भारतीय मानक

*Indian Standard*

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# अंतरिक्ष प्रणालियाँ— परिक्रमा करने वाली वस्तुओं के बीच टकराव से बचना

# Space Systems — Avoiding Collisions Among Orbiting Objects

ICS 49.140

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## NATIONAL FOREWORD

This Indian Standard which is identical to ISO/TR 16158 : 2021 ‘Space systems — Avoiding collisions among orbiting objects’ issued by International Organization for Standardization (ISO), was adopted by the Bureau of Indian Standards on the recommendations of Air and Space Vehicles Sectional Committee and approval of the Transport Engineering Division Council.

The text of ISO standard has been approved as suitable for publication as an Indian Standard without deviations. Certain terminologies and conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words ‘International Standard’ appear referring to this standard, they should be read as ‘Indian Standard’; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

Attention is drawn to the possibility that some of the elements of this standard may be the subject of patent rights. The Bureau of Indian Standards shall not be held responsible for identifying any or all such patent rights.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 2022 ‘Rules for rounding off numerical values (*second revision*)’. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

# Contents

# 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 manoeuvres. 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 manoeuvres 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 manoeuvre or otherwise avoid contact, and the outcomes of past events that are similar guide courses of action.

*Indian Standard*

# 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 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**
**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.

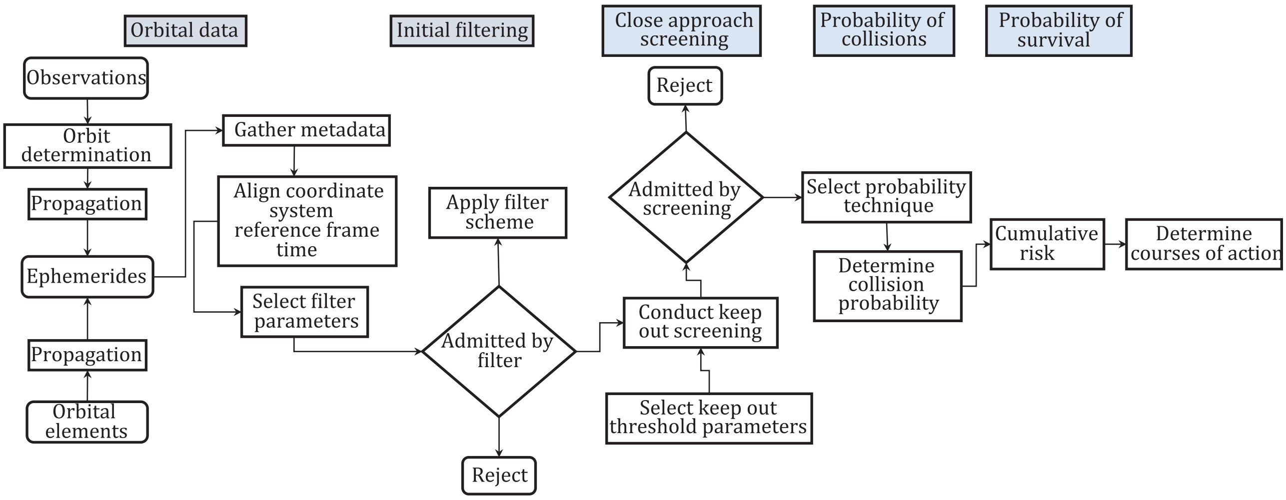


Figure 1 — Top-level collision avoidance workflow

## 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/TR 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 spheres. 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.

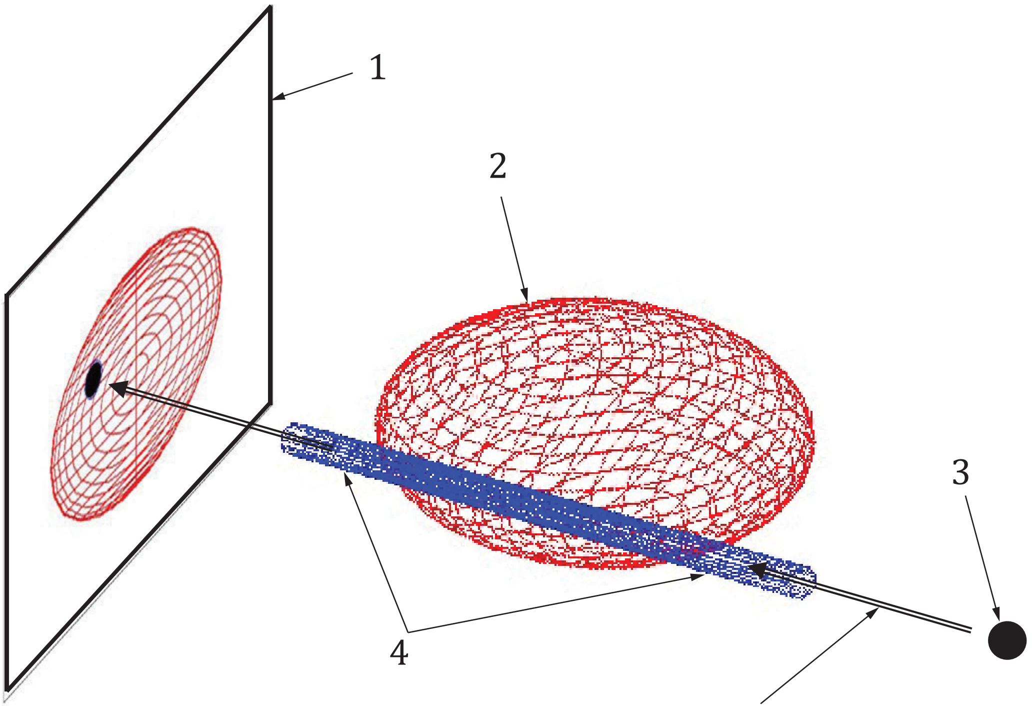
All satellite orbits are imprecise. Approximations to physical processes (process noise) and imprecise observations of satellite states of motion (measurement noise) lead to imprecise estimates of the future states of satellites. The imprecision is represented by variances and covariances of the dependent 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

$$P_{max} \tag{1}$$

where

$r$ is the combined object radius;

$d$ lies along the minor axis;

$A_r$ lies along the major axis;

$P_k$ and $P_k'$ are the respective components of the projected miss distance;

are the corresponding standard deviations.

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

and $C_{\mathrm{HBR}}$

There are several numerical techniques for determining the volume whose value is the collision probability. The mathematical statement is well documented in communication and signal detection theory. The most widely used numerical approximations to this integral are due to Foster, Chan, Patera, and Alfano. These have all been evaluated over wide ranges of governing parameters (miss distance, variances, object sizes, covariance aspect ratios) to provide relationship plots (called “nomograms”) in Annex A.

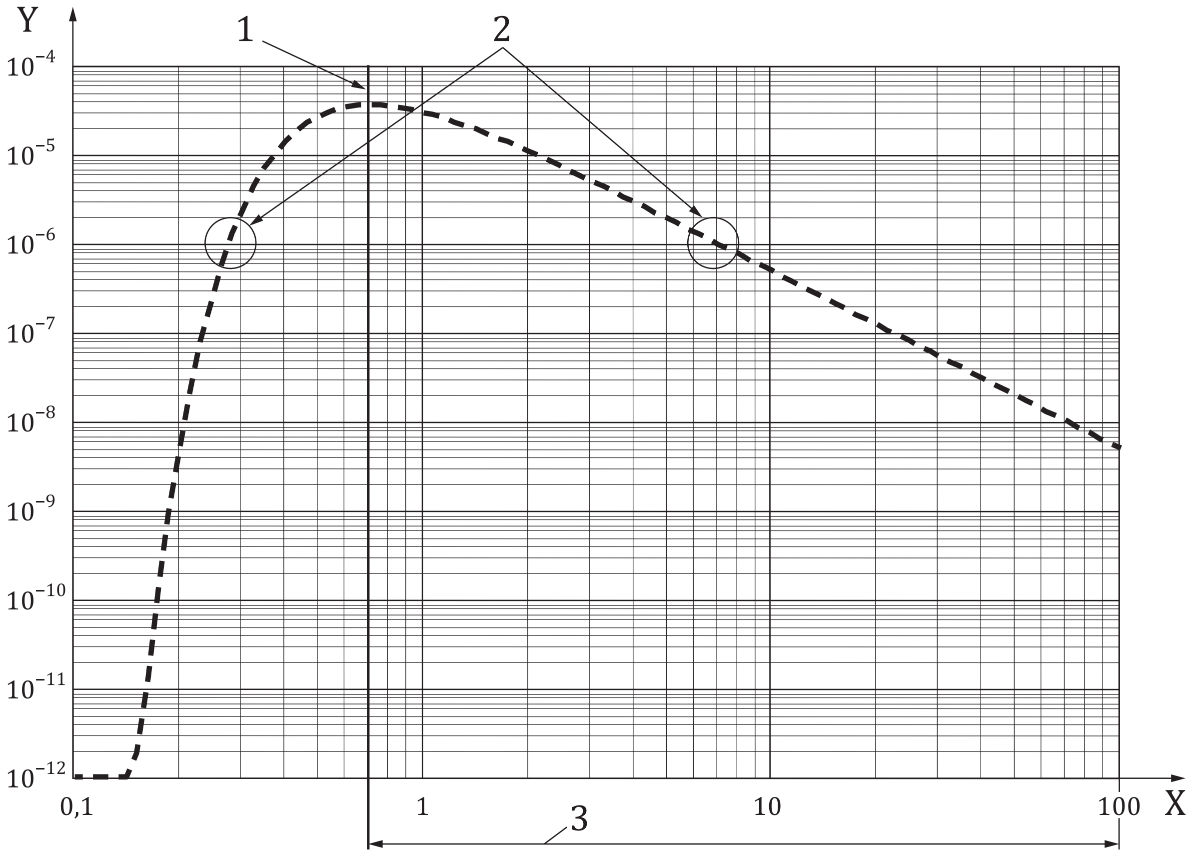
## 6.5 Maximum probability

A significant amount of information is required to estimate the probability that two satellites can collide. This includes the external architecture of the satellite, its attitude, and specific characteristics of both the osculating orbit and the uncertainty in that orbit. Much of this is not available realistically; and it can be infeasible to seek it in a reasonable amount of time. There are two approaches to mitigate this uncertainty while still developing meaningful and trustworthy measures of risk. The first is maximum probability.

Trustworthy and realistic covariances are the essence of probability estimates. There are many reasons for covariances not being trustworthy or realistic. For example, the observations from which orbits are determined can be correlated because of tracking procedures. Much of the orbit uncertainty will be suppressed artificially. Process models can be deficient or the essential matches among observation frequency, mathematical sampling, physical approximations, and numerical procedures can be faulty.

It is well known that the joint probability that two objects occupy the same location in phase space has a maximum as a function of covariance dimensions. Physically, if the two orbits have been estimated precisely, it is extremely unlikely that the satellites would collide for separations greater than the sum of both cross-section dimensions. Conversely, if the orbits are not very precise, the objects can be anywhere within large volumes; and the probability that they were in the same place is small.

Figure 3 demonstrates maximum probability in a representative situation. There is a unique value of combined covariance for which the probability is a maximum and a corresponding unique mean separation between the satellites. Note that the actual probability decreases dramatically on either side of the maximum. Therefore, the maximum probability is always very conservative. In the dilution region, probabilities decrease because we are very uncertain as opposed to the small probabilities before the maximum, which occur because we are certain where the satellites can be.



**Key**

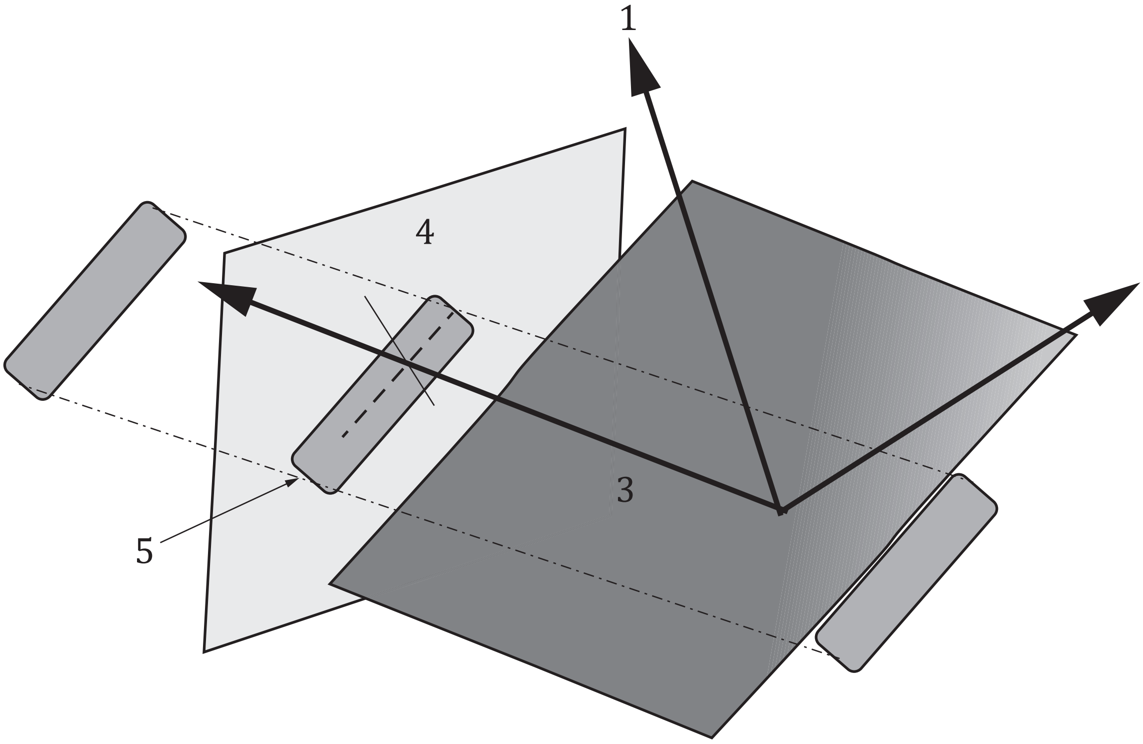
| | |
|---|---|
| X | $\sigma_x$ - 1 sigma combined positional deviation (KM) |
| Y | probability |
| 1 | maximum probability |
| 2 | same probability value occurs twice |
| 3 | dilution region |

**Figure 3 — Maximum probability and associated dilution region**

## 6.6 Bounding volume based on probability

An alternative to mitigating lack of information is the exhaustive and methodical development of a straightforward bounding volume that encompasses as much of the high-probability collision events as is reasonable. This technique can be applied to every satellite of interest and is most practical when an operator is responsible for only a few satellites. However, once an interested and responsible operator has determined the appropriate bounding volume for his satellites, that volume can be shared and employed whenever other observers and providers consider that satellite.

Figure 4 demonstrates the bounding volume determined for the Jules Verne automated transfer vehicle (ATV) based on extensive synthesis of collision circumstances. Table 1 demonstrates that a large, conservative bounding volume has both a high rate of detection for high-probability collisions and a correspondingly high rate of false alarms. Conversely, a smaller volume can have a low probability of detection but also a low probability of false alarms. Generally, operators are well advised to be conservative rather than risk missing potentially catastrophic events.



**Key**

1 conjunction partner's spacecraft velocity

2 owner's spacecraft velocity

3 relative velocity

4 encounter plane

5 exclusion zone designed to capture threatening conjunctions

Figure 4 — Automated transfer vehicle exclusion zone

**Table 1 — Probabilities of detection and probabilities of false alarm for different bounding volumes**

| USAF catalog number | 11332 | | 26847 | | 26063 | |
|---|---|---|---|---|---|---|
| Exclusion zone | Probability of detection | Alerts per year | Probability of detection | Alerts per year | Probability of detection | Alerts per year |
| 3 km sphere | 0,44 | 0,2 | 0,24 | 0,3 | 0,08 | 0,7 |
| 10 km sphere | 0,86 | 5,5 | 0,63 | 3,7 | 0,23 | 4,9 |
| (10 × 25 × 10) km box | 0,92 | 3,6 | 0,78 | 6,7 | 0,28 | 10,1 |
| NASA "pizza box" (0,75 × 25 × 25) km box | 0,98 | 0,4 | 0,93 | 0,4 | 0,33 | 1,4 |
| NASA "hockey puck" cylinder[a] | 0,99 | 3,6 | 0,94 | 5 | 0,37 | 7,5 |
| ATV-CC sweeping rectangle[b] | 1 | 3,6 | 0,99 | 5 | 0,39 | 7,5 |
| Box formerly used by USSTRATCOM[c] | 1 | 7,6 | 0,97 | 9,8 | 0,42 | 11,1 |

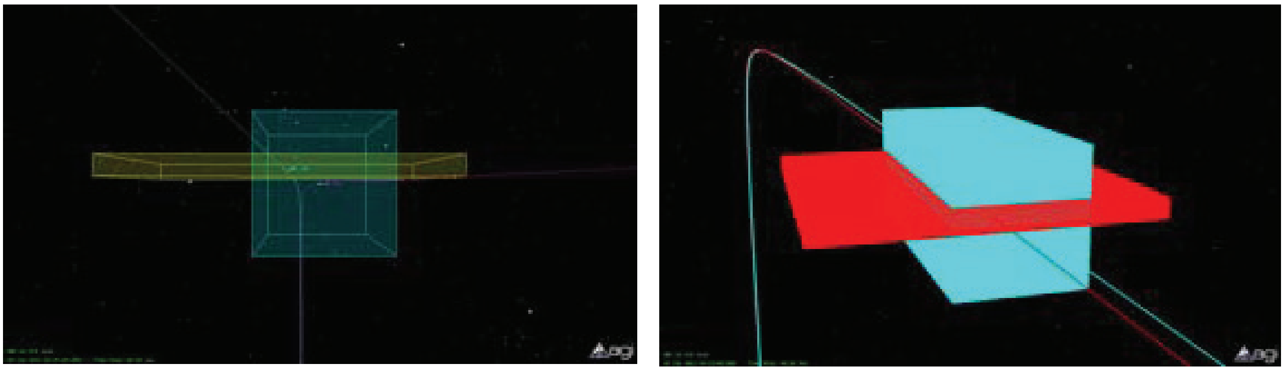
[a] NASA "hockey puck" radially aligned cylinder 10 km in height and 30 km in diameter.

[b] ATV-CC rectangle that is 60 km long and 10 km wide.

[c] USSTRATCOM box that is 38 km along radial direction and 40 km along intrack and crosstrack directions.

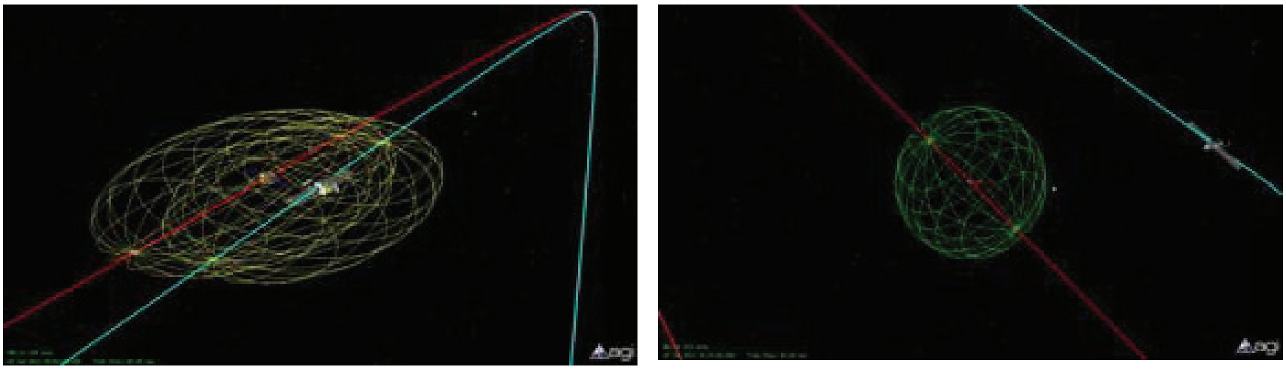
### 6.7 Comparison of techniques

Each assessment and collision probability technique will lead to a different outcome. Figure 5 illustrates the possibilities for a real conjunction between AMC-11 and XM-3, 29 Jan 2011, 10:35 UTC.



a) NASA (0,75 × 5 × 5) km pizza box

b) (5 × 5 × 25) km parallelepiped



c) intersecting covariance ellipsoids

d) 3 km diameter sphere

**Figure 5 — Comparison of different screening and assessment techniques**

Each screening and analysis technique will perceive events differently. These include the so-called NASA pizza box [(0,75 × 5 × 5) km parallelepiped], a (5 × 5 × 25) km parallelepiped, covariance ellipsoids and a 3 km diameter sphere. The bounding value is centred on one of the satellites. Some perceive the close approach of one satellite to other as a threat; some do not.

The differences in screening and assessment approaches make it necessary that those who receive warnings also be informed of the screening and assessment techniques that led to the warning.

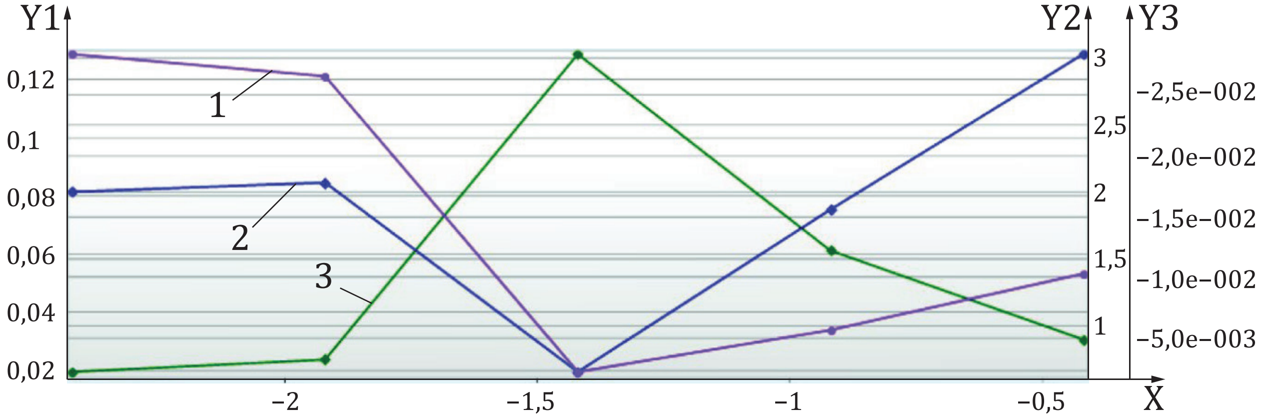
## 7 Probability of survival

### 7.1 General

The goal of the analysis to avoid collisions is that the satellite of interest survives the estimation time interval. The highest probability collision or the one with the minimum separation distance over the time interval generally are not the only conjunctions. Operators wish their satellites not to experience any collisions; and there is a probability that each conjunction can lead to a collision. As orbit estimates evolve with new observations, close approach geometry and epoch will change. The closer the estimated epoch is to the estimated time of closest approach, the more accurate the estimate. Close approaches, even those with notable probability of collision, estimated to occur weeks from the estimated epoch hence almost never materialize.

## 7.2 Trending

Trending is following the progress of close approach between two satellites over the time interval of interest. Figure 6 is an example of the evolution of such a conjunction based on relative range at the time of closest approach (TCA). The trend that a close approach distance exhibits over the estimation interval indicates decreasing separation; hence, reason for concern. Probability of collision can increase or decrease over time. Increasing probability of collision and decreasing separation are causes for concern and preventive action. It is very important to understand that a single discriminant is seldom sufficient for a confident assessment.



**Key**

| | |
|---|---|
| X | # days to conjunction |
| Y1 | range (km) |
| Y2 | N sigma |
| Y3 | probability |
| 1 | min. range |
| 2 | N sigma |
| 3 | true probability |

**Figure 6 — Trend of close approach between two satellites**

A more effective and meaningful method for trending both miss distance and estimated collision probability is provided in Annex B, where probability contours and tables of collision probability are provided as a function of covariance scaling and miss distance.

In addition to the short-term trending of conjunction miss distance associated with a single conjunction event, satellite operators can also minimize collision risk via monitoring and long-term trending of multiple close approach events for all pairings of their operational satellites with each other and with the rest of the orbital population. This is especially effective in the GEO regime or in constellations having common altitude ranges, where recurring close approaches can signal a long-term collision threat.

Conjunction assessment and collision avoidance require continuous vigilance for near-term events that can require unanticipated manoeuvres and long-term monitoring for numerous close approaches that can be mitigated by collaborative stationkeeping among those who occupy the same assigned longitudinal slot.

## 7.3 Cumulative probability

The principle of cumulative probability accrues the probability that a single satellite will survive the analysis time subject to all close approaches that it can experience in that interval. Each close approach taken in the order that they occur has a probability that a collision will occur and its complement, the probability that there will be no collision. If the satellite survives the first encounter, there are corresponding probabilities of demise or survival for the next encounter, and so on. Figure 7 demonstrates this chain for a real satellite in the past.

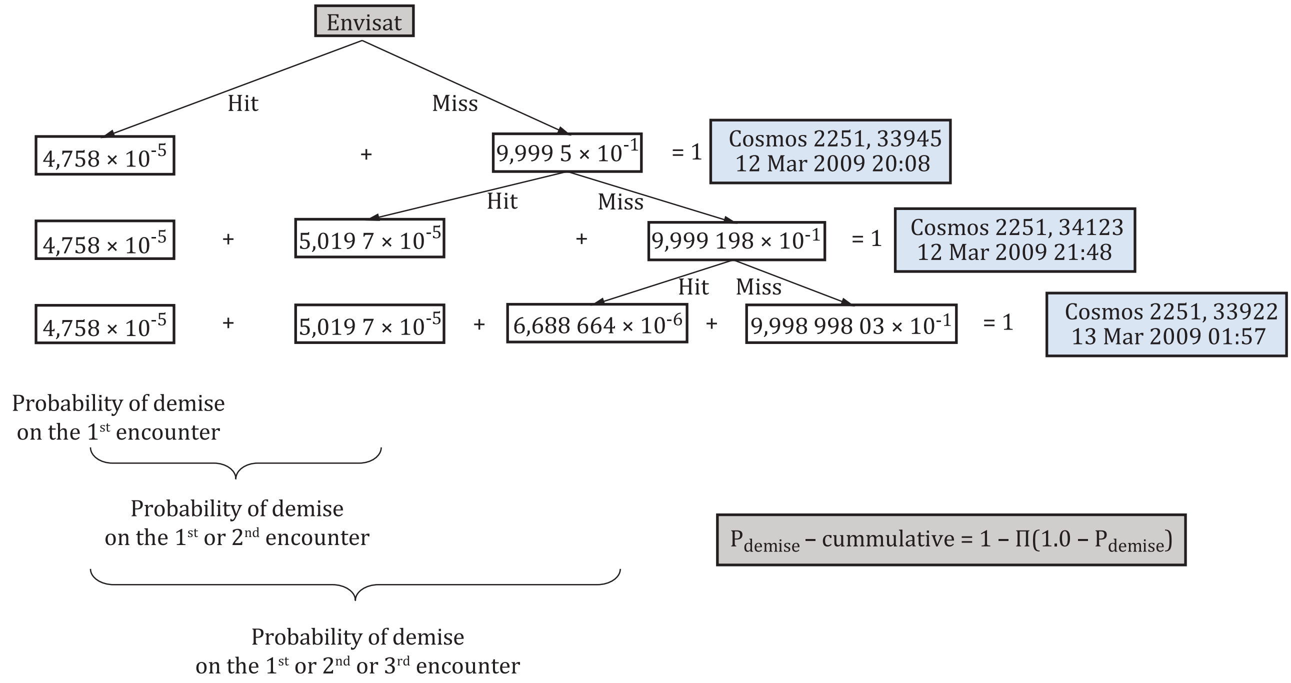


**Figure 7 — Cumulative probability hierarchy**

The sum of possibilities after each successive encounter can be unity since the satellite will have survived or not. The process at each stage reveals the probability that the satellite would have survived one, two, or more of a sequence of encounters. These can be successive encounters with the same object over time.

It is possible that the cumulative probability of demise over several successive encounters can exceed the threshold of concern even though none of the individual encounters can have individual probability of collision above threshold.

The current threat is not the only threat; and a threat far in the future is not as credible as a threat near at hand.

## 7.4 Bayesian assessment

Bayesian assessment exploits the fundamental principles of conditional probability and multi-discriminant signal detection. Bayesian concepts systematically assess the probability that a given outcome is associated with a set of observables. The observables are called discriminants. The discriminants can include physical observables such as minimum close approach separation between two satellites, the largest probability of collision over the analysis period, or the greatest uncertainty in each satellite orbit. There can also be subjective discriminants such as whether the satellite is manoeuvrable or indications of the consequence of the collision, such as the amount of energy stored within the satellite. Some discriminants are explicitly quantitative. Others tend to quantify them subjectively. One example is associating a weight with the fact that the satellite often has close approaches that confidently have not led to collisions. The relationships among outcomes and discriminants can be analytical or implicit based on well-founded empirical beliefs. There is a significant body of research and literature (e.g. Walpole et al. 2012[20]) One disadvantage of beliefs is that, although the statistical formalism can confirm the connections, the physical details of the connections are not exposed. Therefore, such techniques can be very good indicators of the risk of a conjunction being significant, but they do not necessarily reveal why or provide guidance for mitigation.

# 8 Additional information for judging courses of action

## 8.1 General

Courses of action that are available depend on more information than just close approach distance. Sometimes the only course of action or even the best is just to wait and try to mitigate consequences if the collision itself is unavoidable.

## 8.2 Manoeuvre capability

Whether one or both conjunction partners can manoeuvre is very important. However, there are often other considerations. Manoeuvres consume propulsive energy that is intended for orbit or attitude adjustment or for safe disposal at mission end. Adding additional propellant diminishes useful payload mass. Unanticipated manoeuvres can diminish mission capability and duration. Near mission end, it is possible that there is not sufficient stored energy to manoeuvre, but the consequences of a collision can be confidently minor. Operators can consider many factors beyond just manoeuvre capability in determining a course of action.

## 8.3 Spacecraft characteristics

Spacecraft size, geometry, and the ability to adjust attitude with minimal energy expenditure can be considered. Large spacecrafts likely have large solar panels. Most of the cross section can have low areal density, which is less likely to fragment but more likely to remain in orbit. Spacecrafts such as the ISS have large overall dimensions but many voids, although it is risky to hope that another spacecraft would fly through a void, missing the satellite. Nonetheless, the overall probability of collision can account for voids.

## 8.4 Quality of underlying orbit data

Not all orbit data are equally useful or trustworthy. The quality and credibility of orbit information even from the same provider can vary depending on the sensors that provide observations, the frequency and density of those observations, the correlations among observations as a result of data processing at the source, and even the volume of diverse observations of different satellites, burdening observational resources. The provenance of the data is embodied in the metadata that can accompany the quantitative information. This is a mandatory element of standard orbit data messages, as in ISO 26900.

# 9 Consequence assessment

## 9.1 General

All collisions can be avoided if possible. There are so many qualifying conjunctions that all cannot be acted upon simultaneously or that actions cannot be accomplished as rapidly as possible. Even if response can be expeditious, manoeuvres to avoid collisions change the orbital landscape, possibly jeopardizing satellites that were not initially involved. Restoring the original orbit will also consume energy and change the on-orbit traffic patterns. Therefore, a mechanism for prioritizing responses is needed.

## 9.2 Guidance for population risk

While there are many long-term environment models, none of them can be used to address the greatest operational risk occurring in the short term (hours to weeks) evolution of debris. The principal schemes such as MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) and the NASA Orbital Debris Engineering Model (ORDEM) have been compared as noted in informative references. These models are excellent guidance for the initial stages of a mission, but they do not address near-term threats.

There are other simulations of debris production and near-term evolution of the fragments into the resident space catalogue. These are notionally representative models that are intended to provide broad guidance for the consequences of fragmentation over periods of hours to weeks. The outcomes depend upon assumptions of the degree to which the mass of each collider is intimately involved in the collision. Without knowledge of the satellite architectures and the orientations at the instant of collision, reasonable assumptions of degree of involvement are based on the size of each and general understanding of the existence of appendages. Table 2 is an example of the near-term risk to other satellites stemming from debris generated by the Cosmos 2251-Iridium 33 collision.

**Table 2 — Subsequent risk associated with debris from the Cosmos 2251-Iridium 33 collision**

| Satellite | Fraction of mass involved (%) | Collision partner | Conjunction epoch | Fragments created |
|---|---|---|---|---|
| Iridium 0610 | 10 | Cosmos Debris (Catalog 34015) | 11 Mar 09 00:24 UTC | 198 |
| Cosmos 1867 | 5 | Cosmos Debris (Catalog 34054) | 11 Mar 09 10:24 UTC | 278 |
| Fedsat | 50 | Iridium Debris (Catalog 34105) | 13 Mar 09 03:18 UTC | 68 |
| Cosmos | 5 | Iridium 33 Debris (Catalog 33950) | 13 Mar 09 13:20 UTC | 278 |
| Envisat | 2 | Cosmos Debris (Catalog 3370) | 14 Mar 09 08:01 UTC | 626 |

Table 2 delineates each of several probable collisions, indicating the satellites and debris involved and the degree of contact between colliders at the instant of collision. The estimated number of fragments from these encounters is listed. In some cases, there were probable tertiary collisions.

These estimates and warnings of potential secondary or tertiary events can be included in information exchanges.

### 9.3 Traffic impacts

Collision avoidance manoeuvres cannot be executed spontaneously or capriciously. Considerations include energy required to evade and return to mission orbit, satellites that can be encountered during the manoeuvre and thereafter, and consequences of conjunctions that can be suffered because of the manoeuvre. Manoeuvre timing is critical. Manoeuvring as early as possible yields the most energy efficient and safe avoidance strategy. Discrepancies in executing the manoeuvre can be corrected in due course. However, orbit phasing with ground station contacts and other practical matters can delay executing manoeuvres. Evasive manoeuvres can be combined with or influence regular stationkeeping manoeuvres. Manoeuvres for any reason are typically screened against the resident environment to ensure that collision risks are accommodated both while executing manoeuvres and thereafter.

## 10 Requirements for warning and information for avoidance

### 10.1 General

The previous discussion leads to documentary and operational requirements for warning and providing information for avoiding collisions.

### 10.2 Orbit data

It is obvious that complete orbital data (satellite state, covariance, and physical characteristics, contact information, etc., see 10.2) are required for each satellite that is involved in the estimated conjunction. This is essential to plan mitigations and accommodate consequences. The form and format for exchanging orbit data are in ISO 26900. Such orbit data can accompany the conjunction warning or be either stored and maintained elsewhere or transmitted under separate cover. Selection of the best approach can be a collaborative decision between the operator and conjunction analysis service provider. Any orbit data and metadata can be in standard ISO/CCSDS orbit data message configuration (see ISO 26900).

## 10.3 Minimum data required for warning of and avoiding collisions

The irreducible minimum content is as follows. Each data element is justified in terms of what is needed for.

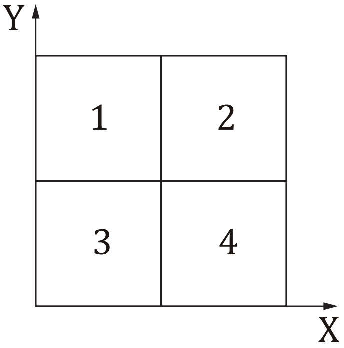
- Time of closest approach in a standard time scale. Required to determine remaining reaction time.
- Identities of the satellites involved and their operational status if known. Required for assessing consequences and mitigation opportunities.
- Satellite owner information for the satellites of interest, if known. Required for coordination and communication of courses of action and potential manoeuvre options.
- Closest approach distance between the two affected satellites in a standard reference frame and coordinate system. Required for assessment if orbit data are not available for each object. Otherwise, it can be computed knowing the estimate time of closest approach.
- A (6 × 6) covariance matrix of three-dimensional position and velocity for both objects in well-defined reference frame at the time of closest approach if available. Required to determine collision probability.
- State of each satellite at the time of closest approach expressed either as a state vector of a single ephemeris in a standard or well-defined orbit determination and propagation scheme. Required to assess consequences and develop manoeuvres that can be developed by propagating each satellite to closest approach.
- Relative velocity at closest approach in the same reference frame and coordinate system as the closest approach distance. Required for assessing consequences and developing manoeuvres, if necessary or if satellite states are not available.
- Close approach threshold, the minimum safe separation that the provider imposes expressed in the same manner as the closest approach. Required because each operator has different risk tolerance. If the reported conjunction is outside the risk threshold of a recipient, the recipient can immediately disregard it.

Object size, shape, and orientation are necessary to determine true probabilities of collision, but often these are truly unknown. This can be mitigated by using a spherical approximation whose diameter is the sum of the largest dimensions of both objects and the maximum probability of collision.

All other information required for planning reaction and assessing consequences can be derived from trustworthy orbit data.

## 10.4 Optional elements of information

Best practices are approaches that are uniformly understood and applicable. Standards codify what is common to most who contribute to the development and share a common need. Information and processes unique to a minority of users can be the subject of interface control documents between specific providers and specific recipients.



**Key**

| | |
|---|---|
| X | amount of common information |
| Y | amount of unique information |
| 1 | ICD |
| 2 | both |
| 3 | neither |
| 4 | standard |

**Figure 8 — Operational execution space**

Figure 8 portrays the operational execution space. If there is considerably more information required by all who participate than there is information unique to only a few, a standard is best. If the amount of unique information far exceeds the amount of data required in common, interface control documents between each pair of participants that can provide or need the unique information are best. If little information of either type is required, no documentary or codified exchange is required. If there are large amounts of optional and mandatory content, both kinds of documents can be used.

## 11 Conjunction and collision assessment workflow and operational concept

Every operation is governed by an operational concept that describes the roles, relationships, and information flows among tasks and stakeholders and the way systems and processes will be used. There are several normative guides for developing and maintaining operational concepts (e.g. see ISO 14950, ISO 17666 and ISO 19971). Since conjunction and collision assessment involves multiple stakeholders, providers, and action recipients, a commonly understood, normative operational concept is essential. Figure 9 and Figure 10 illustrate a representative operational concept.

Figure 9 is a representative operational concept depicting each of the elements in the collision avoidance workflow.

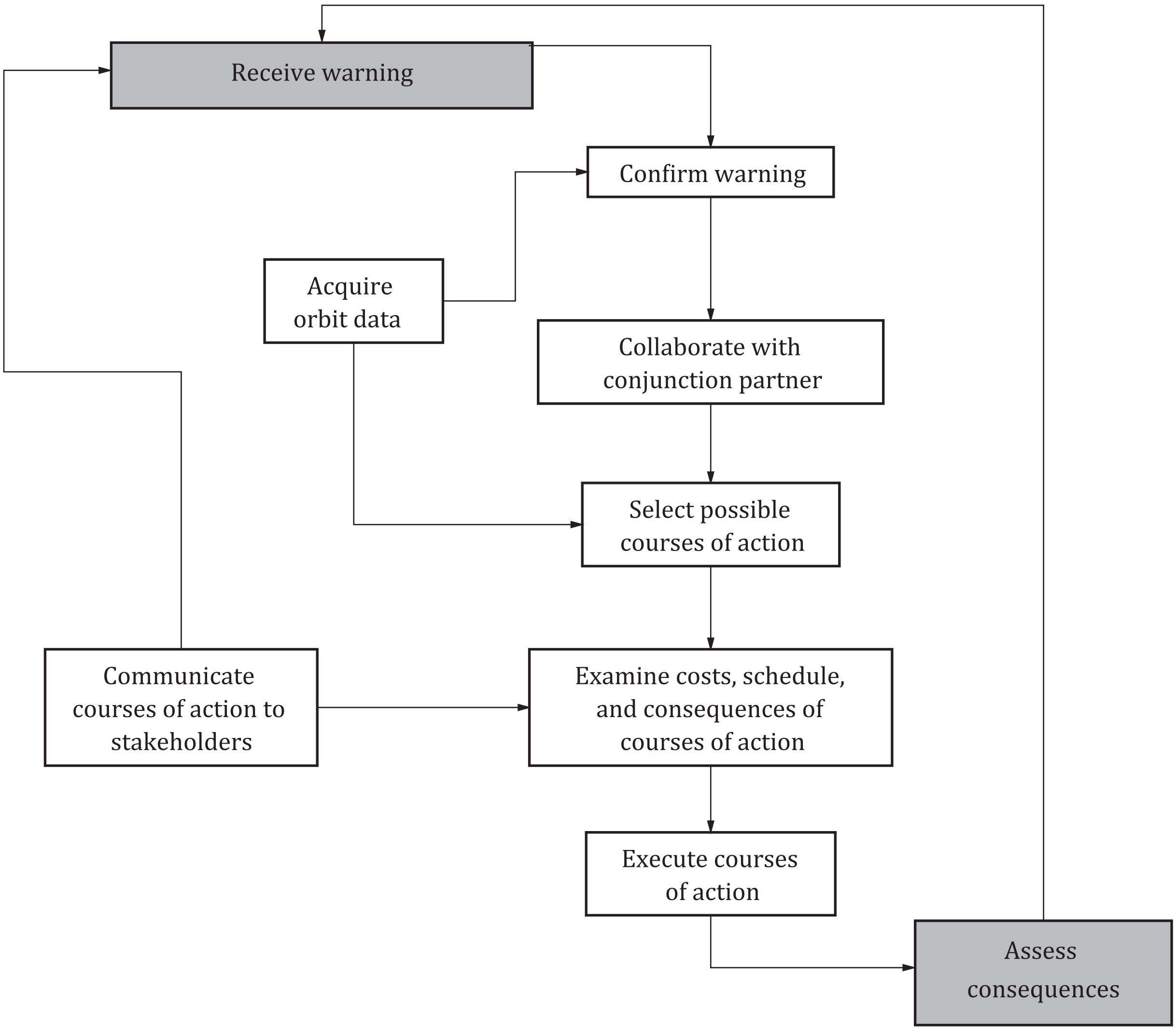


**Figure 9 — Representative operational concept**

Figure 10 expands one of the elements of the representative operational concept.

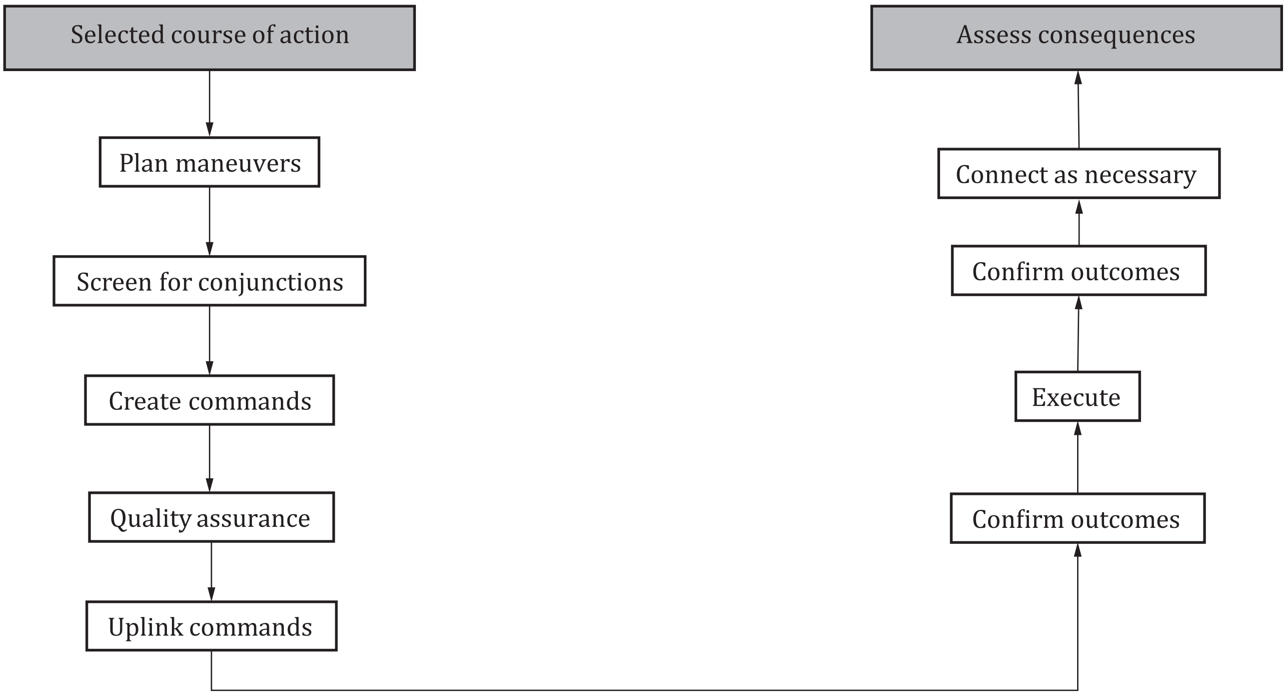


**Figure 10 — Requirements of a function in the operational concept**

This brief exposition is to guide developing sound data requirements that enable a well-understood workflow and interactions among the potentially several organizations that can interact to mitigate the potential consequences of conjunctions and collisions.

# Annex A
(informative)

## Relationship between combined object size, combined positional error, and maximum probability

The relationship between miss distance $d$ and absolute maximum probability $P_{\max}$ for spherical objects can be approximated if the combined object radius $r$ and covariance aspect ratio $A_r$ are known. The formula to be modelled is:

$$x \qquad \text{(A.1)}$$

where $y$ is

$$x_{\mathrm{m}} \qquad \text{(A.2)}$$

and $y_{\mathrm{m}}$ is the combined covariance aspect ratio (major-to-minor axes).

The nomogram of Figure A.1 illustrates these complex relationships by introducing the intermediate variable $\sigma_x$:

$$\sigma_y \qquad \text{(A.3}$$

As an example of the nomogram's use, the goal is to know the maximum probability given a combined object radius of 5 m, a covariance aspect ratio of 5 ( $P_{\max} \cong \left(\frac{\alpha}{1+\alpha}\right)\left(\frac{1}{1+\alpha}\right)^{\frac{1}{\alpha}}$ =5), and a miss distance of 5 km. Following the arrows shown in Figure A.1, the corresponding value appears to be just under $2{,}0 \times 10^{-6}$. For comparison, the numerically computed maximum probability is $1{,}84 \times 10^{-6}$.

With such a nomogram, it is not necessary for the user to solve algebraic equations, to look up values in data tables and possibly interpolate those values, or to use a calculator/computer to obtain results.

The user does not need even to have knowledge of the fundamental formula(e) or principle(s) represented. Typically, a sharp pencil and keen eye will produce results within 5 % of an exact numerical solution. Nomograms not only allow fast estimation; they also can provide insight through the relationship of the various parameters. As in this case, the graphical representation allows the user to readily observe the sensitivity to changes in combined object size, covariance aspect ratio, and/or miss distance.

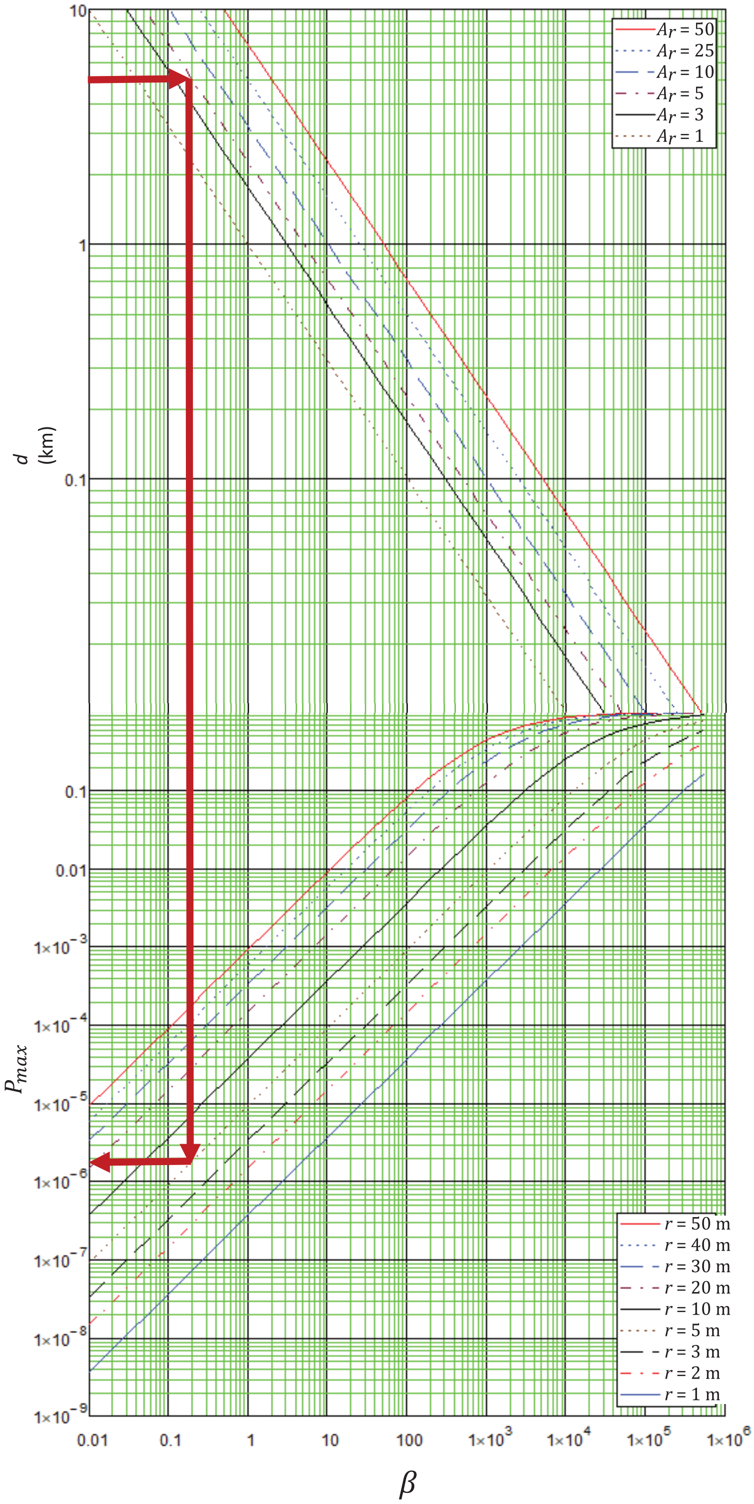


**Figure A.1 — Example of nomogram use to determine $\alpha$ from $\alpha = \frac{r^2 \cdot A_r}{d^2} \, (A_r \geq 1)$, $A_r$, and $\beta$**

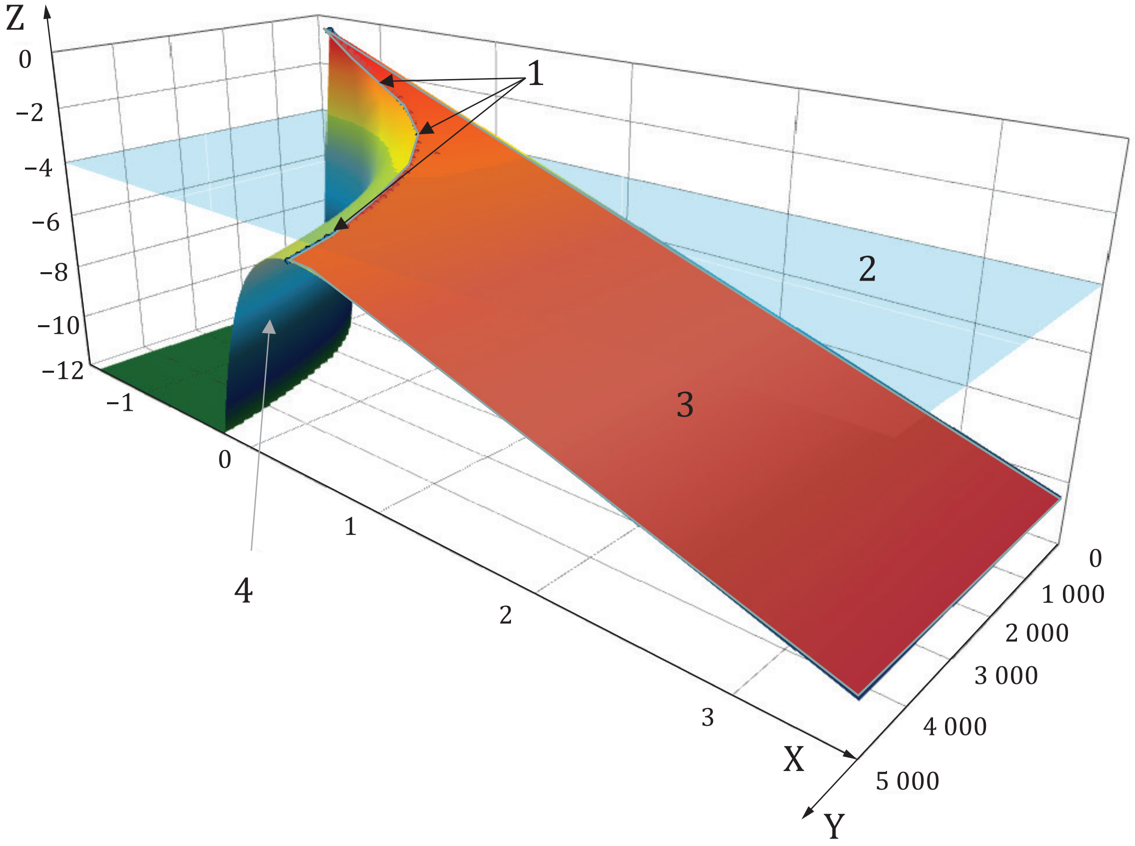
# Annex B
(informative)

# Probability contour visualization

The approach that produced Figure 3 can be extended to show a nominal relationship between $P_c$ and covariance size for a range of miss distances while holding the covariance shape, orientation, and combined hard body object size fixed[19]. Figure B.1 shows a topographical representation of probability contours for fixed hard body radius $r$ in the true space. A grid is created by scaling the distance components by $s_i$ while also scaling the standard deviations by $C_j$. The results are then plotted to show how probability varies with miss distances and covariance size through the following relationships:

$$\beta = \frac{A_r}{d^2} \tag{B.1}$$

$$A_r \tag{B.2}$$



**Key**

X log(sigma)

Y miss distance (m)

Z log($P_c$)

1 maximum probability ‘ridge’ line

2 operator’s $P_c$ threshold

3 data of insufficient quality

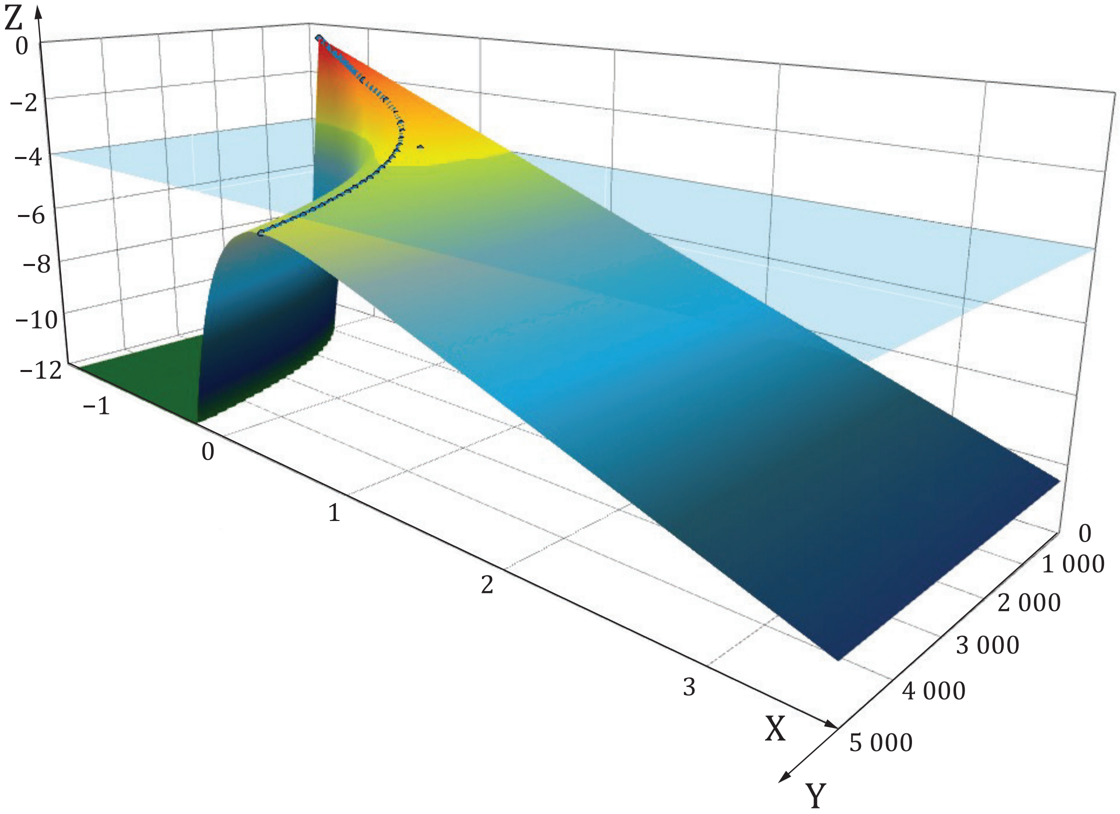
4 data of sufficient quality

**Figure B.1 — Topographical representation of probability contours for fixed hard body radius**

Figure B.1 was generated by an HTML script that created a three-dimensional surface plot[19]. It enables the viewer to interactively reorient the three-dimensional plot and/or zoom in/out using any browser. This HTML is created by varying $s$ and $C$ to create grid points through Formulae (B.1) and (B.2) to generate the topography.

A translucent plane of constant probability is also created to define an action threshold ($P = 10^{-4}$ in this example). If below this plane and outside the dilution region (indicating that data is of sufficient quality) then no remedial action is suggested.

The topology shown in Figure B.2 is unique to all the inputs affecting the probability calculation: combined object size, miss distance components, and covariance size, shape, and orientation.

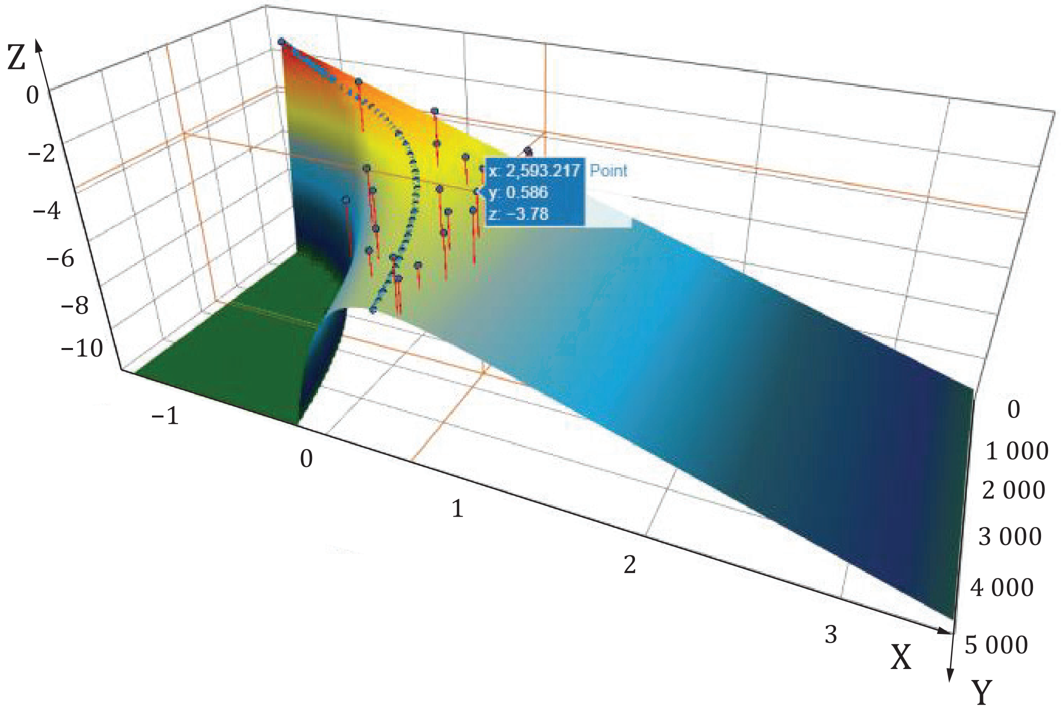


**Key**

| | |
|---|---|
| X | log(sigma) |
| Y | miss distance (m) |
| Z | log($P_c$) |

Figure B.2 — Probability contours in the true space

It is more useful to construct a common, "normalized" version of this surface projection. To accomplish this, a hybrid approach is taken to simultaneously display the estimated actual probability and its representative projection on a reference contour. In this hybrid space the estimated actual probability values (shown as dots) are accurately depicted but the contour below them is not. The surface is merely meant to show where those probabilities rest relative to the maximum probability "ridge." The hybrid depiction is valid even with data points having different covariance aspect ratios, due to the scaling of actual probability value to the ratio of the contour's reference maximum probability[19]. As demonstrated in Figure B.3, hovering the pointer over a data point reveals its information where X is the miss distance in meters, Y is log10 of covariance scale, and Z is log10 of probability. The HTML also projects that point along the orange lines so that one can see precisely where it lies on each axis. Mapping conjunctions into these spaces facilitates the examination of variations in combined object size, miss distance components, and covariance size, shape, and orientation.



**Key**

| | |
|---|---|
| X | log(sigma_scale') |
| Y | miss distance (m) |
| Z | log($P_c$') |

**Figure B.3 — $P_{max}$ and $r$ points displayed in the hybrid space; hovering over a point reveals its associated data**

Table B.1 shows the values of some points on the hybrid space in Figure B.3. Table B.1 facilitates quick and effective conformation of collision probability relating different conditions.

## Table B.1 — Values of some contour surface points of Figure B.3 (1/5)

(1) Miss distance: 0 to 5 000 [m]

z: log($P_c$')

| | | x: Miss distance[m] | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 400 | 800 | 1 200 | 1 600 | 2 000 | 2 400 | 2 800 | 3 200 | 3 600 | 4 000 | 4 400 | 4 800 | 5 000 |
| y: log(sigma_scale') | -1,50 | -1,558 9 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,45 | -1,645 2 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,40 | -1,734 2 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,35 | -1,825 3 | -11,975 6 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,30 | -1,918 3 | -9,980 9 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,25 | -2,012 6 | -8,417 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,20 | -2,108 1 | -7,195 3 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,15 | -2,204 6 | -6,245 5 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,10 | -2,301 7 | -5,511 5 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,05 | -2,399 4 | -4,949 1 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -1,00 | -2,497 6 | -4,522 9 | -10,598 6 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,95 | -2,596 2 | -4,204 9 | -9,031 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,90 | -2,695 1 | -3,972 9 | -7,806 4 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,85 | -2,794 2 | -3,809 2 | -6,854 3 | -11,929 4 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,80 | -2,893 4 | -3,699 7 | -6,118 5 | -10,149 8 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,75 | -2,992 9 | -3,633 3 | -5,554 6 | -8,756 8 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,70 | -3,092 4 | -3,601 1 | -5,127 3 | -7,670 9 | -11,231 9 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,65 | -3,192 0 | -3,596 1 | -4,808 4 | -6,828 9 | -9,657 5 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,60 | -3,291 8 | -3,612 7 | -4,575 7 | -6,180 6 | -8,427 4 | -11,316 3 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,55 | -3,391 5 | -3,646 5 | -4,411 4 | -5,686 2 | -7,470 9 | -9,765 6 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |

## Table B.1 — Values of some contour surface points of Figure B.3 (2/5)

(1) Miss distance: 0 to 5 000 [m] (cont'd)

z: $\log(P_c')$

| | | x: Miss distance[m] | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 400 | 800 | 1 200 | 1 600 | 2 000 | 2 400 | 2 800 | 3 200 | 3 600 | 4 000 | 4 400 | 4 800 | 5 000 |
| y: log(sigma_scale') | -0,50 | -3,491 3 | -3,693 9 | -4,301 4 | -5,314 1 | -6,731 7 | -8,554 5 | -10,782 2 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,45 | -3,591 2 | -3,752 1 | -4,234 7 | -5,039 0 | -6,165 1 | -7,613 0 | -9,382 6 | -11,473 9 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,40 | -3,691 1 | -3,818 9 | -4,202 2 | -4,841 1 | -5,735 6 | -6,885 7 | -8,291 3 | -9,952 5 | -11,869 3 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,35 | -3,791 0 | -3,892 5 | -4,197 0 | -4,704 5 | -5,415 0 | -6,328 6 | -7,445 1 | -8,764 6 | -10,287 2 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,30 | -3,890 9 | -3,971 5 | -4,213 4 | -4,616 6 | -5,180 9 | -5,906 6 | -6,793 5 | -7,841 6 | -9,051 0 | -10,421 7 | -11,953 6 | -12,000 0 | -12,000 0 | -12,000 0 |
| | -0,25 | -3,990 9 | -4,054 9 | -4,247 0 | -4,567 3 | -5,015 6 | -5,592 0 | -6,296 4 | -7,129 0 | -8,089 7 | -9,178 4 | -10,395 3 | -11,740 2 | -12,000 0 | -12,000 0 |
| | -0,20 | -4,090 8 | -4,141 7 | -4,294 3 | -4,548 7 | -4,904 8 | -5,362 6 | -5,922 2 | -6,583 5 | -7,346 6 | -8,211 4 | -9,178 0 | -10,246 3 | -11,416 4 | -12,000 0 |
| | -0,15 | -4,190 8 | -4,231 2 | -4,352 4 | -4,554 5 | -4,837 3 | -5,201 0 | -5,645 5 | -6,170 8 | -6,777 0 | -7,463 9 | -8,231 7 | -9,080 3 | -10,009 7 | -10,504 7 |
| | -0,10 | -4,290 8 | -4,322 9 | -4,419 1 | -4,579 6 | -4,804 3 | -5,093 2 | -5,446 3 | -5,863 6 | -6,345 0 | -6,890 7 | -7,500 6 | -8,174 6 | -8,912 9 | -9,306 1 |
| | -0,05 | -4,390 7 | -4,416 2 | -4,492 7 | -4,620 2 | -4,798 7 | -5,028 1 | -5,308 6 | -5,640 1 | -6,022 5 | -6,455 9 | -6,940 4 | -7,475 8 | -8,062 2 | -8,374 5 |
| | 0,00 | -4,490 7 | -4,511 0 | -4,571 7 | -4,673 0 | -4,814 8 | -4,997 0 | -5,219 8 | -5,483 1 | -5,786 9 | -6,131 2 | -6,516 0 | -6,941 3 | -7,407 1 | -7,655 2 |
| | 0,05 | -4,590 7 | -4,606 8 | -4,655 0 | -4,735 5 | -4,848 1 | -4,992 9 | -5,169 8 | -5,379 0 | -5,620 3 | -5,893 8 | -6,199 4 | -6,537 2 | -6,907 2 | -7,104 3 |
| | 0,10 | -4,690 7 | -4,703 5 | -4,741 8 | -4,805 7 | -4,895 1 | -5,010 1 | -5,150 7 | -5,316 8 | -5,508 5 | -5,725 7 | -5,968 5 | -6,236 9 | -6,530 8 | -6,687 3 |
| | 0,15 | -4,790 7 | -4,800 8 | -4,831 3 | -4,882 0 | -4,953 1 | -5,044 4 | -5,156 1 | -5,288 0 | -5,440 3 | -5,612 9 | -5,805 7 | -6,018 9 | -6,252 3 | -6,376 7 |
| | 0,20 | -4,890 7 | -4,898 7 | -4,922 9 | -4,963 2 | -5,019 7 | -5,092 2 | -5,180 9 | -5,285 7 | -5,406 7 | -5,543 7 | -5,696 9 | -5,866 3 | -6,051 7 | -6,150 5 |
| | 0,25 | -4,990 7 | -4,997 1 | -5,016 3 | -5,048 3 | -5,093 1 | -5,150 8 | -5,221 2 | -5,304 5 | -5,400 5 | -5,509 4 | -5,631 1 | -5,765 6 | -5,912 9 | -5,991 4 |
| | 0,30 | -5,090 7 | -5,095 7 | -5,111 0 | -5,136 4 | -5,172 1 | -5,217 8 | -5,273 8 | -5,339 9 | -5,416 2 | -5,502 7 | -5,599 4 | -5,706 2 | -5,823 2 | -5,885 5 |
| | 0,35 | -5,190 7 | -5,194 7 | -5,206 8 | -5,227 0 | -5,255 3 | -5,291 7 | -5,336 1 | -5,388 7 | -5,449 3 | -5,518 0 | -5,594 7 | -5,679 6 | -5,772 5 | -5,822 0 |
| | 0,40 | -5,290 7 | -5,293 9 | -5,303 5 | -5,319 5 | -5,342 0 | -5,370 9 | -5,406 2 | -5,447 9 | -5,496 1 | -5,550 6 | -5,611 6 | -5,679 0 | -5,752 9 | -5,792 2 |
| | 0,45 | -5,390 7 | -5,393 2 | -5,400 9 | -5,413 6 | -5,431 4 | -5,454 4 | -5,482 4 | -5,515 6 | -5,553 8 | -5,597 2 | -5,645 6 | -5,699 2 | -5,757 8 | -5,789 0 |
| | 0,50 | -5,490 7 | -5,492 7 | -5,498 8 | -5,508 9 | -5,523 1 | -5,541 3 | -5,563 6 | -5,589 9 | -5,620 3 | -5,654 7 | -5,693 2 | -5,735 7 | -5,782 3 | -5,807 1 |
| | 0,55 | -5,590 6 | -5,592 3 | -5,597 1 | -5,605 1 | -5,616 4 | -5,630 9 | -5,648 6 | -5,669 5 | -5,693 6 | -5,721 0 | -5,751 5 | -5,785 3 | -5,822 3 | -5,842 0 |
| | 0,60 | -5,690 6 | -5,691 9 | -5,695 8 | -5,702 1 | -5,711 1 | -5,722 6 | -5,736 7 | -5,753 3 | -5,772 4 | -5,794 2 | -5,818 4 | -5,845 3 | -5,874 7 | -5,890 3 |
| | 0,65 | -5,790 6 | -5,791 7 | -5,794 7 | -5,799 8 | -5,806 9 | -5,816 0 | -5,827 2 | -5,840 4 | -5,855 6 | -5,872 9 | -5,892 2 | -5,913 5 | -5,936 8 | -5,949 2 |

## Table B.1 — Values of some contour surface points of Figure B.3 (3/5)

(1) Miss distance: 0 to 5 000 [m] (cont'd) z: log($P_c$')

| | | x: Miss distance[m] | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 400 | 800 | 1 200 | 1 600 | 2 000 | 2 400 | 2 800 | 3 200 | 3 600 | 4 000 | 4 400 | 4 800 | 5 000 |
| y: log(sigma_scale') | 0,70 | -5,890 6 | -5,891 5 | -5,893 9 | -5,897 9 | -5,903 5 | -5,910 8 | -5,919 7 | -5,930 2 | -5,942 2 | -5,956 0 | -5,971 3 | -5,988 2 | -6,006 7 | -6,016 6 |
| | 0,75 | -5,990 6 | -5,991 3 | -5,993 2 | -5,996 4 | -6,000 9 | -6,006 7 | -6,013 7 | -6,022 0 | -6,031 6 | -6,042 5 | -6,054 7 | -6,068 1 | -6,082 9 | -6,090 7 |
| | 0,80 | -6,090 6 | -6,091 2 | -6,092 7 | -6,095 2 | -6,098 8 | -6,103 4 | -6,109 0 | -6,115 6 | -6,123 2 | -6,131 9 | -6,141 5 | -6,152 2 | -6,163 9 | -6,170 1 |
| | 0,85 | -6,190 6 | -6,191 0 | -6,192 3 | -6,194 3 | -6,197 1 | -6,200 7 | -6,205 2 | -6,210 4 | -6,216 5 | -6,223 4 | -6,231 1 | -6,239 5 | -6,248 8 | -6,253 8 |
| | 0,90 | -6,290 6 | -6,291 0 | -6,291 9 | -6,293 5 | -6,295 8 | -6,298 7 | -6,302 2 | -6,306 4 | -6,311 2 | -6,316 6 | -6,322 7 | -6,329 5 | -6,336 9 | -6,340 8 |
| | 0,95 | -6,390 6 | -6,390 9 | -6,391 7 | -6,392 9 | -6,394 7 | -6,397 0 | -6,399 8 | -6,403 1 | -6,407 0 | -6,411 3 | -6,416 1 | -6,421 5 | -6,427 4 | -6,430 5 |
| | 1,00 | -6,490 6 | -6,490 8 | -6,491 5 | -6,492 5 | -6,493 9 | -6,495 7 | -6,497 9 | -6,500 6 | -6,503 6 | -6,507 0 | -6,510 9 | -6,515 2 | -6,519 8 | -6,522 3 |
| | 1,05 | -6,590 6 | -6,590 8 | -6,591 3 | -6,592 1 | -6,593 2 | -6,594 7 | -6,596 4 | -6,598 5 | -6,600 9 | -6,603 7 | -6,606 7 | -6,610 1 | -6,613 8 | -6,615 8 |
| | 1,10 | -6,690 6 | -6,690 8 | -6,691 2 | -6,691 8 | -6,692 7 | -6,693 8 | -6,695 2 | -6,696 9 | -6,698 8 | -6,701 0 | -6,703 4 | -6,706 1 | -6,709 0 | -6,710 6 |
| | 1,15 | -6,790 6 | -6,790 7 | -6,791 1 | -6,791 6 | -6,792 3 | -6,793 2 | -6,794 3 | -6,795 6 | -6,797 1 | -6,798 9 | -6,800 8 | -6,802 9 | -6,805 3 | -6,806 5 |
| | 1,20 | -6,890 6 | -6,890 7 | -6,891 0 | -6,891 4 | -6,891 9 | -6,892 7 | -6,893 5 | -6,894 6 | -6,895 8 | -6,897 2 | -6,898 7 | -6,900 4 | -6,902 3 | -6,903 2 |
| | 1,25 | -6,990 6 | -6,990 7 | -6,990 9 | -6,991 2 | -6,991 7 | -6,992 2 | -6,992 9 | -6,993 8 | -6,994 7 | -6,995 8 | -6,997 0 | -6,998 4 | -6,999 9 | -7,000 7 |
| | 1,30 | -7,090 6 | -7,090 7 | -7,090 8 | -7,091 1 | -7,091 5 | -7,091 9 | -7,092 5 | -7,093 1 | -7,093 9 | -7,094 8 | -7,095 7 | -7,096 8 | -7,098 0 | -7,098 6 |
| | 1,35 | -7,190 6 | -7,190 7 | -7,190 8 | -7,191 0 | -7,191 3 | -7,191 7 | -7,192 1 | -7,192 6 | -7,193 2 | -7,193 9 | -7,194 7 | -7,195 5 | -7,196 5 | -7,197 0 |
| | 1,40 | -7,290 6 | -7,290 7 | -7,290 8 | -7,290 9 | -7,291 2 | -7,291 4 | -7,291 8 | -7,292 2 | -7,292 7 | -7,293 2 | -7,293 9 | -7,294 5 | -7,295 3 | -7,295 7 |
| | 1,45 | -7,390 6 | -7,390 7 | -7,390 7 | -7,390 9 | -7,391 1 | -7,391 3 | -7,391 6 | -7,391 9 | -7,392 3 | -7,392 7 | -7,393 2 | -7,393 7 | -7,394 3 | -7,394 6 |
| | 1,50 | -7,490 6 | -7,490 7 | -7,490 7 | -7,490 8 | -7,491 0 | -7,491 2 | -7,491 4 | -7,491 6 | -7,491 9 | -7,492 3 | -7,492 7 | -7,493 1 | -7,493 6 | -7,493 8 |
| | 1,55 | -7,590 6 | -7,590 7 | -7,590 7 | -7,590 8 | -7,590 9 | -7,591 0 | -7,591 2 | -7,591 4 | -7,591 7 | -7,591 9 | -7,592 3 | -7,592 6 | -7,593 0 | -7,593 2 |
| | 1,60 | -7,690 6 | -7,690 7 | -7,690 7 | -7,690 8 | -7,690 8 | -7,691 0 | -7,691 1 | -7,691 3 | -7,691 5 | -7,691 7 | -7,691 9 | -7,692 2 | -7,692 5 | -7,692 6 |
| | 1,65 | -7,790 6 | -7,790 7 | -7,790 7 | -7,790 7 | -7,790 8 | -7,790 9 | -7,791 0 | -7,791 1 | -7,791 3 | -7,791 5 | -7,791 7 | -7,791 9 | -7,792 1 | -7,792 2 |
| | 1,70 | -7,890 6 | -7,890 7 | -7,890 7 | -7,890 7 | -7,890 8 | -7,890 8 | -7,890 9 | -7,891 0 | -7,891 2 | -7,891 3 | -7,891 5 | -7,891 6 | -7,891 8 | -7,891 9 |
| | 1,75 | -7,990 6 | -7,990 7 | -7,990 7 | -7,990 7 | -7,990 7 | -7,990 8 | -7,990 9 | -7,991 0 | -7,991 1 | -7,991 2 | -7,991 3 | -7,991 4 | -7,991 6 | -7,991 6 |
| | 1,80 | -8,090 6 | -8,090 6 | -8,090 7 | -8,090 7 | -8,090 7 | -8,090 8 | -8,090 8 | -8,090 9 | -8,091 0 | -8,091 1 | -8,091 2 | -8,091 3 | -8,091 4 | -8,091 4 |
| | 1,85 | -8,190 6 | -8,190 6 | -8,190 7 | -8,190 7 | -8,190 7 | -8,190 7 | -8,190 8 | -8,190 8 | -8,190 9 | -8,191 0 | -8,191 0 | -8,191 1 | -8,191 2 | -8,191 3 |

## Table B.1 — Values of some contour surface points of Figure B.3 (4/5)

(1) Miss distance: 0 to 5 000 [m] (cont'd)

z: $\log(P_c')$

| | | x: Miss distance[m] | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 400 | 800 | 1 200 | 1 600 | 2 000 | 2 400 | 2 800 | 3 200 | 3 600 | 4 000 | 4 400 | 4 800 | 5 000 |
| y: log(sigma_scale') | 1,90 | -8,290 6 | -8,290 6 | -8,290 7 | -8,290 7 | -8,290 7 | -8,290 7 | -8,290 8 | -8,290 8 | -8,290 8 | -8,290 9 | -8,291 0 | -8,291 0 | -8,291 1 | -8,291 1 |
| | 1,95 | -8,390 6 | -8,390 6 | -8,390 7 | -8,390 7 | -8,390 7 | -8,390 7 | -8,390 7 | -8,390 8 | -8,390 8 | -8,390 9 | -8,390 9 | -8,391 0 | -8,391 0 | -8,391 0 |
| | 2,00 | -8,490 6 | -8,490 6 | -8,490 7 | -8,490 7 | -8,490 7 | -8,490 7 | -8,490 7 | -8,490 7 | -8,490 8 | -8,490 8 | -8,490 8 | -8,490 9 | -8,490 9 | -8,491 0 |
| | 2,05 | -8,590 6 | -8,590 6 | -8,590 7 | -8,590 7 | -8,590 7 | -8,590 7 | -8,590 7 | -8,590 7 | -8,590 7 | -8,590 8 | -8,590 8 | -8,590 8 | -8,590 9 | -8,590 9 |
| | 2,10 | -8,690 6 | -8,690 6 | -8,690 6 | -8,690 7 | -8,690 7 | -8,690 7 | -8,690 7 | -8,690 7 | -8,690 7 | -8,690 7 | -8,690 8 | -8,690 8 | -8,690 8 | -8,690 8 |
| | 2,15 | -8,790 6 | -8,790 6 | -8,790 6 | -8,790 7 | -8,790 7 | -8,790 7 | -8,790 7 | -8,790 7 | -8,790 7 | -8,790 7 | -8,790 7 | -8,790 8 | -8,790 8 | -8,790 8 |
| | 2,20 | -8,890 6 | -8,890 6 | -8,890 6 | -8,890 7 | -8,890 7 | -8,890 7 | -8,890 7 | -8,890 7 | -8,890 7 | -8,890 7 | -8,890 7 | -8,890 7 | -8,890 8 | -8,890 8 |
| | 2,25 | -8,990 6 | -8,990 6 | -8,990 6 | -8,990 6 | -8,990 7 | -8,990 7 | -8,990 7 | -8,990 7 | -8,990 7 | -8,990 7 | -8,990 7 | -8,990 7 | -8,990 7 | -8,990 7 |
| | 2,30 | -9,090 6 | -9,090 6 | -9,090 6 | -9,090 6 | -9,090 7 | -9,090 7 | -9,090 7 | -9,090 7 | -9,090 7 | -9,090 7 | -9,090 7 | -9,090 7 | -9,090 7 | -9,090 7 |
| | 2,35 | -9,190 6 | -9,190 6 | -9,190 6 | -9,190 6 | -9,190 7 | -9,190 7 | -9,190 7 | -9,190 7 | -9,190 7 | -9,190 7 | -9,190 7 | -9,190 7 | -9,190 7 | -9,190 7 |
| | 2,40 | -9,290 6 | -9,290 6 | -9,290 6 | -9,290 6 | -9,290 6 | -9,290 7 | -9,290 7 | -9,290 7 | -9,290 7 | -9,290 7 | -9,290 7 | -9,290 7 | -9,290 7 | -9,290 7 |
| | 2,45 | -9,390 6 | -9,390 6 | -9,390 6 | -9,390 6 | -9,390 6 | -9,390 7 | -9,390 7 | -9,390 7 | -9,390 7 | -9,390 7 | -9,390 7 | -9,390 7 | -9,390 7 | -9,390 7 |
| | 2,50 | -9,490 6 | -9,490 6 | -9,490 6 | -9,490 6 | -9,490 6 | -9,490 6 | -9,490 7 | -9,490 7 | -9,490 7 | -9,490 7 | -9,490 7 | -9,490 7 | -9,490 7 | -9,490 7 |
| | 2,55 | -9,590 6 | -9,590 6 | -9,590 6 | -9,590 6 | -9,590 6 | -9,590 6 | -9,590 6 | -9,590 7 | -9,590 7 | -9,590 7 | -9,590 7 | -9,590 7 | -9,590 7 | -9,590 7 |
| | 2,60 | -9,690 6 | -9,690 6 | -9,690 6 | -9,690 6 | -9,690 6 | -9,690 6 | -9,690 6 | -9,690 7 | -9,690 7 | -9,690 7 | -9,690 7 | -9,690 7 | -9,690 7 | -9,690 7 |
| | 2,65 | -9,790 6 | -9,790 6 | -9,790 6 | -9,790 6 | -9,790 6 | -9,790 6 | -9,790 6 | -9,790 6 | -9,790 7 | -9,790 7 | -9,790 7 | -9,790 7 | -9,790 7 | -9,790 7 |
| | 2,70 | -9,890 6 | -9,890 6 | -9,890 6 | -9,890 6 | -9,890 6 | -9,890 6 | -9,890 6 | -9,890 6 | -9,890 6 | -9,890 7 | -9,890 7 | -9,890 7 | -9,890 7 | -9,890 7 |
| | 2,75 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 6 | -9,990 7 | -9,990 7 | -9,990 7 | -9,990 7 |
| | 2,80 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 6 | -10,090 7 | -10,090 7 | -10,090 7 |
| | 2,85 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 6 | -10,190 7 |
| | 2,90 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 | -10,290 6 |
| | 2,95 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 | -10,390 6 |
| | 3,00 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 | -10,490 6 |
| | 3,05 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 | -10,590 6 |

## Table B.1 — Values of some contour surface points of Figure B.3 (5/5)

(1) Miss distance: 0 to 5 000 [m] (cont'd)

z: $\log(P_c')$

| | | x: Miss distance[m] | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 400 | 800 | 1 200 | 1 600 | 2 000 | 2 400 | 2 800 | 3 200 | 3 600 | 4 000 | 4 400 | 4 800 | 5 000 |
| y: log(sigma_scale') | 3,10 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 | -10,690 6 |
| | 3,15 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 | -10,790 6 |
| | 3,20 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 | -10,890 6 |
| | 3,25 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 | -10,990 6 |
| | 3,30 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 | -11,090 6 |
| | 3,35 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 | -11,190 6 |
| | 3,40 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 | -11,290 6 |
| | 3,45 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 | -11,390 6 |
| | 3,50 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 | -11,490 6 |

Such a visualization tool also allows an analyst to project and examine either a time sequence, or a filtered set of samples (e.g. all LEO conjunctions over the past year) of conjunction probabilities on to a common surface. These depictions indicate the usability (soundness) of data feeding a conjunction screening process. Comparing the probability predictions from different sources and epochs can be easily characterized. As shown in Figure B.4, one can discover how deep into the dilution region the conjunctions are and/or examine the progression of updates relative to the maximum probability ridge line.

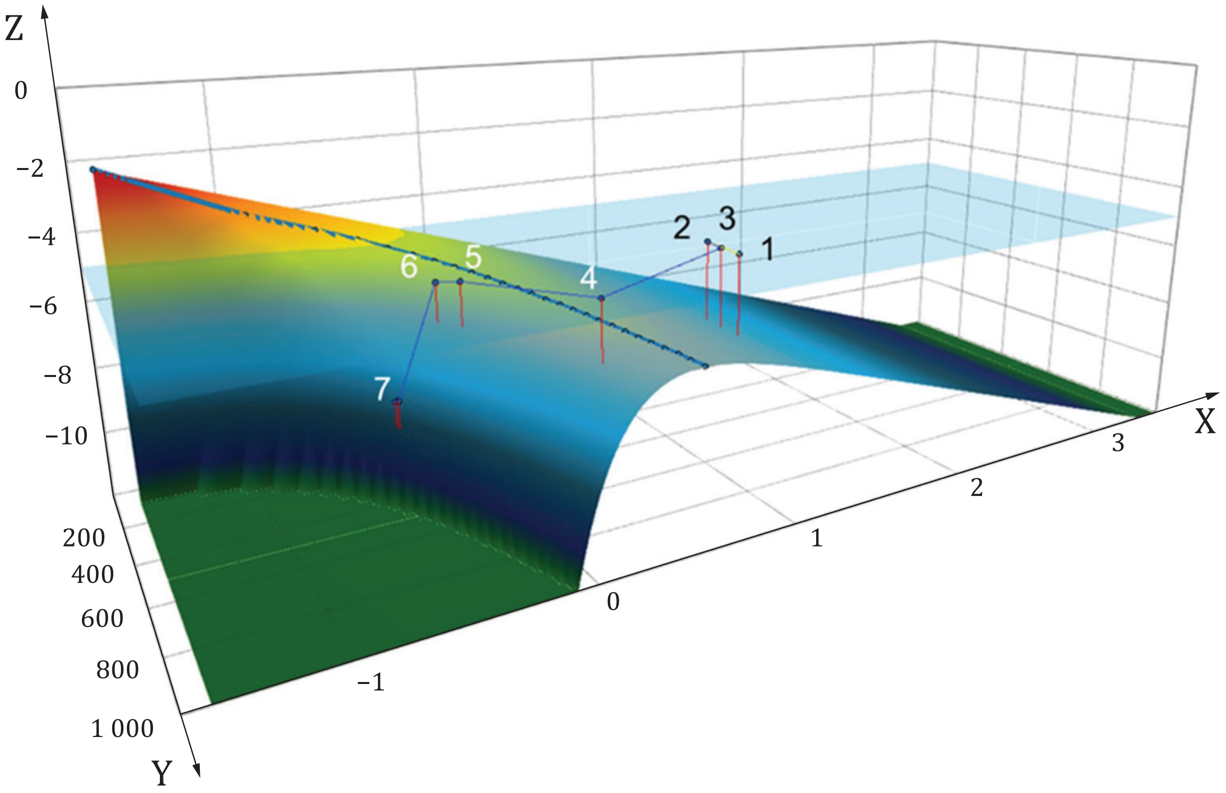


Figure B.4 — Conjunction progression

**Key**

| | |
|---|---|
| X | log(sigma') |
| Y | miss distance (m) |
| Z | log($P_c$') |
| 1 | 1st conjunction prediction in time sequence (oldest, 4.5 days prior to TCA) |
| 2 | 2nd conjunction prediction in time sequence |
| 3 | 3rd conjunction prediction in time sequence |
| 4 | 4th conjunction prediction in time sequence |
| 5 | 5th conjunction prediction in time sequence |
| 6 | 6th conjunction prediction in time sequence |
| 7 | 7th conjunction prediction in time sequence (newest, 8 hours prior to TCA) |

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