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Avoiding Collisions Among Orbiting Objects: Best Practices, Data Requirements, and Operational Concepts

Élément introductif — Élément central — Élément complémentaire

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Foreword

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ISO N385 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

1 Introduction

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

Avoiding Collisions Among Orbiting Objects: Best Practices, Data Requirements, and Operational Concepts

2 Scope

This standard describes the work flow for perceiving and avoiding collisions among orbiting objects, data requirements for these tasks, techniques that can be used to estimate the probability of collision, and guidance for executing avoidance maneuvers. It is a guide for establishing essential collaborative enterprises to sustain the space environment and employ it effectively. This requires normative collaboration 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 must be compared with each other to discern physically feasible approaches that could result in collisions. The trajectories so revealed must then be examined more closely to estimate the probability of collision. Should a collision be likely within criteria established by each satellite operator, the spectrum of feasible maneuvers must be examined.

There are several different approaches to conjunction assessment. All have merits and deficiencies. Most focus on how closely satellites approach each other. This is often very uncertain since satellite orbits generally change more rapidly under the influence of nonconservative forces than observations of satellites in orbit can be acquired and employed to improve orbit estimates. Spacecraft operators require the fullness of orbit data in order to judge the credibility and quality of conjunction perception. This information includes the time at which the orbits were last determined from observations (the epoch), the force models that were used to estimate the orbit, the reference frame/coordinate system in which the orbit data is presented, the effect of uncertainties in the initial observations, and the mathematical approximations that were employed. Essential elements of information for this purpose are specified in ISO 26900, Orbit Data Messages, a normative reference.

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

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

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

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

SATELLITE OPERATORS MUST ACCEPT THAT ALL CONJUNCTION AND COLLISION ASSESSMENT TECHNIQUES ARE STATISTICAL. ALL MUST SUFFER FALSE POSITIVES AND 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.

3 Symbols and abbreviated terms

- Conjunction The apparent meeting or passing of two or more objects in space
- Collision The act of colliding; an instance of one object striking another
- Covariance The measure of how much variables change together. For multiple dependent variables, a square, symmetric, positive definite matrix of dimensionality NxN, where N is the number of variables.
- False Alarm A statistical Type II error, when a statistical test fails to reject a false null hypotesis.
- ICD Interface Control Document, a formal means of describing the inputs and outputs of a system, the interfaces among systems, or the protocols among physical or electronic elements of an entity.
- Operational Concept The roles, relationships, and information flows among tasks and stakeholders and the manner in which systems and processes will be used

4 Collision Avoidance Work Flow

4.1 Overview

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

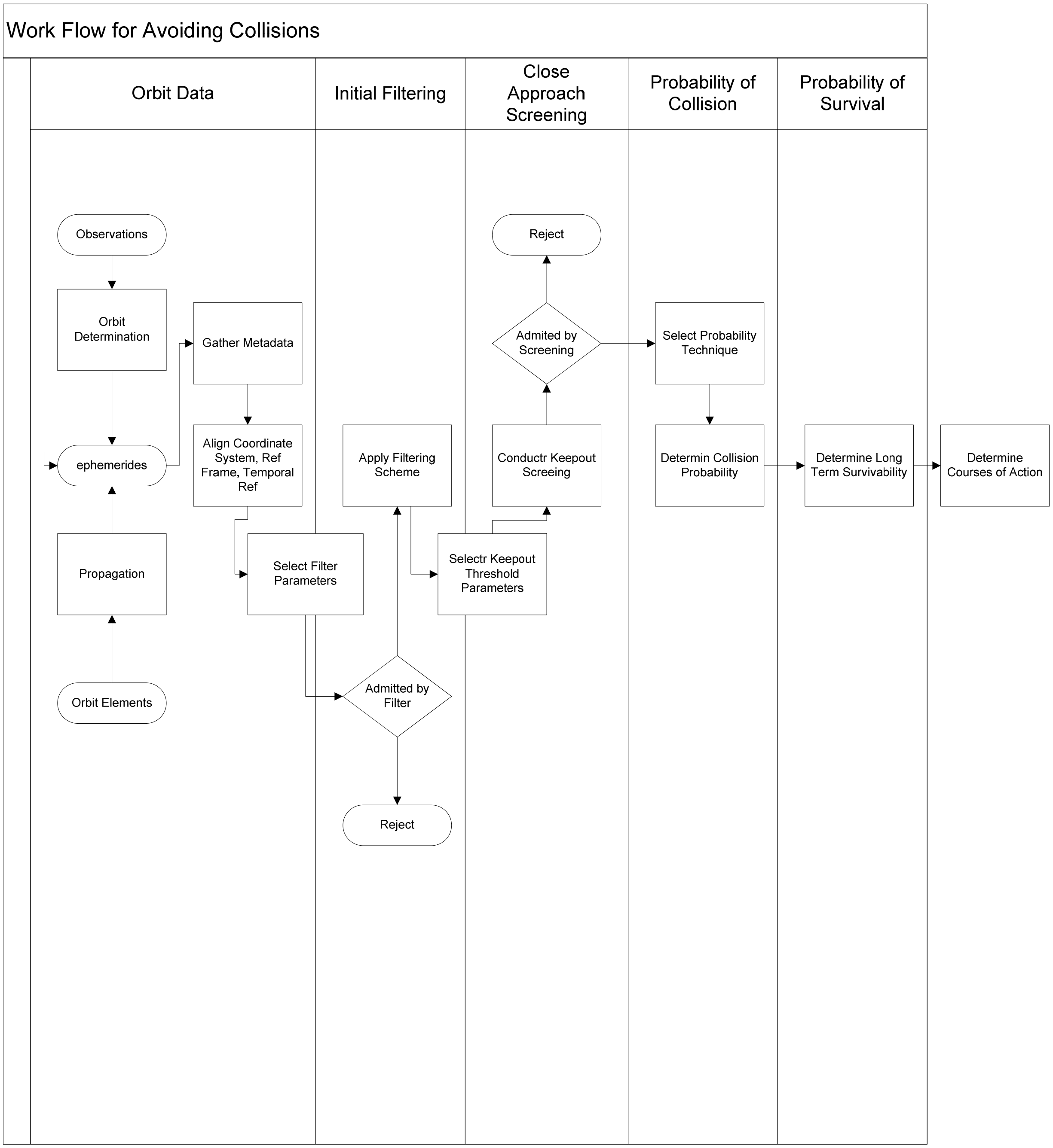


Figure 1: Top level collision avoidance work flow

5 Perceiving Close Approaches

5.1 Orbit Data

5.1.1 Inputs

Inputs to conjunction assessment are principally data that specify the trajectories of the objects of interest. These are one of three types of information: orbit elements, ephemerides, or observations of satellites. Orbit elements in this context include parameters that describe the evolution of the trajectory and which can be used to estimate the trajectory in the future. They are derived from past observations of satellites. Ephemerides are time ordered sets of position and velocity within which one interpolates to estimate the position and velocity at intermediate times. Ephemerides should span the future time interval of interest, the equations of motion having been propagated by the provider. Observations are measurements of satellite position and velocity from one or more well characterized and registered instruments. The recipient must use those observations to estimate the evolution of the trajectory either through direct numerical integration of governing equations or by developing orbit elements for subsequent propagation. ISO S-1123 describes the manner in which a provider's orbit determination scheme should be codified. There are normative formats for orbit elements and ephemerides, ISO S-26900. There are no normative formats for transmitting observations.

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

5.1.2 Propagating All Orbits Over the Interval of Interest

All orbits to be considered must be propagated precisely over the future time period of interest. Since orbit determination and propagation are uncertain, the propagation scheme must be well suited for this interval. AIAA ANSI S-131-2010 is a normative reference for orbit propagation. Osculating orbit estimates grow uselessly imprecise over long propagation intervals. Therefore, conjunction assessment is infeasible at the present state of the art for periods longer than approximately one week beyond the latest orbit determination, depending on the orbit of interest. Some particularly stable orbits might be estimated reliably for longer periods. Probability of conjunction can be estimated over long periods using consistent statistical descriptions of satellite orbits and the evolution of the debris environment. These techniques estimate whether a conjunction will occur or not but cannot expose which specific objects might be involved.

5.2 Initial Filtering

5.2.1 All Against All

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

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

5.2.2 Eliminating Impossible Collisions

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

6. Eliminating Infeasible Conjunctions

6.1 Sieve

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

6.2 Toroidal Elimination

Toroidal elimination screens by determining which mean orbits might touch a toroidal volume defined by the orbit of the satellite of interests and a keepout volume keepout volume cross sectional area.

6.3 Apogee-Perigee Filters

This approach eliminates satellites whose apogees and perigees are greater than those of the satellite of interest. 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.

6.4 Statistical Errors

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

7 Determining Potential Collisions for Warning and Further Action (Close Approach Screening)

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

7.1 Symmetric Keepout

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

7.2 Bounding Volume Keepout

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

7.3 Estimating Probability of Collision

The probability that if two objects are separated by a given distance they might actually collide is the volume of the intersection of the objects' position probability densities. It is 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 physical hypotheses from the measurements. These form a covariance matrix. The covariance matrix is a volume within the phase space of independent variables. It connects imprecision in independent variables with uncertainty in dependent variables.

When the duration of a conjunction is very short with respect to the distance that the satellites move in unit time, the collision path may 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 3x3 position submatrix of the full covariance. These concepts are described in the normative reference ANSI/AIAA-S-131-2010, Best Practices in Astrodynamics.

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 problem is nonlinear, and a more complete position and velocity submatrix is required, at least 6x6.

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 is 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 references. 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 and contained within a cylinder whose cross section is the combined areas of both objects. Figure 2 depicts the geometry of the problem.

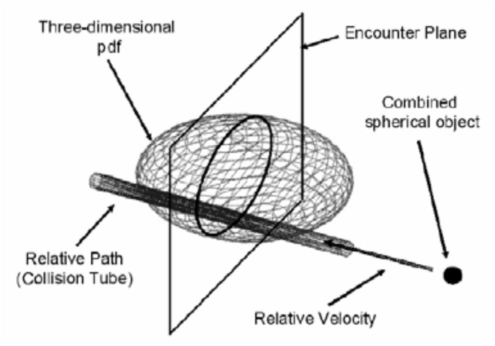


Figure 2: The collision estimation problem

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 must be accommodated consistent with the change in orbit curvature over the encounter interval. This is the case for conjunctions among geostationary objects. Informative references describe the techniques.

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:

$$P = \frac{1}{2 \cdot \pi \cdot \sigma x \cdot \sigma y} \cdot \int_{-OBJ}^{OBJ} \int_{-\sqrt{OBJ^2 - x^2}}^{\sqrt{OBJ^2 - x^2}} \exp\left[\frac{-1}{2} \cdot \left[\left(\frac{x - xm}{\sigma x}\right)^2 + \left(\frac{y - ym}{\sigma y}\right)^2\right]\right] dy\, dx \qquad (1)$$

where OBJ is the combined object radius, x lies along the minor axis, y lies along the major axis, xm and ym are the respective components of the projected miss distance, and σx and σy are the corresponding standard deviations.

There are several numerical techniques for determining the volume whose value is the collision probability. The mathematical statement is often called a Rician Integral and is well documented in communication and signal detection theory. The most widely used numerical approximations to this integral are due to Foster (used by NASA), Chan (Aerospace Corporation), Patera (Aerospace Corporation), and Alfano (Center for Space Standards and Innovation). These have all been evaluated over wide ranges of governing parameters (miss distance, variances, object sizes, covariance aspect rations).

Figure 3 demonstrates the error in each technique compared to exquisite and precise evaluation of the probability. The region of operational interest is probabilities from e-07 to e-01. The threshold of confidence is 1% error. Within this region, all techniques are within 1% of the actual probability for objects whose dimensions are small compared with the dimensions of the covariance volume. Citing any of these techniques is sufficient for users to have confidence in the probability estimate.

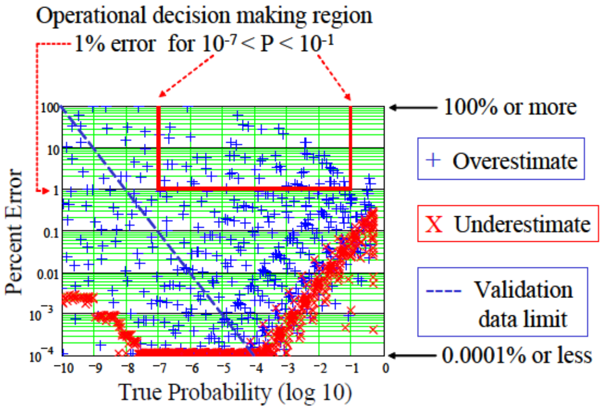


Figure 3: Assessment of confidence in probability of collision

7.4 Maximum Probability

A significant amount of information is required in order to estimate the probability that two satellites might 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 might 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 might be correlated as a result of tracking procedures. Much of the orbit uncertainty will be suppressed artificially. Process models may be deficient or the essential matches among observation frequency, mathematical sampling, physical approximations, and numerical procedures may 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 could be anywhere within large volumes, and the probability that they were in the same place is small.

Figure 4 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.

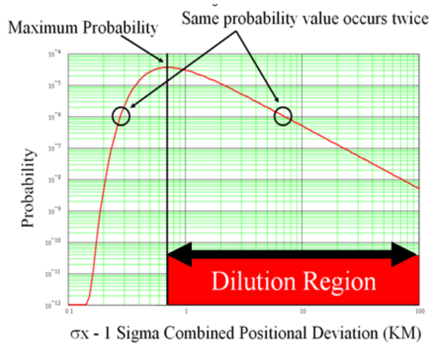


Figure 4: Maximum probability and dilution

7.5 Bounding Volume Based on Probability

An alternative to mitigating lack of information is exhaustive and methodical development of a straightforward bounding volume that encompasses as much of the high probability collision events as is reasonable. CNES excels at this approach. This technique must 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 could be shared and employed whenever other observers and providers consider that satellite.

Figure 5 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 might 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.

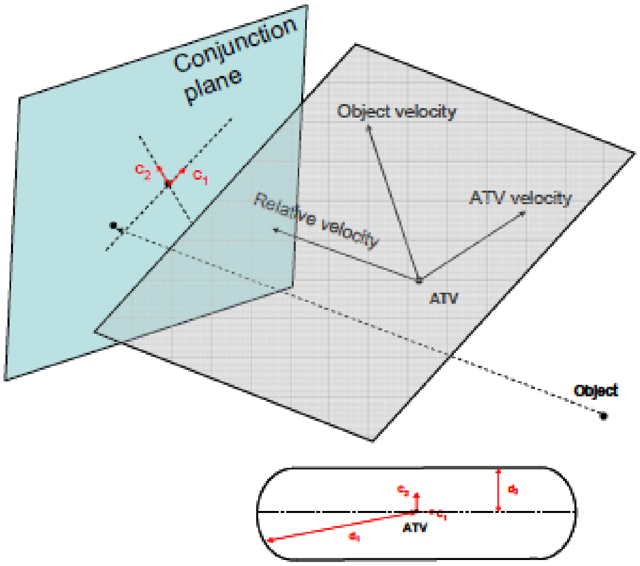
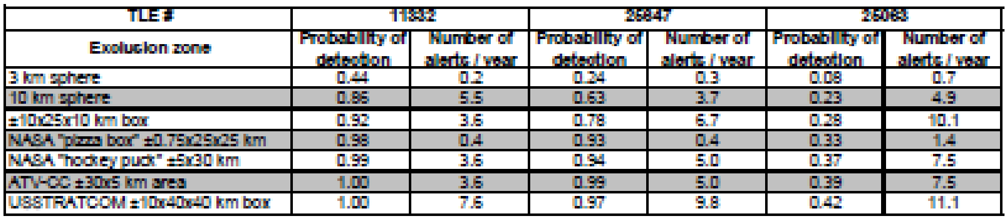


Figure 5: Automated Transfer Vehicle Exclusion Zone



TLE #	11332		26847		26063	
Exclusion zone	Probability of detection	Number of alerts / year	Probability of detection	Number of alerts / year	Probability of detection	Number of alerts / 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
±10x25x10 km box	0.92	3.6	0.78	6.7	0.28	10.1
NASA "pizza box" ±0.75x25x25 km	0.98	0.4	0.93	0.4	0.33	1.4
NASA "hockey puck" ±5x30 km	0.99	3.6	0.94	5.0	0.37	7.5
ATV-CC ±30x5 km area	1.00	3.6	0.99	5.0	0.39	7.5
USSTRATCOM ±10x40x40 km box	1.00	7.6	0.97	9.8	0.42	11.1

Table I: Probabilities of Detection and Probabilities of False Alarm for Different Bounding Volumes

8 Estimating Probability of Survival

The goal of analysis to avoid collisions is that the satellite of interest survive the estimation time interval. The highest probability collision or that with the minimum separation over the time interval generally are not the only conjunctions. They are not necessarily the only conjunctions between the two satellites over this interval. Operators wish their satellites not to experience any collisions, and there is a probability that each conjunction might lead to a collision. As orbit estimates evolve with new observations, close approach between two satellites will change. The closer the current conjunction estimation 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 hence almost never materialize.

8.1 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. The trend that close approach distance exhibits over the estimation interval indicates decreasing separation; hence reason for concern. Probability of collision may increase or decrease. Increasing probability of collision and decreasing separation are cause for concern and preventive action. It is very important that a single discriminant is seldom sufficient for a confident assessment.

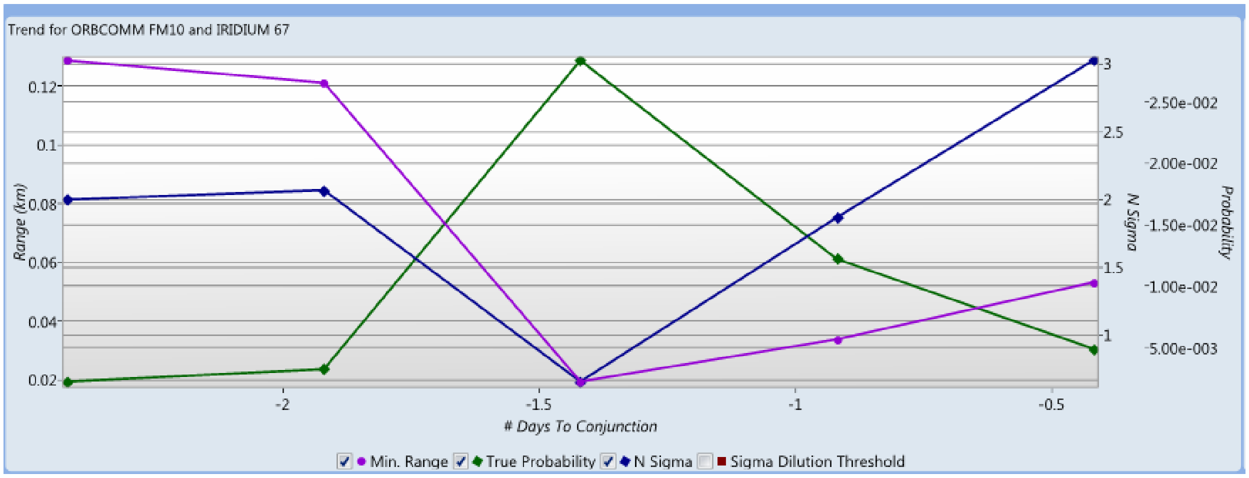
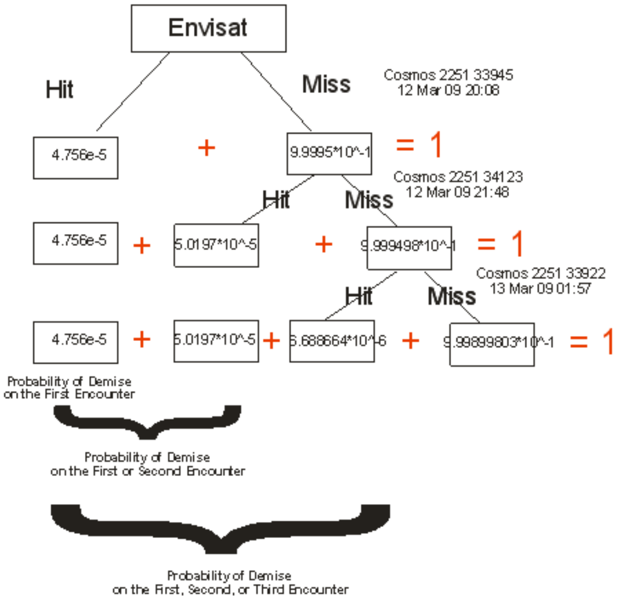


Figure 6: The Trend of Close Approach Between Two Satellites

8.2 Cumulative Probability

The principle of cumulative probability accrues the probability that a single satellite will survive the analysis time period subject to all close approaches that it might 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.



$$Pdemise - cumulative = 1 - \prod_{i=1}^{n}(1 - Pdemise_i)$$

Figure 7: Cumulative Probability Hierarchy

The sum of possibilities after each successive encounter must 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 could be successive encounters with the same object over time.

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

8.3 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 may be 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 may also be subjective discriminants such as whether the satellite is maneuverable or indications of the consequence of the collision, such as the amount of energy stored within the satellite. Some discriminants are explicitly quantitative. Others may be quantified 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 may be analytical or implicit based on well founded empirical beliefs. There is a significant body of research and literature. 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 might be very good indicators of the risk of a conjunction being significant, but they do not necessarily reveal why or provide guidance for mitigation.

9 Additional Information for Judging Courses of Action

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.

9.1 Maneuver Capability

Whether one or both conjunction partners can maneuver is very important. However, this itself may not be a deciding factor. Maneuvers 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 maneuvers can diminish mission capability and duration. Near mission end, there might not be sufficient stored energy to maneuver, but the consequences of a collision might be confidently minor. Operators must consider many factors beyond just maneuver capability in determining a course of action.

9.2 Spacecraft Characteristics

Spacecraft size, geometry, and ability to adjust attitude with minimal energy expenditure must be considered. Large spacecraft likely have large solar panels. Most of the cross section might have low areal density, which is less likely to fragment but more likely to remain in orbit. Spacecraft 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 might account for voids.

9.3 Quality of Underlying Orbit Data

Not all orbit data is 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 metadata that must accompany the quantitative information. This is a mandatory element of standard orbit data messages, as in ISO 26900.

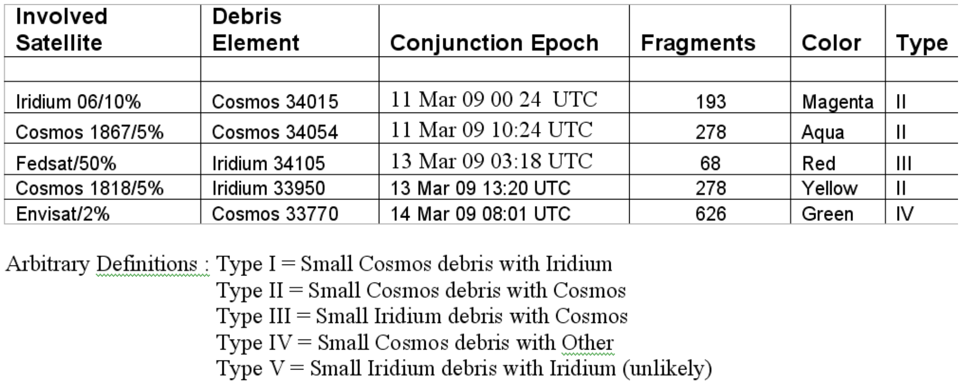
10 Consequence Assessment

All collisions must 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, maneuvers 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, there should be a mechanism for prioritizing responses.

10.1 Contamination and Increased Population Risk

Creating more debris is the most important consequence. There are several models of the long term evolution of the debris environment. Kitazawa has compared the principal schemes such as Master and Evolve, which are noted in informative appendices. Others, such as PODEM, recognize nonlinearities that lead to a more threatening population, but no exponential catastrophe. These models are excellent guidance for the initial stages of a mission, but they do not address the near term threats.

There are simulations of debris production and near term evolution of the fragments into the resident space catalog. These are immature, but they 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 II is an example of the evolution of Cosmos 2251-Iridium 33 debris early in the aftermath.



Involved Satellite	Debris Element	Conjunction Epoch	Fragments	Color	Type
Iridium 06/10%	Cosmos 34015	11 Mar 09 00 24 UTC	193	Magenta	II
Cosmos 1867/5%	Cosmos 34054	11 Mar 09 10:24 UTC	278	Aqua	II
Fedsat/50%	Iridium 34105	13 Mar 09 03:18 UTC	68	Red	III
Cosmos 1818/5%	Iridium 33950	13 Mar 09 13:20 UTC	278	Yellow	II
Envisat/2%	Cosmos 33770	14 Mar 09 08:01 UTC	626	Green	IV

Arbitrary Definitions : Type I = Small Cosmos debris with Iridium
Type II = Small Cosmos debris with Cosmos
Type III = Small Iridium debris with Cosmos
Type IV = Small Cosmos debris with Other
Type V = Small Iridium debris with Iridium (unlikely)

Table II: Subsequent risk associated with debris from the Cosmos 2251-Iridium 33 collision.

The figure 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.

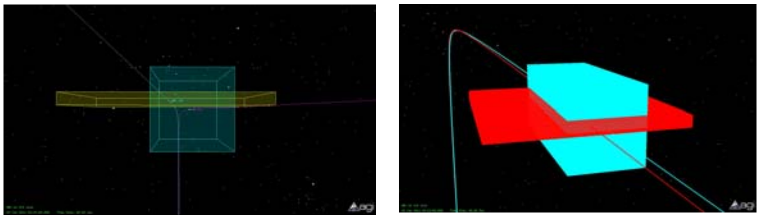
These estimates and warnings of potential secondary or tertiary events should be included in information exchanges.

10.2 Traffic Impacts

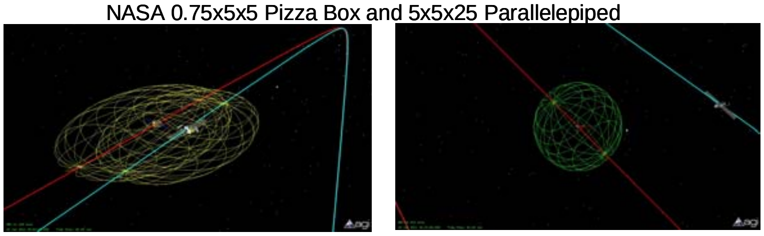
Maneuvers necessary to avoid or mitigate collisions cannot be executed spontaneously or capriciously. Considerations include: energy required to evade and return to mission orbit, satellites that might be encountered during the maneuver and thereafter, and consequences of conjunctions that might be suffered as a result of maneuver. Maneuver timing is critical. Maneuvering as early as possible should be most energy efficient and safe. Discrepancies in executing the maneuver can be corrected in due course. However, orbit phasing with ground station contact and other practical matters might delay executing maneuvers. Evasive maneuvers might be combined with or influence regular stationkeeping maneuvers. Maneuvers for any reason should be screened against the resident environment to assure that collision risks are accommodated.

11. Comparison of Techniques

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



NASA 0.75x5x5 Pizza Box and 5x5x25 Parallelepiped



Intersecting Covariance Ellipsoids 3 Km Diameter Sphere

Figure 8: Comparison if Different Screening and Assessment Techniques.

Figure 8 demonstrates that each screening and analysis technique will perceive events differently. The chart includes the so-called NASA Pizza Box (0.75x5x5 Km parallelepiped) a 5x5 x25 km parallelepiped, covariance ellipsoids and a 3 km diameter sphere. The bounding value is centered 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.

12 Documentary and Operational Requirements

The previous discussion leads to documentary and operational requirements for avoiding collisions. Table III summarizes those requirements. Plans, documents, procedures, and information exchanges shall include all of these elements.

12.1 Orbit Data

It is obvious that complete orbit data is required for each satellite that participates in the estimated conjunction. This is essential to plan mitigations and accommodate consequences. The form and format for exchanging orbit data is in ISO 26900, a normative reference. The decision is whether this should be included in the conjunction warning or whether it is easily accessible otherwise, either stored and maintained current, or transmitted under separate cover. Which is best is an operator and provider collaborative decision. Therefore, Table II presents requirements from both perspectives. Any orbit data and metadata must be in standard ISO/CCSDS orbit data message configuration (ISO 26900).

12.2 Minimum Data Required for Avoiding Collisions

The irreducible minimum content of Conjunction Warning 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 (active, inactive, uncontrolled/debris for example) Required for assessing consequences and mitigation opportunities.
- Closest approach between the two affected satellites in a standard reference frame and coordinate system.

- Three dimensional covariance (6x6) matrix for the secondary object in well defined reference frame at the time of closest approach.
- If one of the objects has a "protected identity", the relative velocity at closest approach in a well defined reference frame.

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

12.3 Data Required to Minimize the Recipient's Computational Burden and Reaction Resource Requirements

The organization that issued the warning must already have synthesized additional products that can facilitate developing courses of action. This information does not change rapidly and can be acquired and stored for rapid access rather than transmitting it of the moment in a congested communications environment. These secondary requirements are as follow.

- 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 maneuvers. Perhaps not absolutely essential, since it can be developed by propagating each satellite to closest approach.
- 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.
- Relative velocity at closest approach in the same reference frame and coordinate system as the closest approach distance. Required for assessing consequences and developing maneuvers, if necessary.
- Probability that the collision might actually lead to contact between the satellites (a collision) and metadata describing how that probability was estimated. Required by some recipients in order to judge what the reaction should be.

12.4 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 should be the subject of interface control documents between specific providers and specific recipients.

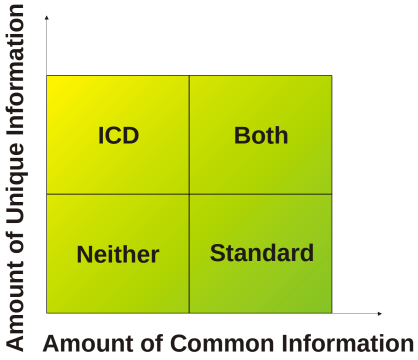


Figure 9: Operational Execution Space

Figure 9 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 should be used. Standardized exchanges should not contain a preponderance of optional content. If most of the content is optional, that is not a standard.

13. Conjunction and Collision Assessment Work Flow 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 manner in which systems and processes will be used. There are several normative guides for developing and maintaining operational concepts. Since conjunction and collision assessment by definition involves multiple stakeholder, providers, and action recipients, a commonly understood, normative operational concept is essential.

Figure 10 is a representative operational concept. Each of the elements in the work flow is presented in the following sections.

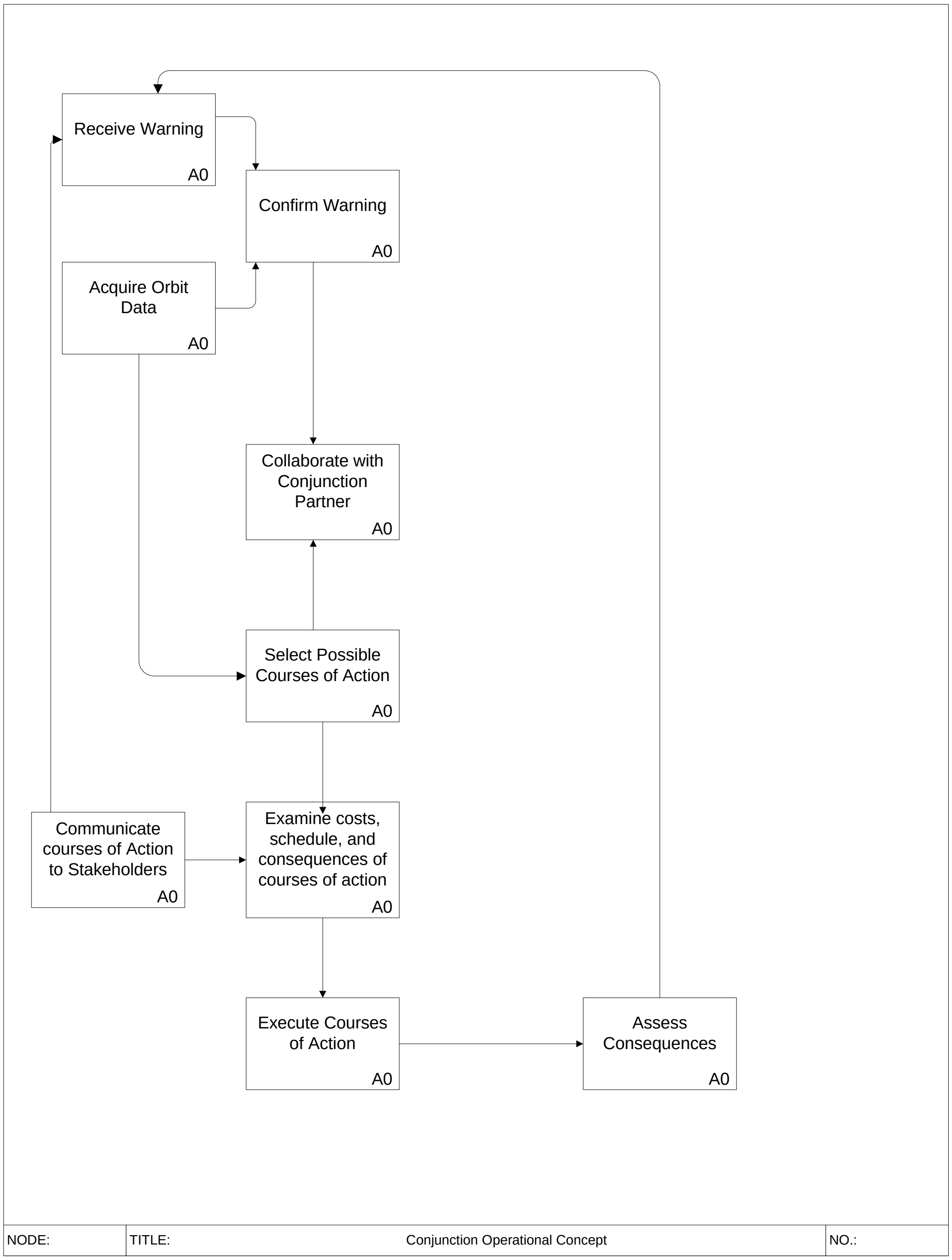


Figure 10: Representative Operational Concept

Figure 13 expands one of the elements of the representative operational concept.

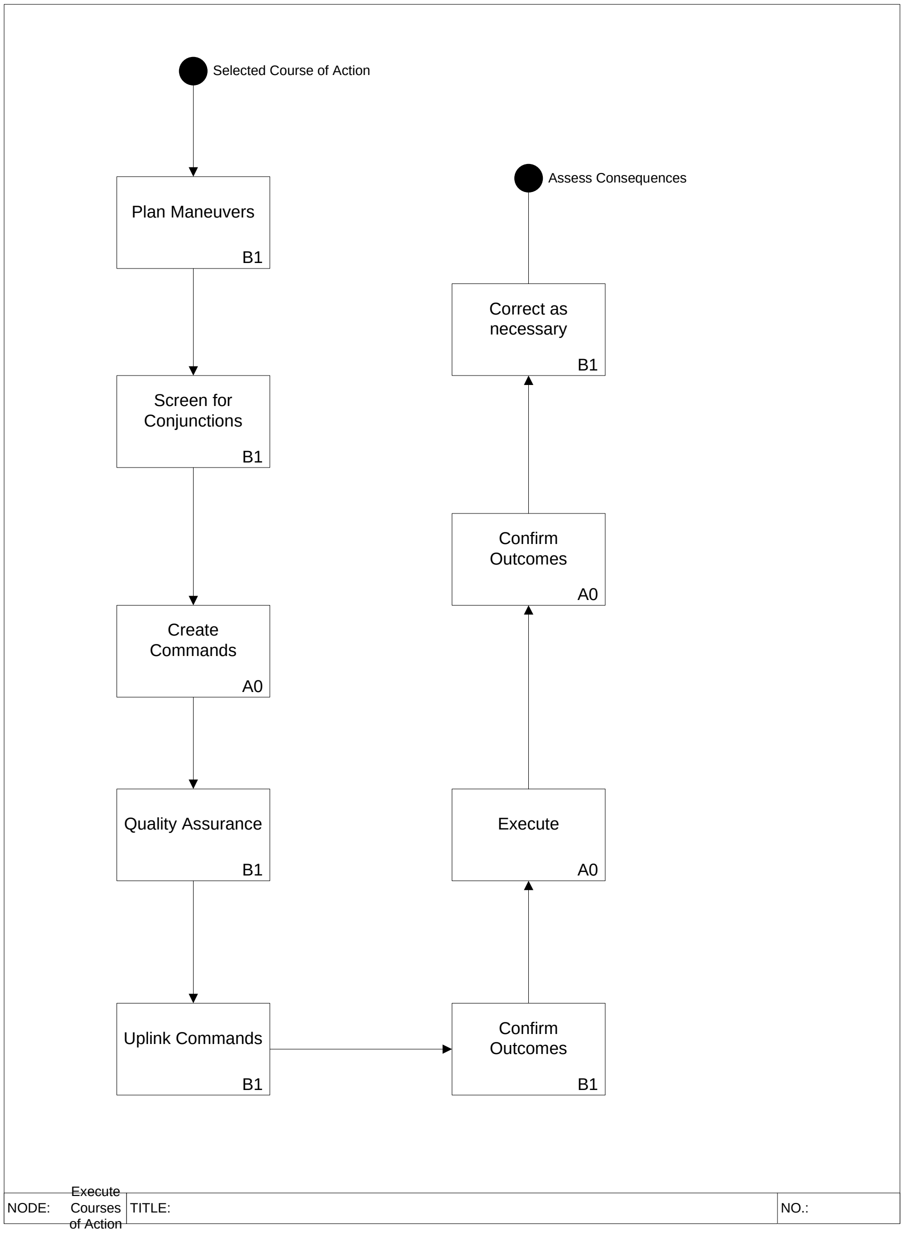


Figure 14: Data requirements of each function of the operational concept

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

NOMATIVE REFERENCES

ANSI/AIAA S-131-2010	Best Practices in Astronautics: Propagation
ISO S-26900	Orbit Data Messages
AIAA G-043-1992	Guide to Developing Operational Concepts

INFORMATIVE REFERENCES

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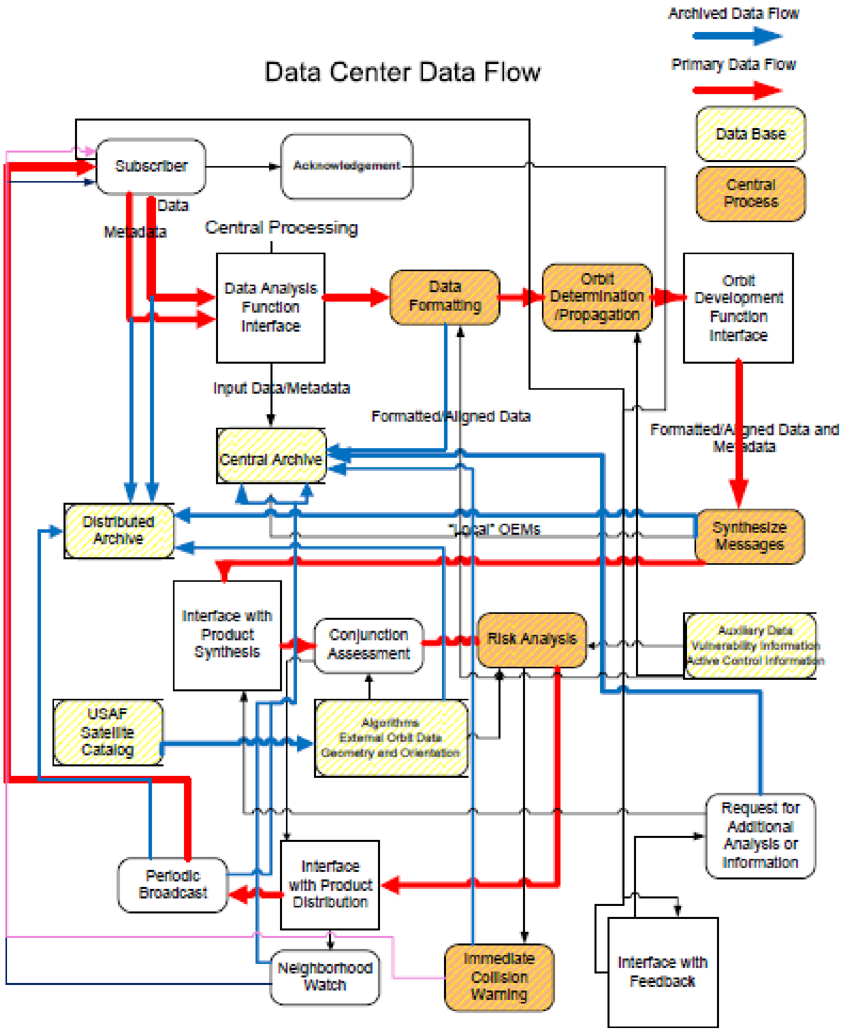
Appendix A: Mathematics of Collision Probability Estimation

Appendix B: Use Cases



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