TECHNICAL REPORT

# ISO/TR 16158

Second edition

# Space systems — Avoiding collisions among orbiting objects

*Systèmes spatiaux — Évitement des collisions entre objets en orbite*



PROOF/ÉPREUVE

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# Foreword

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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).

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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*.



This second edition cancels and replaces the first edition (ISO/TR 16158:2013), which has been technically revised.

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

— improved figures for clarity;

— added plot of maximum probability;

— switched to “decimal comma” per ISO editorial rules;

— simplified operational concepts figures;

— added informative annexes containing collision probability relational nomograms;

— added collision probability topology in both graphical and tabular look-up formats;

— reordered the bibliography

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

This document describes the workflow 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. Diligent collaboration is strongly encouraged among all who operate satellites.

The process begins with the best possible trajectory data, provided by satellite operators or sensor systems developed for this purpose. The orbits of satellites can be compared with each other to discern physically feasible approaches that can result in collisions. The trajectories so revealed can then be examined more closely to estimate the probability of collision. Where the possibility of a collision has been identified within the criteria established by each satellite operator, the spectrum of feasible maneuvers is 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 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 can 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 can be accompanied by metadata that allows operators to interpret the information within their own operational procedures.



How near satellites can be to each other and the probability they can 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 can only delay the demise of the satellite or even contribute to a subsequent more serious event. The evolution of close approaches and the cumulative probability that a satellite can survive 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.

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# Space systems — Avoiding collisions among orbiting objects

## 1 Scope

This document is a guide for establishing essential collaborative enterprises to sustain the space environment and employ it effectively.

This document 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

There are no normative references in this document.



## 3 Terms and definitions

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



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/

**3.1**
**collision**
act of colliding; instance of one object striking another

**3.2**
**conjunction**
apparent meeting or passing of two or more objects in space

**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**
**ephemeris**
time-ordered set of position and velocity within which one interpolates to estimate the position and velocity at intermediate times

**3.6**
**false alarm**
statistical Type I error, when a statistical test fails to reject a false null hypothesis

**3.7**
**interface control document**
**ICD**
specification that describes the characteristics that can be controlled at the boundaries between systems, subsystems, and other elements

**3.8**
**operational concept**
roles, relationships, and information flows among tasks and stakeholders and the way systems and processes will be used

**3.9**
**orbital elements**
parameters that describe the evolution of the trajectory and which can be used to estimate the trajectory in the future

## 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. It is also important to know the nature of each object if possible. This information includes size, mass, geometry, and the operational state (e.g. active or inactive). Finally, collision probability estimates consider the inevitable imprecision associated with orbit determination and other hypotheses and measurements. Figure 1 depicts this top-level workflow.



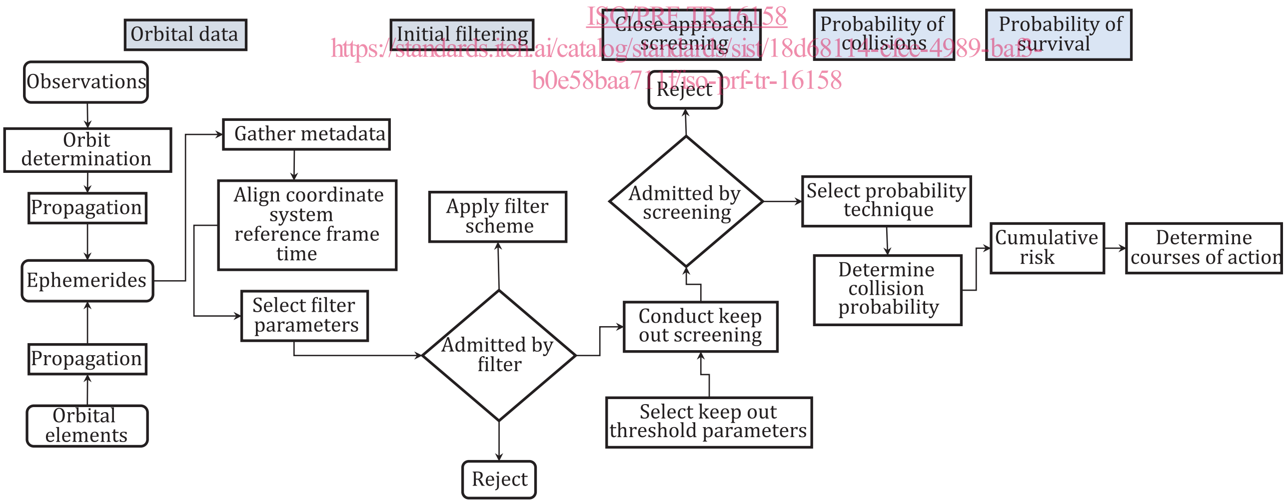



**Figure 1 — Top-level collision avoidance workflow**

## 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: orbital elements, ephemerides, or observations of satellites. Orbital 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 need to span the future time interval of interest, where 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 can use those observations to estimate the evolution of the trajectory either through direct numerical integration of governing equations or by developing orbital elements for subsequent propagation. ISO 11233 describes the way a provider's orbit determination scheme is codified. There are normative formats for orbital elements and ephemerides (see ISO 26900). See CCSDS 503.0-B-2 for 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. Therefore, they are called “estimates.” The input information can include characterized uncertainties. Uncertainty in any of the independent variables or parameters introduces imprecision in all 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 can collide.

### 5.1.2 Propagating all orbits over the interval of interest

All orbits being under consideration are best forecasted by the model in which they were created. Since orbit determination and propagation are uncertain, the propagation scheme can 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 can 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 can 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 can be present.

## 5.3 Eliminating infeasible conjunctions

### 5.3.1 General

Much of the population in orbit physically cannot 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.

### 5.3.2 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) can 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 do not need to 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.

#### 5.3.3 Toroidal elimination

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

#### 5.3.4 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.

#### 5.3.5 Statistical errors

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



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

### 6.1 General

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 can 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.

### 6.2 Symmetric keepout

The most straightforward keepout volume is symmetric. These are easiest to implement but can 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 can be enveloped symmetrically, and osculating orbits of other satellites tested for penetrating the volume. Alternatively, the bounding volumes of both satellites can be screened for intersection. This is generally the most conservative approach, identifying as potential collisions requiring action many events that are extremely improbable.

## 6.3 Bounding volume keepout

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

## 6.4 Probability techniques

The probability that two objects separated by a given distance at closest approach would actually collide is assessed as the integral of the intersection of the objects' position probability densities as a function of time.

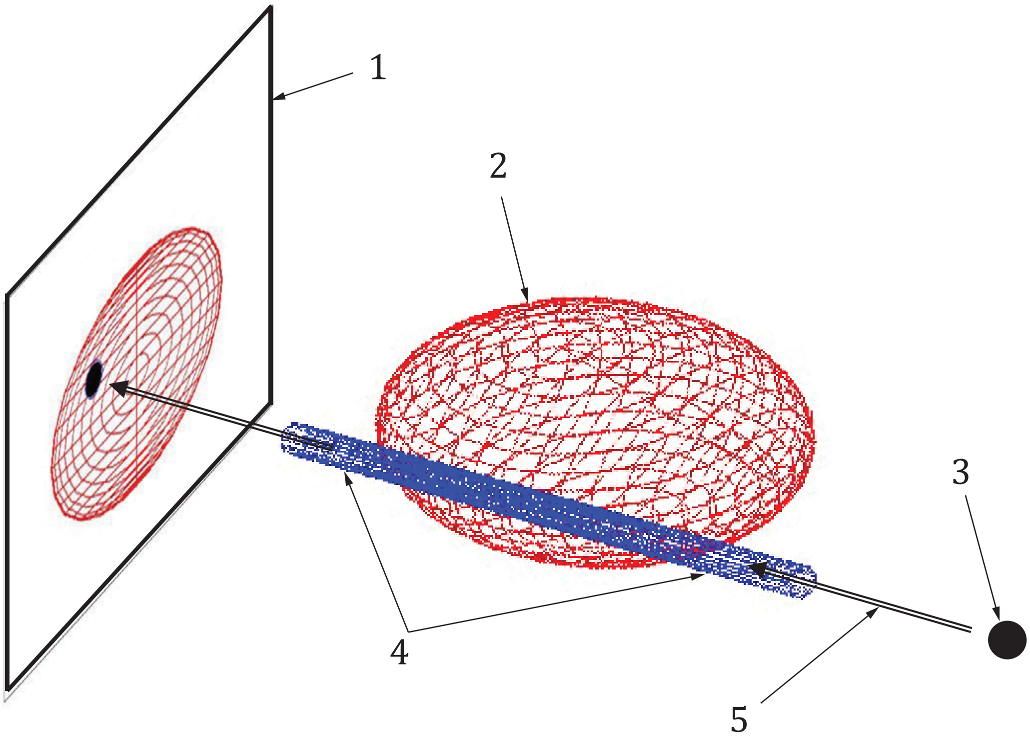
All satellite orbits are imprecise. Approximations to physical processes (process noise) and imprecise observations of satellite states of motion (measurement noise) lead to imprecise estimates of the future states of satellites. The imprecision is represented by variances and covariances of the dependent parameters among each other. These form a covariance matrix. It represents generally mean squared deviations of estimated (expected) values of each dependent variable from those inferred from measurements. A covariance matrix is symmetric and positive-definite if all of the variables are independent.

When the duration of a conjunction is very short with respect to the time it takes for the satellites to move through the covariance volume, the collision path can be assumed a straight line. Since satellite position is the quantity of interest in that case, the covariance volume for estimating the location of an object is the 3 × 3 position submatrix of the full covariance. These concepts are described in ANSI/AIAA S-131-2010.

When the duration of the encounter is comparable to or greater than the distance satellites move in a unit time, the collision path is not straight, the relative velocity cannot be assumed linear, and a more complete position and velocity submatrix is required, at least 6 × 6.

Satellite orbits and covariances are propagated or interpolated over the future interval of interest, depending on whether the orbit is state vector and covariance at the initiation time or whether the orbit data are ephemerides and covariances already determined at time increments over the interval of interest. The probability of collision is determined at each time increment.

The complex mathematical process of determining whether the covariance volumes of two objects touch or intersect and the methods for determining the volume of the intersection are described in normative and informative documents. The process reduces to combining the covariance volumes of both objects in the direction of the relative velocity between the objects and determining the volume contained within a cylinder whose cross section is the combined areas of both objects. Figure 2 depicts the geometry of the problem.




**Key**

1 encounter plane

2 combined covariance ellipsoid shell

3 combined spherical object

4 relative path (collision tube)

5 relative velocity



**Figure 2 — The collision estimation problem**

The process depicted is valid when the rate at which the encounter occurs is small compared to the relative velocity. The collision tube can be assumed linear. When the encounter occurs over a long time compared to that in which the object would move a distance comparable to the longest dimension of the covariance volume, the collision tube cannot be assumed to be straight. Bending can be accommodated consistent with the change in relative orbit curvature of one of the objects relative to the other over the encounter interval. This is the case for conjunctions among geostationary objects and conjunctions in other orbital regimes having slow closing velocity with respect to orbital velocity.

The covariance ellipsoid can be reduced to a sphere by normalizing its dimensions by the variance in each orthogonal axis. This is called Mahalanobis space. Since all cross sections are affine, scaled transformations of a circle, the problem is reduced to determining an area in a two-dimensional space. Informative references describe the formalism.

In the two-dimensional reduction, the collision probability is

$$P = \frac{1}{2 \cdot \pi \cdot \sigma_x \cdot \sigma_y} \cdot \int_{-C_{\mathrm{HBR}}}^{C_{\mathrm{HBR}}} \int_{-\sqrt{{C_{\mathrm{HBR}}}^2 - x^2}}^{\sqrt{{C_{\mathrm{HBR}}}^2 - x^2}} e^{\left\{-\frac{1}{2}\left[\left(\frac{x - x_{\mathrm{m}}}{\sigma_x}\right)^2 + \left(\frac{y - y_{\mathrm{m}}}{\sigma_y}\right)^2\right]\right\}} dy\, dx \tag{1}$$

where