as described in 5.2 for constellation members and associated launch services.

5.2 Spacecraft design

5.2.1 Reliability design

5.2.1.1 General

Large constellation spacecraft designs shall safeguard against deployment of DoA spacecraft, unintentional termination of operation, accidental break-ups including due to collision, failure to conduct proper disposal actions conforming to requirements in 5.2.

NOTE 1 For details of a rigorous qualification and testing program, see 5.3, which mentions that all relevant components are examined in the testing program given the mass production of constellation spacecraft.

NOTE 2 For details for the collision avoidance, see 5.4.2.

NOTE 3 For information on a proper disposal, see 5.5.

5.2.1.2 Availability of components and materials that have a limit for useful life

5.2.1.2.1 General

Any components and materials whose useful life (including “operation life” and “storage life”) is limited shall be designed or selected to assure the design life. If the operation is expected to be extended beyond the design life, they shall satisfy the planned extended life.

5.2.1.2.2 Operation time limited items

For components essential for the disposal function which have limited operation time or cycles and whose remaining usable service life is uncertain, an operations log shall be developed and procedurally maintained to enable analysts to assess the component’s residual life to ensure successful post-mission disposal prior to component failure.

5.2.1.2.3 Storage life limited items

If the mission’s operational period is extended, the total operation period shall not exceed the “storage life” of any components used for disposal.

5.2.1.3 Critical components in new flight application

All components that are essential for the disposal function (including those required for maintaining spacecraft control and performing active collision avoidance and de-orbiting) shall have either been demonstrated on-orbit, or pass a rigorous testing regimen as specified in 5.3.2.

5.2.1.4 Design for post-mission orbital lifetime

a) Besides the requirement of ISO 24113, the post-mission orbital lifetime of large constellation spacecraft shall be controlled to be within the same duration as the spacecraft was designed to be operational, up to a maximum of five years.

   EXAMPLE If the mission lifetime is 4 years, then the spacecraft is brought down within 4 years after its decommissioning.

b) When disposed to a circular orbit, the selected disposal altitudes should be selected in a manner that avoids creating highly crowded orbit altitudes.

c) When disposing into an eccentric orbit, the disposal apogee should be placed below the constellation's lowest operational orbit radius at the epoch of disposal; and the perigee should be selected to avoid highly crowded orbits.

5.2.1.5 Predicted probability of successful disposal

In the design phase (prior to constellation launch and deployment), large constellation spacecraft shall be designed, configured, and operated to maximize the probability of successful disposal to be greater than 95 % with a goal of 100 %. Assessment of the probability of successful disposal shall apply at least until the end of the disposal manoeuvre. The time period during the passive decay until the end of passivation, when conjunction assessment is continued according to 5.5.4 b), can be excluded from the assessment of the probability of successful disposal on the condition that passivation can be immediately conducted when the symptom of failure is detected.

It is attained with following:

a) allocation and sequestering of propellants for planned disposal manoeuvre(s);

b) reliabilities are assured by the measures defined by the approval agent preferably including the reliability of the disposal function based on the failure rate, the single point failures in the electrical and electronic devices, the limitation of operation / storage life, etc.;

c) in the calculation of reliability, use of reliable electrical and electronic components and circuit design relating to the disposal function drawing upon the latest component failure rate and anomaly data as mandated by the responsible authority;

d) design and operational procedures to ensure that components are used within their designed operational lifetime, accompanied by procedures to identify when components are exhibiting characteristics of degradation, fatigue or imminent failure (see 5.2.1.2);

e) system design to facilitate continuous monitoring of all critical components to assess the health and readiness for proper disposal, etc. (see 5.4.1);

NOTE 1 The probability of successful disposal is required to be 0,9 in ISO 24113, but in the case of a large constellation, such a requirement would allow 10 % of large constellation spacecraft to not be properly disposed, greatly increasing collision risk in an important orbital region. Improvements to design and operating procedures can contribute to meeting the goal of higher probability of successful disposal of at least 0,95.

NOTE 2 The probability of successful disposal can be calculated using system and component reliability data provided by the manufacturers, and also considering previous on-orbit use of the same systems and components.

5.2.2 Design to support collision avoidance

5.2.2.1 Spacecraft manoeuvrability for collision avoidance

Large constellation spacecraft shall have a collision avoidance capability and implement an operational process to effectively avoid collisions.

5.2.2.2 Trackability

Spacecraft shall be independently trackable and readily identifiable by non-extraordinary means (e.g. beacons, corner reflectors, LED emitters, RCS augmentation), independent of operator intervention.

NOTE Trackability enhancements and augmentation (e.g. by adding onboard active and/or passive components) are encouraged.

5.2.3 Space debris mitigation design

Considering the cumulative effect of the large number of spacecraft involved in a large constellation, the debris mitigation design requirements in ISO 24113 shall be applied.

5.2.4 Design to support successful disposal

5.2.4.1 Automated spacecraft disposal

As a contingency plan for the malfunction of disposal functions, an autonomous spacecraft disposal sequence can be incorporated and initiated in the event of clear indication of an unexplained, mission-threatening loss of control, ability to charge batteries, or contact for more than a predefined time period appropriate for the spacecraft.

5.2.4.2 Active debris removal by design

As a contingency plan for the malfunction of disposal functions, active removal operations can be incorporated.

NOTE These design features can also facilitate on-orbit servicing.

5.2.5 Safe re-entry

Deorbited and re-entering objects shall not pose a significant threat to people, property, or the environment, aggregated over the entire constellation, commensurate with the safety thresholds set by the approving agent considering that the world space fairing nations take the threshold for the expected number of casualties per spacecraft to be less than 0,000 1.

NOTE The quantity of spacecraft in a large constellation and associated high numbers of ground impacts dictate that large constellation spacecraft are disposed by controlled re-entry/demise in line with thresholds set by the approving agent.

5.2.6 Large constellation radio frequency interference mitigation

Large constellation spacecraft shall be designed in a manner that limits the potential for RFI between themselves and other spacecraft. It is presupposed that ITU regulations and filings are observed.

5.2.7 Large constellation minimization of disruptive visual brightness

Large constellation designers shall seek to control the apparent magnitude of their spacecraft, during both the checkout and operations phases, to limit disruptions to the astronomy and naked-eye observing communities.

NOTE 1 Objects up to about apparent magnitude 6 are visible to the naked eye. An existing constellation owner strives to achieve an apparent magnitude of 7 or dimmer.

NOTE 2 The impact on astronomy can be minimized by design, using mechanisms (e.g. deployable visors), vehicle orientations, shutters, and/or operating characteristics to reduce the overall reflectivity of the spacecraft. The necessity of such techniques depends on orbit altitude, reflectance of surface components, overall surface area, and flight attitude rules.

5.3 Qualification and testing

5.3.1 Verification and validation based upon established standards and procedures

The design and production procedures for the components, sub-systems and spacecraft shall be verified through qualification testing, analysis, demonstration, or similarity, and validated through acceptance testing, demonstration, or inspection, based upon established test standards and procedures (including, for example, ISO 15864[4], ISO 19683[5], and other equivalent authorized standards[6]-[22]), without skipping any process even where a manufacturing qualification classification system may allow tailoring of tests or analysis.

NOTE While there is a natural tendency to prioritize and classify the types of testing according to the relative importance to mission success, the space debris mitigation function of a spacecraft of the large constellation is thoroughly tested because potential defects or system flaws can cause large adverse effects on the orbital environment.

5.3.2 Test and checkout before to injecting into the planned orbit

Large constellation spacecraft shall be deployed into a checkout orbit with a natural orbit lifetime shorter than 5 years to confirm the spacecraft is free of initial defects prior to orbit raising to the operational orbit.

NOTE This is particularly critical when launching spacecraft or utilizing components are based upon a new design.

5.4 Operations and collision avoidance

5.4.1 Quality and reliability control during operation

5.4.1.1 Monitoring for anomalous conditions

Operators shall monitor the state-of-health of their large constellation spacecraft for anomalous conditions or trends that can lead to fragmentation or loss of disposal capability.

5.4.1.2 Anomaly root cause investigation

Throughout the mission phase, any orbital transfer phase(s), and until collision avoidance manoeuvres are no longer practical, if a spacecraft failure or anomaly occurs, a root cause investigation shall be conducted to determine whether such failures are endemic to the design such that conformity with space debris mitigation requirements cannot be met. If so, then further launches of large constellation satellites shall be suspended until corrective and preventive measures are successfully implemented.

5.4.1.3 Monitoring the consequence of disposal

To assure the complete and successful disposal of large constellation spacecraft, large constellation owners and operators of any on-orbit servicing or active debris removal systems relevant to the operation or disposal of the satellite shall gather, maintain, and regularly review statistical data on the probability and success

rate of disposal for conformity with 5.2.1.5. Spacecraft design and operational process improvements shall be taken to address deficiencies in disposal success.

5.4.1.4 Cyber security

5.4.1.4.1 Cyber-security measures

Operators shall employ cyber-security measures in both their ground and space systems, including encryption and authentication in spacecraft command links.

5.4.1.4.2 Cryptographic standards and measures

It is strongly recommended to employ agile, software-based cryptographic standards and measures that can be responsive to evolving hacking technologies and threats.

5.4.2 Conjunction assessment and collision avoidance

5.4.2.1 Accuracy of positional knowledge

To perform collision avoidance operations, operators shall maintain sufficiently accurate predictive positional knowledge of their assets to support the collision avoidance manoeuvre go/no-go criteria as selected by the responsible authority.

NOTE Required accuracy is a function of the go/no-go criteria, orbit regime and responsible authority mandates. As an example, research[23] has identified that to operationally use a collision probability threshold of one in ten thousand as a go/no-go criteria, a two-sigma accuracy of between 48 m (LEO) and 234 m (GEO) over the prediction period can be required.

5.4.2.2 Data exchange

5.4.2.2.1 Space data exchange

Flight path predictions, manoeuvre plans and spacecraft attitude and characteristics shall be exchanged with other operators for conjunction management, re-entry management, and long-term sustainability purposes.

Such attitude, orbit, re-entry, conjunction, data shall be exchanged using ISO 26900, ISO 19389 and other standards related to data exchange, drawing upon keywords and definitions posted at https://sanaregistry.org/.

5.4.2.2.2 Space operator contact information/phonebook

Operators shall register contact information for their spacecraft operations centres to the SSA service provider or publish it.

5.4.2.2.3 Prompt response to space data exchange request

In the case of an urgent request or emergency (as identified by the notification agent), a response time of less than an hour shall be maintained, either by human operators or by an automated system. Such a response can consist of an acknowledgement of message receipt and confirmation that a response is being formulated.

5.4.2.3 Collision avoidance manoeuvres

Operators shall be capable of performing timely and effective collision avoidance manoeuvres throughout the mission phase and until collision avoidance manoeuvres are no longer practical in the disposal phase, based on predefined operational procedures that reduce collision probabilities below the responsible authority's mandated threshold.

5.4.2.4 Inter-operator coordination to resolve collision risk

Mitigation of conjunctions involving two active spacecraft shall be coordinated between the two operators and resolved with a mutually agreeable course of action or inaction.

5.4.2.5 Intra-constellation collision risk mitigation

Large constellation operators shall mitigate collision risk among their own spacecraft in the constellation.

5.4.2.6 Autonomous collision avoidance process

Large constellation designers and operators should consider incorporating autonomous collision avoidance capabilities to reduce operator workload and collision threats.

5.4.3 Large constellation Radio frequency interference mitigating operation

Large constellation spacecraft shall be operated in a manner that limits the potential for RFI between themselves and other spacecraft. It is presupposed that ITU regulations and filings are observed.

5.4.4 Large constellation operation to minimise disruptive visual brightness

Large constellation operators shall seek to minimise visual brightness of their spacecraft, both during the checkout and operations phases, to limit disruptions to the astronomy and naked-eye observing communities (see 5.2.7, NOTEs 1 and 2).

5.5 Disposal of spacecraft

5.5.1 Post-mission disposal

Spacecraft shall be disposed of upon mission completion generally in accordance with ISO 24113 with the exception that the post mission orbital lifetime is defined in 5.2.1.4, and safe re-entry defined in 5.2.5.

5.5.2 Criteria for initiating disposal

Specific criteria for initiating the disposal of large constellation spacecraft shall be developed, evaluated during the mission and, if met, consequent actions executed.

5.5.3 Determination of mission extension or termination

The owner shall establish and conduct a procedure for the determination of mission extension or termination (see a model in ISO/TR 18146[24]) which includes the assessment of the criteria for mission termination (defined in 5.5.2) and the probability of successful disposal.

NOTE The procedure prevents operations beyond the ability of spacecraft hardware or resources, to comply with the threshold for mission termination (to preclude sudden death during operation, etc.).

5.5.4 Disposal upon decommissioning

a) Once decommissioned, according to the disposal plan, spacecraft shall transfer to a disposal orbit while avoiding collisions with other space objects.

b) The spacecraft of the large constellation shall continue conducting collision avoidance operation even after the disposal manoeuvre as late as technically feasible toward the re-entry (i.e. less than 5 years).

NOTE 1 Technical feasibility of collision avoidance in low altitude depends on the trackability from the ground, or limit of function of on-board command and communication devices, etc.