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Space systems — Avoiding collisions with orbiting objects

Systèmes spatiaux — Évitement des collisions avec les objets en orbite

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Foreword

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The committee responsible for this document is ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

This Technical Report describes the work flow for perceiving and avoiding collisions among orbiting objects, data requirements for these tasks, techniques that can be used to estimate the probability of collision and guidance for executing avoidance maneuvres.

The process begins with the best possible trajectory data, provided by satellite operators or sensor systems developed for this purpose. The orbits of satellites must be compared with each other to discern physically feasible approaches that could result in collisions. The trajectories so revealed must then be examined more closely to estimate the probability of collision. Should a collision be likely within the criteria established by each satellite operator, the spectrum of feasible maneuvers must be examined.

There are several different approaches to conjunction assessment. All have merits and deficiencies. Most focus on how closely satellites approach each other. This is often very uncertain since satellite orbits generally change more rapidly under the influence of non-conservative forces than observations of satellites in orbit can be acquired and employed to improve orbit estimates. Spacecraft operators require the fullness of orbit data in order to judge the credibility and quality of conjunction perception. This information includes the moment of time of the last elaboration of orbit (the epoch) and the standard time scale employed, state vector value or elements of orbit at this moment of time, the coordinate system description that presents the orbital data, the forces model description that was used for orbital plotting, and information about the estimation errors of the orbital parameters. Essential elements of information for this purpose are specified in ISO 26900.

There are also diverse approaches to estimating the probability that a close approach might really result in a collision. This is a statistical process very similar to weather forecasting. Meteorologists no longer make definitive predictions. They provide the probability of precipitation, not whether it will rain. All conjunction assessment approaches are in some way founded in probabilities. Probability of collision is also a highly desirable element of data. It must be accompanied by metadata that allows operators to interpret the information within their own operational procedures.

How near satellites might be to each other and the probability they might collide if they were that close are only two discriminants of potentially catastrophic events. Since the objective is that the satellite survives despite many potential close approaches, cumulative probability of survival is also important information. Responding precipitously to the close approach nearest at hand might only delay the demise of the satellite or even contribute to a subsequent more serious event. The evolution of orbits toward close approaches and the cumulative probability that a satellite might survive for a period of time are also important.

Finally, the state of each of the conjunction partners, their ability to maneuver or otherwise avoid contact, and the outcomes of past events that are similar guide courses of action.

Space systems — Avoiding collisions with orbiting objects

1 Scope

This Technical Report is a guide for establishing essential collaborative enterprises to sustain the space environment and employ it effectively. This requires diligent collaboration among all who operate satellites.

This Technical Report describes some widely used techniques for perceiving close approaches, estimating collision probability, estimating the cumulative probability of survival, and manoeuvring to avoid collisions.

NOTE Satellite operators accept that all conjunction and collision assessment techniques are statistical. All suffer false positives and/or missed detections. The degree of uncertainty in the estimated outcomes is not uniform across all satellite orbits or all assessment intervals. No comparison within a feasible number of test cases can reveal the set of techniques that is uniformly most appropriate for all.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TR 11233, *Space Systems — Orbit determination and estimation — Process for describing techniques*

ISO 26900, *Space data and information transfer systems — Orbit data messages*

ANSI/AIAA S-131-2010, *Best Practices in Astronautics: Propagation*

AIAA G-043-1992, *Guide to Developing Operational Concepts*

3 Terms and definitions

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

3.1
conjunction
apparent meeting or passing of two or more objects in space

3.2
collision
act of colliding; an instance of one object striking another

3.3
covariance
measure of how much variables change together

Note 1 to entry: For multiple dependent variables, a square, symmetric, positive definite matrix of dimensionality $N \times N$, where N is the number of variables.

3.4
encounter plane
plane normal to the relative velocity at the time of closest approach

3.5
false alarm
statistical Type I error, when a statistical test fails to reject a false null hypothesis

3.6
ICD
Interface Control Document
formal means of describing the inputs and outputs of a system, the interfaces among systems, or the protocols among physical or electronic elements of an entity

3.7
operational concept
roles, relationships, and information flows among tasks and stakeholders and the manner in which systems and processes will be used

4 Collision avoidance workflow

The avoidance process begins with orbit data, the content of which is specified in ISO 26900. The data can be provided by collaborating satellite operators and from observers who are capable of viewing satellites. The nature of each object should also be known if possible. This information includes size, mass, geometry, and the operational state (for example, whether active or inactive). Finally, collision probability should be estimated based on the inevitable imprecision associated with orbit determination and other hypotheses and measurements. Figure 1 depicts this top-level work flow.

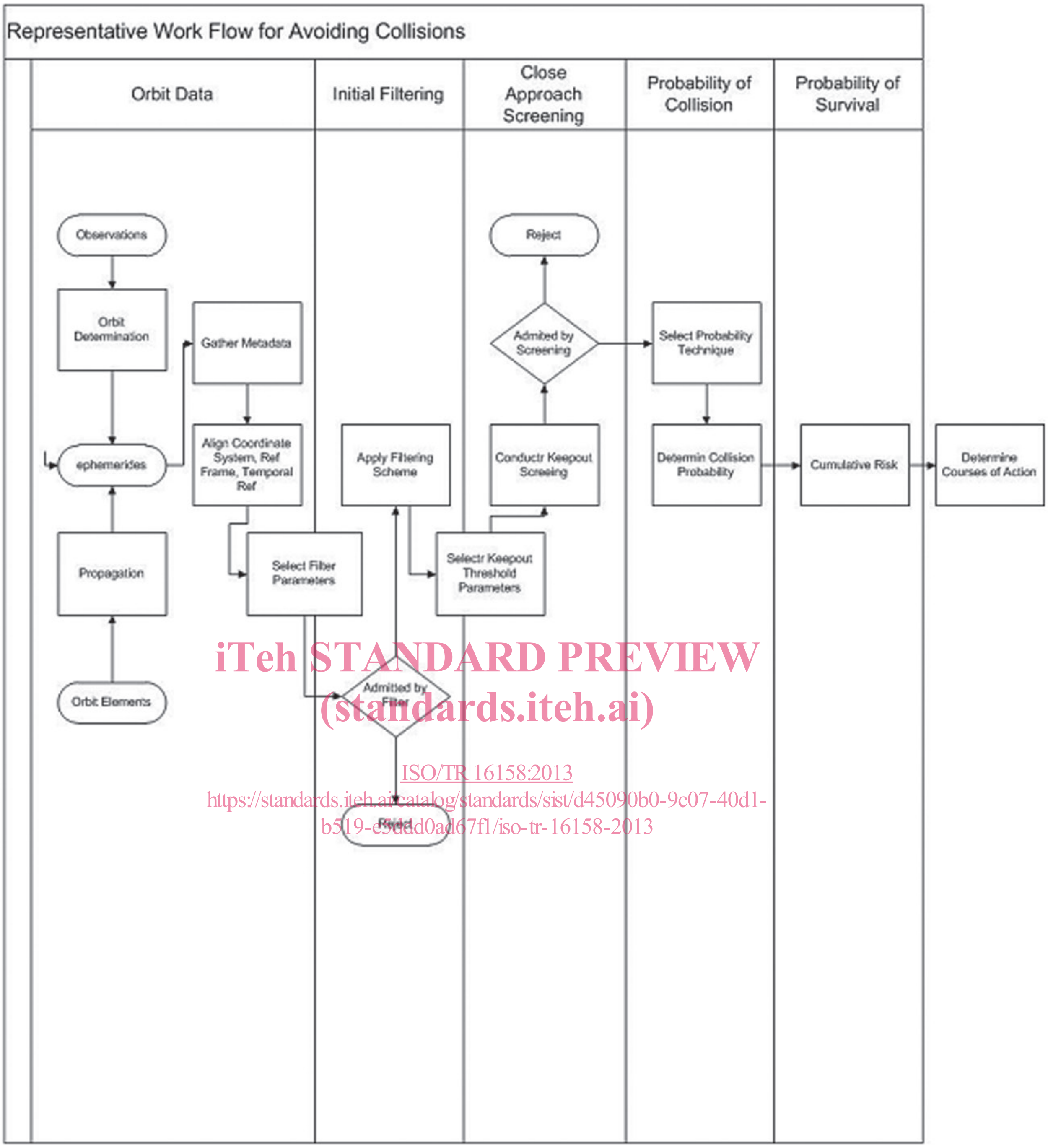

Figure 1 — Top-level collision avoidance work flow

5 Perceiving close approaches

5.1 Orbit data

5.1.1 Inputs

Inputs to conjunction assessment are principally data that specify the trajectories of the objects of interest. These are one of three types of information: orbit elements, ephemerides, or observations of satellites. Orbit elements in this context include parameters that describe the evolution of the trajectory and which can be used to estimate the trajectory in the future. They are derived from past observations of satellites. Ephemerides are time-ordered sets of position and velocity within which one interpolates to estimate the position and velocity at intermediate times. Ephemerides should span the future time interval of interest, the equations of motion having been propagated by the provider. Observations are measurements of satellite position and velocity from one or more well-characterized and registered instruments. The recipient must use those observations to estimate the evolution of the trajectory either through direct numerical integration of governing equations or by developing orbit elements for subsequent propagation. ISO 11233 describes the manner in which a provider's orbit determination scheme should be codified. There are normative formats for orbit elements and ephemerides (see ISO 26900). There are no normative formats for transmitting observations.

It is extremely important to realize that trajectory estimates are derived from measurements that cannot be precise such as aspheres. This is why they are called "estimates." The input information must include characterized uncertainties. Uncertainty in any of the independent variables or parameters introduces imprecision in all of the dependent variables that describe the evolution. The appropriate expression of uncertainty is, therefore, a square matrix whose dimension is the number of elements of the state, called a state vector. If uncertainties are not provided or are wrong, one cannot determine properly the probability that two objects might collide.

5.1.2 Propagating all orbits over the interval of interest

All orbits being under consideration shall be forecast in the model in which they were created. Since orbit determination and propagation are uncertain, the propagation scheme must be well suited for this interval. ANSI/AIAA S-131-2010 is a normative reference for orbit propagation. Osculating orbit estimates grow imprecise over time intervals long compared to the time span of underlying observations. This imprecision is sufficient to make collision probabilities misleading. Therefore, conjunction assessment in low Earth orbit is unreliable at the present state of the art for periods longer than approximately one week beyond the latest orbit determination, depending on the orbit of interest. Some particularly stable orbits might be estimated reliably for longer periods. Probability of collision can be estimated over long periods using consistent statistical descriptions of satellite orbits and the evolution of the debris environment. These techniques estimate whether a conjunction will occur or not but cannot expose which specific objects might be involved.

5.2 Initial filtering

5.2.1 All against all

The most complete process would examine each object in orbit against all others over the designated time span. Most techniques eliminate A-B duplication, defined as screening B against A in addition to A against B. Therefore, the number of screenings necessary is not the factorial of the number of satellites.

It is impossible to know how many objects orbit the Earth. Many escape perception. The best a satellite operator can do is to consider those that have been detected. One cannot screen against unknown objects that one estimates might be present.

5.3 Eliminating infeasible conjunctions

Much of the population in orbit physically could not encounter many other satellites during the period of interest. For example, even if uncontrolled, geostationary satellites 180 degrees apart in longitude are not threats to each other.

5.3.1 Sieve

Sieve techniques employ straightforward geometric and kinematic processes to narrow the spectrum of feasible conjunctions based on the minimum separation between orbits. They are based variously on orbit geometry, numerical relative distance functions, and actual orbit propagation. The concept is to examine proximity of one satellite to another sequentially in parameter space beginning with the parameter that most effectively discriminates separation distance. To account for approximations in orbit analysis, a distance buffer (pad) may be added to the filter screening distance threshold. For example, if in-track separation is likely to be the best indicator of separation, satellites that are far apart in-track need not be screened further cross-track. They differ in computational efficiency and the degree to which close approaches are all perceived. There is no normative approach since different techniques are satisfactory for different satellites and operator judgements.

5.3.2 Toroidal elimination

Toroidal elimination eliminates objects by determining which mean orbits might touch a toroidal volume defined by the orbit of the satellite of interest and a keepout volume cross-sectional area.

5.3.3 Apogee-Perigee filters

This approach eliminates satellites whose apogees are lower than the perigee of the satellite of interest and perigees are sufficiently greater than the apogee of the satellite of interest. The criterion for sufficiency is based either on operator experience or risk tolerance. Risk can be quantified with techniques of signal detection and receiver operating characteristics discussed subsequently. Volumetric screening is of the same nature, eliminating satellites whose orbits are outside the volume of space described by the orbit of the satellite of interest.

5.3.4 Statistical errors

Since each of these techniques relies on trajectory information that is imprecise, these filters will suffer Type I, failure to identify real threats, and Type II errors (including satellites that are not threats). Filter parameter selection should be based on the user's tolerance for both kinds of errors. Every filtering scheme will include events that should be discarded and discard events that should be included.

6 Determining potential collisions for warning and further action (close approach screening)

Initial filtering provides little information for mitigating collisions. The next task is judging whether the actual states of the involved satellites are sufficiently threatening. The first step is determining whether satellites come extremely close to each other. This is the judgement of each satellite operator. It may be based on satellite sizes, the consequences of a collision, the confidence one has in orbit estimates and propagation, and other subjective factors. As with initial filtering, even this more refined level of discrimination will miss some threats. The possibility of false alarms and missed detections increases the farther in the future one extrapolates.

6.1 Symmetric keepout

The most straightforward keepout volume is symmetric. These are easiest to implement but might encompass considerably more than the vulnerable geometry of the satellite. These can be spheres, cubes, or any other three-dimensional volumes of operator-judged size. The satellite of interest may be enveloped symmetrically and osculating orbits of other satellites tested for penetrating the volume. Alternatively, the bounding volumes of both satellites may be screened for intersection. This is generally the most conservative approach, identifying as potential collisions requiring action many events that are extremely improbable.

6.2 Bounding volume keepout

This approach envelops the satellite of interest in a volume that is not symmetric. The volume could be ellipsoidal, a rectangular parallelepiped, or a shape composed of surfaces nearly conformal with the satellite. The geometry of the bounding volume could be based on operator experience. For example, one might use fairly consistent orbit uncertainties along track, radial from Earth Center, and normal to the plane defined by both of these directions. The volume could also be determined from more exhaustive probabilistic calculations that are too resource intensive to use frequently.