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Space systems — Space debris mitigation design and operation manual for spacecraft

Systèmes spatiaux — Conception de réduction des débris spatiaux et manuel d'utilisation pour les engins spatiaux

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the second edition (ISO/TR 18146:2015), which has been technically revised.

The main changes compared to the previous edition are as follows:

— text has been updated to be aligned with ISO 24113:2019[1];

— information has been added that the ejection of slag debris from solid rocket motors is limited newly in low Earth orbit in addition to GEO previously;

— information relating to collision avoidance against catalogued space objects has been improved;

— information of the intention of the new requirement avoiding fragmentation caused by impact of space debris and meteoroid, and typical assessment procedure in the world space agencies has been added;

— corresponding to the new requirement limiting the total probability of successful disposal to be at least 0,9, the state of the art to confirm the compliance with that taken in the world space industries and national agencies has been added;

— other information relating to the changes in ISO 24113 has been added.

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

Coping with debris is essential to preventing the deterioration of the orbital environment and ensuring the sustainability of space activities. Effective actions are also taken to ensure the safety of those on the ground from re-entering objects that were disposed of from low-Earth orbit.

Recently, the orbital environment has become so deteriorated by debris that action is taken to prevent damage due to the impact. Collision avoidance manoeuvres are taken to avoid large debris (larger than 10 cm, for example), which can be observed from the ground. Spacecraft design protects against micro-debris (even smaller than 1 mm) that can cause critical damage to vulnerable components.

ISO 24113:2019[1] and other ISO documents, introduced in Bibliography, were developed to encourage debris mitigation activities.

In Clause 5, the major space debris mitigation requirements are informed.

In Clause 6, the information of life-cycle implementation of space debris mitigation related activities is provided.

In Clause 7, the system level aspects stemming from the space debris mitigation requirements are highlighted; while in Clause 8, the impacts at subsystem and component levels are detailed.

This document provides comprehensive information on what ISO requires to do for the design and operation of the launch vehicles, and where such requirements and recommendations are registered in a set of ISO documents.

Space systems — Space debris mitigation design and operation manual for spacecraft

1 Scope

This document contains information on the design and operational practices for launch vehicle orbital stages for mitigating space debris.

This document provides information to engineers on what are required or recommended in the family of space debris mitigation standards to reduce the growth of space debris by ensuring that spacecraft is designed, operated, and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime.

2 Normative reference

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

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

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

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

4 Symbols and abbreviated terms

A/M	area-to-mass
AOCS	attitude and orbit control system
CDR	critical design review
CFRP	carbon-fibre-reinforced plastic
CNES	Centre National d'Etudes Spatiales
CSpOC	Combined Space Operations Center (USA)
DAS	debris assessment software (NASA)
COTS	commercial off-the-shelf
DRAMA	debris risk assessment and mitigation analysis (ESA)
EOMDP	end-of-mission (operation) disposal plan
ESA	European Space Agency
FDIR	failure detection, isolation and recovery

FMEA	failure mode and effect analysis
GEO	geosynchronous Earth orbit
GPSR	global positioning system receiver
IADC	Inter-Agency Space Debris Coordination Committee
IRU	inertial reference unit
LEO	low Earth orbit
MASTER	meteoroid and space debris terrestrial environment reference
MIDAS	MASTER (-based) impact flux and damage assessment software
NOTAM	notice to airmen and notice to mariners
OLI	operation time limited item
ORDEM	orbital debris engineering model
PDR	preliminary design review
PNF	probability of no failures
QA	quality assurance
QR	qualification review
RCS	reaction control system
SDA	Space Data Association
SDR	system definition review
SDMP	space-debris-mitigation plan
STELA	semi-analytic tool for end of life analysis (CNES)
USSTRATCOM	United States strategic command
TLE	two-line element set
TT&C	telemetry tracking and command
UN	United Nations

5 System-level activities

5.1 General

To accomplish comprehensive activities for debris mitigation and protection work, the following steps are considered:

a) Identify debris-related requirements, recommendations and best practices.

b) Determine how to comply with these requirements, recommendations, and best practices.

c) Apply those methods early and throughout development and manufacturing to ensure sound debris mitigation capability in the final product.

d) Apply appropriate quality assurance and qualification program to ensure compliance with debris mitigation requirements

e) Apply appropriate procedures during operation/utilisation and disposal to implement proper space debris mitigation and protection.

This subclause provides information useful for taking comprehensive action at the system level. More detailed information for action of subsystem and component levels is provided in Clause 6. The following specific subjects are emphasized:

— limiting the release of objects in protected orbital regions;

— preventing fragmentation in orbit (including intentional break-ups, and accidental break-ups caused by collision with trackable objects, impact of tiny debris, and stored energy);

— proper disposal at the end of operation;

— minimization of hazard on the ground from re-entering debris;

— quality, safety and reliability assurance.

5.2 Design for limiting the release of objects

5.2.1 Intents of requirements in ISO 24113:2019[1]

ISO 24113:2019[1], 6.1 requires avoiding the intentional release of space debris into Earth orbit during normal operations, including general objects such as fasteners, fragments from pyrotechnics, slag from solid rocket motors, etc.

The following objects are of concern from an orbital debris mitigation standpoint:

a) objects released as directed by mission requirements (not directory indicated in ISO 24113:2019[1], 6.1.1.1, though);

b) mission-related objects, such as fasteners, apogee motor cases, etc. (ISO 24113:2019[1], 6.1.1.1);

c) fragments and combustion products from pyrotechnic devices (ISO 24113:2019[1], 6.1.2.1);

d) slag ejected from solid motors (ISO 24113:2019[1], 6.1.2.2).

It implies that if objects are unavoidably released despite requirements in ISO 24113:2019[1], 6.1.1.1, the orbital lifetime of such objects in LEO and interference with GEO is limited as described in ISO 24113:2019[1], 6.1.1.3.

5.2.2 Work breakdown

Table 1 shows the work breakdown for the actions required to prevent the releasing of debris.

Table 1 — Work breakdown for preventing the release of objects

Process	Subjects	Major work
Preventive measures	Identification of released objects and design measures	a) In the mission, which releases objects required by mission objectives, the effect on the orbital environment and the expected benefit for the mission will be assessed." b) Take preventive design to avoid releasing objects turning into space debris (ISO 24113:2019[1], 6.1). c) If objects might be released unintentionally, designers will investigate design problems and take appropriate action during design phase (e.g. insulators). d) If release is unavoidable, designers will estimate the orbital lifetime of released objects and check compliance with ISO 24113:2019[1], 6.1.1.3. e) When applying the solid motors, the possible generation of slag and its risk posed to space activities will be assessed.
Risk detection	Monitoring during operation	a) Confirm that the orbiting characteristics of released parts are as estimated, if needed. b) If an unexpected object is detected, the origin of the objects will be confirmed.
Countermeasures	Preventive measures	If an object is released unexpectedly, it will be investigated, and appropriate action will be taken to avoid repeating the release in the following missions.

5.2.3 Identification of released objects and design measures

Identify the parts designed is released, estimate their orbital lifetimes, and determine the propriety of their release.

a) Mission requirements that require dispersing objects

Assess the effects of proposed mission requirements on the environment. If the proposed mission may deteriorate the environment more than justified by its benefit, system engineering may suggest alternative approaches.

Examples are:

1) The experiment called "WESTFORD NEEDLES," conducted in *1961 and* 1963, scattered 480 million needles in orbit. More than 100 clumps of needles have been registered and many of them are still in orbit. NASA, JSC, Orbital Debris Quarterly News, Volume 17[2] reported that *the legacy of Project West Ford can still be found in international policies, including the first major United Nations accord on activities in outer space that calls for international consultations before undertaking an experiment which might cause "potentially harmful interference with activities of other State Parties in the peaceful exploration and use of outer space.*

2) Missions that conduct intentional fragmentation (one of the major causes of deterioration of the orbital environment).

b) Mission-related objects

Release of the following objects are avoided by appropriate mission and spacecraft design (ISO 24113:2019[1], 6.1.1):

1) fasteners for deploying and holding devices for panels or antennas;

2) nozzle closures and igniters of solid motors;

3) clamp bands that tie spacecraft and launch vehicles (usually as launch vehicle components).

NOTE The structural elements which support upper spacecraft used in the multi-payloads launching missions can be released due to their unavoidability. Disposal orbit of these elements are complied with ISO 24113:2019[1], 6.1.1.2. (These elements usually belong to the launch vehicle, not the spacecraft.)

c) Fragments and combustion products from pyrotechnic devices

Devices are selected and/or designed to avoid the production and release of the fragments of parts or the combustion by-products. Employing vehicle components that trap all fragments and combustion products inside for segregation (ISO 24113:2019[1], 6.1.2.1).

d) Combustion products from solid motors

Solid motors are designed not to generate slag in both GEO and LEO protected regions (higher than the manned orbit [≒approximately 400 km]). (ISO 24113:2019[1], 6.1.2.2)

5.2.4 Design measures

In general, only devices that do not release parts into the space environment are selected.

CSpOC sometimes detects released cases of the apogee kick motors. The solid motors are not used for the apogee kick motors if they generate slag. Furthermore, it is refrained from disposing the motor cases into the orbit crossing the GEO protected region.

If parts would be released due to unavoidable reasons, the orbital lifetime of the parts and the risk of impact on another spacecraft are assessed. The orbital lifetime can be assessed according to ISO 27852:2016[3]. ISO 27852:2016[3] does not designate a specific analysis tool but rather expects that the users employ their reliable techniques depending upon orbit regime, so that designers can select any tool(s) which adhere to ISO 27852:2016[3] approved techniques. Available simplified tools that can be used to estimate the long term orbital lifetime are, for instance: NASA DAS (https://orbitaldebris.jsc.nasa.gov/mitigation/debris-assessment-software.html), ESA DRAMA (after creating an account at https://sdup.esoc.esa.int/ one can obtain a license before downloading), or CNES STELA (https://logiciels.cnes.fr/content/stela?language=en).

5.2.5 Monitoring during operation

The released objects, if they are larger than 10 cm, are confirmed with ground-based space tracking facilities to ensure that they released as expected and that their orbital lifetimes are sufficiently short. The space situation report provided by the CSpOC provides a good reference.

5.2.6 Preventing failure

If objects are released unexpectedly, the origin of the objects may be identified to help prevent recurrence in future missions. Because such phenomena may indicate a malfunction, the situation is reviewed carefully, and appropriate action taken to prevent further abnormal conditions.

5.3 Prevention of break-up

5.3.1 General

ISO 24113:2019[1], 6.2 requires the prevention of break-ups caused by intentional behaviour, stored energy, collision with catalogued objects, and impact of debris or meteoroid. In 5.3.2, the first two subjects are discussed. The collision with catalogued objects is addressed in 5.3.3, and the impact of debris and meteoroid in 5.3.4.

ISO 16127:2014[4] provides more detailed requirements and procedures for complying with them.

5.3.2 Break-up caused by intentional behaviour, or stored energy

5.3.2.1 Work breakdown for preventing orbital break-up caused by stored energy

Table 2 shows the work breakdown for preventing orbital break-up caused by stored energy.

Table 2 — Work breakdown for preventing orbital break-ups caused by stored energy

Process	Subjects	Major work
Preventive measures	Mission assessment	Mission which involves the intentional break-up will be assessed to justify its intention is essential for peaceful use of space, and its effect on the environment can be controllable.
	Identification of sources of breakup	Identify components that may cause fragmentation during or after operation.
	Design measures	a) Missions that involve intentional break-ups are not designed. b) Take preventive design to limit the probability of accidental break-up. Confirm it in FMEA. c) Provide functions for to prevent break-ups after disposal.
Risk detection	Monitoring during operation	a) Provide functions to monitor symptoms of break-up. b) Monitor the critical parameters periodically. c) Take immediate actions if the symptom of a malfunction that can lead to a breakup is detected.
Countermeasures	Preventive measures for break-up	Perform the disposal operations to eliminate the risk of break-ups.

5.3.2.2 Identification of the sources of break-up

For post-operation break-ups, ISO 16127:2014[4] identifies the following components as the most likely causes of the break-up of spacecraft:

a) batteries in the electrical subsystem;

b) propulsion mechanisms and associated components (such as engines, thrusters, etc.);

c) pressurized components (such as tanks or bottles in the propulsion subsystems, or pneumatic control system, and heat pipes);

d) rotating mechanisms.

5.3.2.3 Design measures

a) Intentional break-up

Missions that involve intentional break-ups are prohibited if the fragments would be ejected outer space. This includes attacks from the ground or airplane as well as self-destruction in orbit. For the case that there would be justification to conduct intentional destruction to improve ground safety, IADC *Space Debris Mitigation Guidelines*[5] state that it is conducted at sufficiently low altitudes so that orbital fragments are short-lived.

b) Accidental break-up during operation

According to ISO 24113:2019[1], *the probability of accidental break-up is no greater than* 10^{-3} *until its end of life.* The causes of break-ups are identified in FMEA, and preventive measures are incorporated in the design. Causes of break-ups are typically controlled by FDIR concept in system-safety management. More detailed assessment procedures are presented in ISO 16127:2014[4], Annex A. For engineers wondering how to cope with rotating mechanism or complicated subsystems such as apogee engines, ISO 16127:2014[4], Annex A provides good instruction.

Note that quality and reliability management are emphasized, as well as design for debris mitigation.

c) Break-ups that occur after the end of operation

Many break-ups have occurred long after the end of operation life (e.g. 10 years after disposal). ISO 24113:2019[1] and ISO 16127:2014[4] require detailed concepts and procedures for preventing these break-ups. The key points are to provide venting mechanisms for residual fluids and shut-off functions for charging lines for battery-cells, etc. Historically, for example, separating propellant tank design combined fuel and oxygen tanks only by a common bulkhead in a way caused many explosions.

5.3.2.4 Monitoring during operations

ISO 24113:2019[1], 6.2.2.5 and ISO 16127:2014[4], 4.3.1 requires monitoring of critical parameters to detect the symptoms that can lead to a) break-up, b) loss of mission capability, or c) the loss of orbit and attitude control function, and requires immediate action when any symptoms are detected.

To prevent the occurrence of a break-up, a detection mechanism and operation procedures are designed to monitor and facilitate immediate mitigation once any possible detection of malfunction is observed to prevent break-ups.

5.3.2.5 Disposal operations

Sources of break-ups listed in 5.3.2.2 are mitigated (vented or operated in safe mode) according to ISO 16127:2014[4], 4.4.

5.3.3 Break-up caused by a collision with catalogued objects

5.3.3.1 Intents or requirements in ISO 24113:2019[1]

ISO 24113:2019[1], 6.2.3.1 to 6.2.3.3 require collision avoidance to prevent from generating fragments. (Fragmentation caused by impact with orbital objects is mentioned in ISO 24113:2019[1], 6.2.3.4 and explained in 5.3.4.)

Collision with a large object (observable from the ground; typically, larger than approximately 10 cm) causes critical damage to spacecraft and poses great risk to other intact spacecraft when thousands of fragments are dispersed within a range of a thousand of kilometres. Therefore, the UN Space Debris Mitigation Guidelines[6] recommend conducting the collision avoidance. ISO/TR 16158:2019[7] addresses best practices to evaluate and avoid collisions among orbital objects.

NOTE To conduct collision avoidance, space operators need a propulsion system (such as actuators in AOCS), technology for conjunction assessment, and the capability to conduct avoidance and returning manoeuvres. Each operator defines its philosophy, policy, and strategy for collision avoidance. The philosophy for collision avoidance, including the following, is described in the system specification to avoid the risk of insufficient propellant or manoeuvre function when needed.

a) a basic concept for collision avoidance (determination of allowable criteria for collision probability, apply functions in design to avoid collision, prepare propellant for avoidance manoeuvre, etc.);

b) collision detection measures (including self-analysis, or analysis performed by external collision service providers at present they are, for example CSpOC, the Space Data Association, etc.) https://www.space-data.org/sda/;

c) criteria for notification (conjunction distance, probability of collision, etc.);

d) criteria for conducting avoidance manoeuvres (conjunction distance, features of approaching objects, etc.);

e) method of estimating the number of manoeuvres, amount of propellant for avoidance and returning manoeuvres, and how to ensure the propellant;

f) a sequence for avoidance and returning manoeuvre (methods of avoidance, concepts for avoidance by altitude change or phase shift);

g) how to access contact points to plan coordinated avoidance manoeuvres, data exchanging rules, etc.

5.3.3.2 General information

ISO/TR 16158:2019[7] describes the workflow for perceiving and avoiding collisions among orbiting objects, the data requirements for these tasks, the techniques that can be used to estimate the probability of collision, and guidance for executing avoidance manoeuvres.

5.3.3.3 Work breakdown

Table 3 shows the work breakdown for avoiding collisions with catalogued objects.

Table 3 — Work breakdown for avoiding collision with catalogued objects

Process	Subjects	Major work
Preventive measures	Estimation of probability	Estimate collision probability by debris population models.
	Design measures	a) If the collision probability cannot be ignored, the function to avoid collision is incorporated in design. b) Define the criteria of decision-making for avoidance and estimate the expected number of collision avoidance manoeuvres during mission operations. It will be reflected in the design of the mass of propellant.
	Standardize the procedures	The criteria of collision avoidance and the standard procedure for collision avoidance is documented.
Risk detection	Receipt of warning from the collision avoidance services	a) If warning of close approach comes from USSTRATCOM/CSpOC, check the conjunction risk and identify the approaching object in detail. Reconfirm that the up-to-date, authoritative orbit ephemerides are provided to CSpOC for re-analysis. b) Operators can also use commercial services (e.g. the Space Data Association's conjunction assessment process) or one provided by other agencies. c) Determine the necessity of collision avoidance based on the result of re-analysis conducted by collision avoidance service and, if possible, by internal analysis.
	Internal detection of risk	If the operators have their own observation data and conjunction analysis systems, they may be capable of performing their own analysis.
Counter-measures	Avoidance and returning manoeuvres	a) Decide to conduct avoidance manoeuvres, if necessary. b) Ahead of time, develop an avoidance manoeuvre plan (include return plan, if needed). c) Communicate avoidance manoeuvre plan to collision avoidance service and if any to the operator of the approaching spacecraft. d) Develop the avoidance manoeuvre plan (include returning manoeuvre, if needed) coordinating with them. e) Confirm conjunction probability during avoidance and returning manoeuvres. f) Execute avoidance and returning manoeuvres.

5.3.3.4 Estimation of collision probability

Collision probability can be roughly estimated using the following databases and models:

a) information on in-orbit objects from the "Space-Track" website posted by the United States (https://www.space-track.org/auth/login);

b) ESA-MASTER provides statistical debris population (an account at; https://www.esa.int/ESA_Multimedia/Images/2013/04/ESA_s_MASTER_software_tool);

c) NASA-ORDEM provides statistical debris population; the point of contact can be known from the user's guide available at: https://www.orbitaldebris.jsc.nasa.gov/modeling/engrmodeling.html;

d) ESA-DRAMA has dedicated routines based on MASTER to assess statistically the number of expected collision / avoidance manoeuvres (an account at https://sdup.esoc.esa.int/).

NOTE The expected number of avoidance manoeuvres during operational life can be estimated from the probability of conjunction with the allowable distance of conjunction or allowable probability of collision.

The procedure to determine the probability is described in ISO/TR 16158:2019[7], Clause 8.

5.3.3.5 Design measures

If the probability cannot be ignored, considering mission importance and the impact of collision on orbital environment, the decision is made to incorporate the function of collision avoidance in design.

The criteria of decision-making for avoidance is defined, and the expected number of collision avoidance manoeuvres during mission operations is defined. They will be reflected in the design of the mass of propellant.

If the spacecraft has an enough orbit and attitude control function, the practice of collision avoidance manoeuvres would be possible without any design changes. If high-risk conjunction events are identified early enough using actionable data, a timely manoeuvre can be conducted such that propellant required for collision avoidance is minimized, and it would not affect the planned mission operation.

5.3.3.6 Procedures for collision avoidance

The criteria of collision avoidance and the standard procedure for collision avoidance are documented. It will include

a) criteria of warning for conjunction;

b) criteria to conduct re-analysis with up-to-dated authoritative orbit ephemerides;

c) criteria to decide the collision manoeuvre;

d) standard collision manoeuvre planning.

Procedures will be facilitated timely avoidance manoeuvres.

5.3.3.7 Detection of risk

5.3.3.7.1 Receipt of warning from the collision avoidance services

The CSpOC provides ready access to a conjunction warning service. When conjunctions involve actively-manoeuvring satellites (particularly in GEO), an approach such as the SDA's, which incorporates authoritative operator data (planned manoeuvres, momentum dumps, high-fidelity 3 degrees of freedom and 6 degrees of freedom attitude and orbit propagation, and active transponder ranging across the orbital arc) is more actionable and credible. Both CSpOC and SDA sides recommend applying both services in a complementary fashion.