Commercial Collaboration For Collision Avoidance and Flight Operations

David Finkleman[*]

On Behalf Of

The SDC Team[†]

Abstract

The Space Data Center demonstrates the ability of industry to respond rapidly and effectively to demonstrated need industry-wide and among Governments. This paper will describe SDC architecture and operations, exposing unique capabilities and lessons learned since inception in July 2010. The paper will trace development, describe capabilities, and suggest future collaboration and improvement.

1. Introduction

The investment, utility, and productive capacity of man-made satellites in Earth orbit demand safe and reliable operations. Presently there are no rules, agreements, or legal instruments that facilitate or enforce operational safety among satellites or operators from diverse nations or organizations. It is traffic as existed in cities at the turn of the 19th century except that the elements of transportation travel at kilometers per second and cannot easily arrest their motion nor divert their courses responsively to avoid imminent catastrophe. Most are juggernauts with massive, uncontrolled inertia.

Space traffic cannot be controlled. It can only be planned, trusting that plans can be executed as intended and that the parties involved develop and execute maneuvers collaboratively to avoid exacerbating an already dangerous situation.

Voluntary collaboration for the common good is currently the most proactive and realistic approach to collision threat mitigation. Not all operators will be willing to participate because knowledge of a competitor's movements and capabilities can be perceived as a competitive advantage. Benefit for one can be another's disadvantage. Undisclosed military satellites are the most obvious example of bearing collision risk to preserve important knowledge. Collision risk is contagious. It involves two parties and many other satellites could suffer the consequences. An operator cannot in good conscience decide the risk to be imposed on others or ignore the impact (pun intended) on others. A collision in space benefits no one.

The inevitable inability to know where all satellites are at all times precisely compounds the problem. All observation measurements are imprecise. This imprecision and unavoidable approximation of the forces that govern satellite motion make estimates of satellite trajectories quantifiably uncertain and extrapolation into the future for the purpose of avoiding collisions questionable. Risk mitigation must be extremely conservative to accommodate these uncertainties. Only a few satellites whose motion is almost continuously monitored and for which there are dedicated avoidance processes can claim great confidence in collision avoidance. The International Space Station is the best example.

Fortunately, what is perceived as a crowded environment is still reasonably sparse by terrestrial standards. The environment is also not uniformly congested. Some orbit regimes are more densely occupied than others. Two examples are sun synchronous or geosynchronous orbits. There are hundreds of perceived approaches within a few kilometers every day. The instantaneous probabilities of actual physical contact for a single close approach are extremely small by terrestrial standards[1] Even though the probability across the entire space population is one collision in ten years when aggregated over the next 50 years.[2]

[*] Senior Scientist, Center for Space Standards and Innovation, Analytical Graphics, Inc., 7150 Campus Drive, Colorado Springs, CO 80920, USA, dfinkleman@centerforspace.com

[†] Daniel Oltrogge, TS Kelso, James Wilson, Adam Himes, David Vallado, Salvatore Alfano, Paul Welsh, Analytical Graphics, Inc., 220 Valley Creek Blvd, Exton, PA 19341, USA and many others.

The consequences of collision are unacceptably high; therefore while these probabilities may be low by terrestrial standards, they still justify extreme caution. The threshold established by most owner/operators is one in ten thousand or even one in a million in some cases.[3] Collision probability numbers can be misleading, because the inputs which feed the collision probability assessment can be deceptive. Orbital state vectors, uncertainties, object sizes and object orientations (up to 38 individual parameters) are all key inputs which must be accurately known in order to estimate collision probability. An error in any one of those 38 parameters can affect the collision probability significantly. Low probabilities can be deceptive. The probability of physical contact is low when orbits are known very precisely even though the satellites might approach each other very closely. It is unlikely that the satellites will stray from their accurate mean orbits. The probability of physical contact is also low in the more common situation when we think we know the orbits very precisely but really do not because measurements are very imprecise and models of forces are insufficient. We may be very close to a hypothesized orbit that itself is wrong. However, the probabilities are also low when we do not know well where the satellites are, particularly when it appears that the satellites are far apart even though that might only be a perception. [4]

Unintentional collisions during active operations may be the most serious threat; that is satellites maneuvering in a manner that inadvertently places them and others in jeopardy or satellite trajectories that deviate from what was expected leading to inadvertent close approaches.

No single entity has a complete and timely data set. The United States Air Force (USAF) has the most comprehensive data set, particularly the orbits of inactive and natural debris in Earth orbit. However, USAF orbits are derived only from United States Government (USG) sensors, which limit their ability to keep up with actively maneuvering satellites and to observe some satellites frequently. Consequently, orbits derived only from USG sensor data can be significantly different from where owner/operators know their satellites are during and after maneuvers.[5]

The Space Data Center is executing a phased approach to mitigating, if not overcoming, these issues by employing owner/operator knowledge of their own operations and plans. In the future the SDC hopes to include diverse and pervasive civil, commercial, and governmental sources of additional observations.

2. SDC Evolution

Collision avoidance practices were established in concert with the first STS mission. United States Space Command directed these operations from Cheyenne Mountain using Air Force resources and orbit estimates. Since the Shuttle and the ISS were NASA missions, DoD supported NASA decisions with more intense observation schedules and more timely orbit estimates. NASA manned missions naturally have different threat criteria and procedures than unmanned (robotic) missions. Unique mechanisms were established for data transfer (Conjunction Summary Messages) and collaboration. The fullness of even classified data available to NASA operators is an essential element of the process. Where established data exchange content and format are insufficient for the mission, NASA and DoD users can delve more deeply. Other owner/operators may not enjoy that privilege.

Commercial operators were so concerned that some established compensated relationships with organizations that could use (but not release) privileged data to monitor risks to specific satellites or constellations. Intelsat arrangements with the MIT Lincoln Laboratory and the Aerospace Corporation were most visible. MIT could gather independent observations of geostationary satellites within the field of regard of its radars in Massachusetts. Aerospace Corporation operated under the aegis of the Air Force Space and Missile Systems Center.

The Center for Space Standards and Innovation began a free, web-based conjunction assessment service in 2005. SOCRATES has provided at least twice daily assessments of man made objects in Earth orbit based on publicly available Two Line Element Sets. SOCRATES evolved from TS Kelso's CelesTrak website, widely used for more than 25 years.[6] CSSI also developed advanced probabilistic conjunction assessment techniques, debris and other consequence management models, and techniques for extracting greater value from TLEs.[7] These enabled analyses of the Fengyun 1-C, Iridium 33-Cosmos 2251, and other very important events. Figure 1 is an example of the nearly real time SOCRATES reports.

Action	NORAD Catalog Number	Name	Days Since Epoch	Max Probability	Dilution Threshold (km)	Min Range (km)	Relative Velocity (km/sec)
				Start (UTC)	TCA (UTC)	Stop (UTC)	
Analysis	38036	SOYUZ-TMA 03M [+]	1.982	1.000E+00	0.000	0.000	0.000
	38222	PROGRESS-M 15M [+]	1.982	2012 May 03 12:00:00.000	2012 May 03 12:00:00.000	2012 May 10 12:00:00.000	
Analysis	38096	ATV-3 (EDOARDO AMALDI) [+]	1.982	1.000E+00	0.000	0.000	0.000
	38222	PROGRESS-M 15M [+]	1.982	2012 May 03 12:00:00.000	2012 May 03 12:00:00.000	2012 May 10 12:00:00.000	
Analysis	06659	METEOR 1-15 [?]	5.259	3.710E-02	0.009	0.036	14.773
	26654	CZ-4B DEB [-]	6.338	2012 May 07 16:15:42.490	2012 May 07 16:15:42.829	2012 May 07 16:15:43.167	
Analysis	09481	METEOR 1-26 [?]	1.110	2.620E-03	0.053	0.089	3.397
	38124	FENGYUN 1C DEB [-]	5.950	2012 May 03 13:10:57.312	2012 May 03 13:10:58.784	2012 May 03 13:11:00.255	
Analysis	25394	RESURS O1-N4 [?]	3.952	2.604E-03	0.035	0.136	13.714
	33865	IRIDIUM 33 DEB [-]	4.752	2012 May 06 19:57:10.016	2012 May 06 19:57:10.381	2012 May 06 19:57:10.745	

Figure 1: Sample SOCRATES report.

Collegial relationships and research collaboration with major communication satellite operators fostered extrapolating the SOCRATES capability to owner/operator trajectories and much more refined orbit data in general. Presaged by discussions between Intelsat and NASA and commercial operator discussions with the Aerospace Corporation, meetings between CSSI and Intelsat flight dynamics principals in 2007 and 2008 led to a seminal gathering at Telesat in Ottawa in December 2009. This led to preliminary terms of reference and organizational concepts for the Space Data Association, incorporated on the Isle of Man in 2010.

SDA Objectives

- Seek and facilitate improvements in the safety and integrity of satellite operations through wider and improved coordination between satellite operators
- Seek and facilitate improved management of the shared resources of the Space Environment and the RF Spectrum

SDA founding members are Intelsat, SES, and INMARSAT, who, together with Eutelsat comprise the SDA executive membership. Operational concepts and doctrine were exceptionally important. The principals are competitors. Their collaboration was a milestone in industrial cooperation to meet a common challenge. Data integrity and security, actionability, and reliability were major considerations. Neutrality among claimants from different nations and jurisdictions was critical. The SDA conceived requirements for a conjunction assessment center with these criteria and doctrines. The SDA solicited operational and technical capabilities, and a contract was awarded to AGI in the spring of 2010. Initial operational capability was achieved in the July 2010 based on SOCRATES capabilities and technology. Final operational capability followed in September 2011 based on modern web services, flexible software architecture, and state of the art security and reliability.

SDA membership via a commercial contract or agreement is required in order to contribute data to the SDC and receive conjunction assessments. Currently there are 17 active member organizations, and over 300 geostationary and lower orbit satellites in the scheme. These include several governmental organizations.

Membership continues to grow. Figure 2 depicts current active population of the geostationary protected region, denoting SDA subscribers and those who are not yet subscribers.

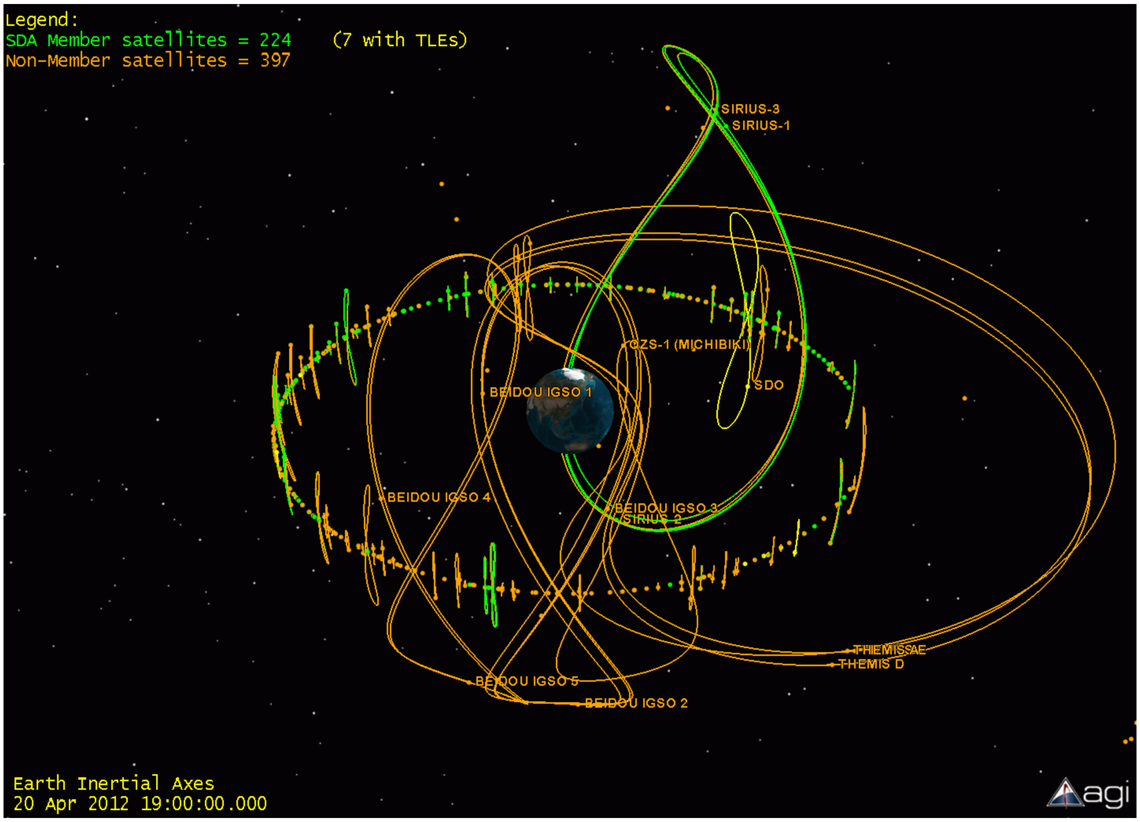

Figure 2: Active satellite population in the geostationary protected region. SDC members in green (224), non members in orange (397)

3. SDC Capabilities

The SDC is based on commercial off the shelf elements and state of the art service oriented software architecture and web services. The capabilities are illustrated in the representative work flow shown in Figure 3.

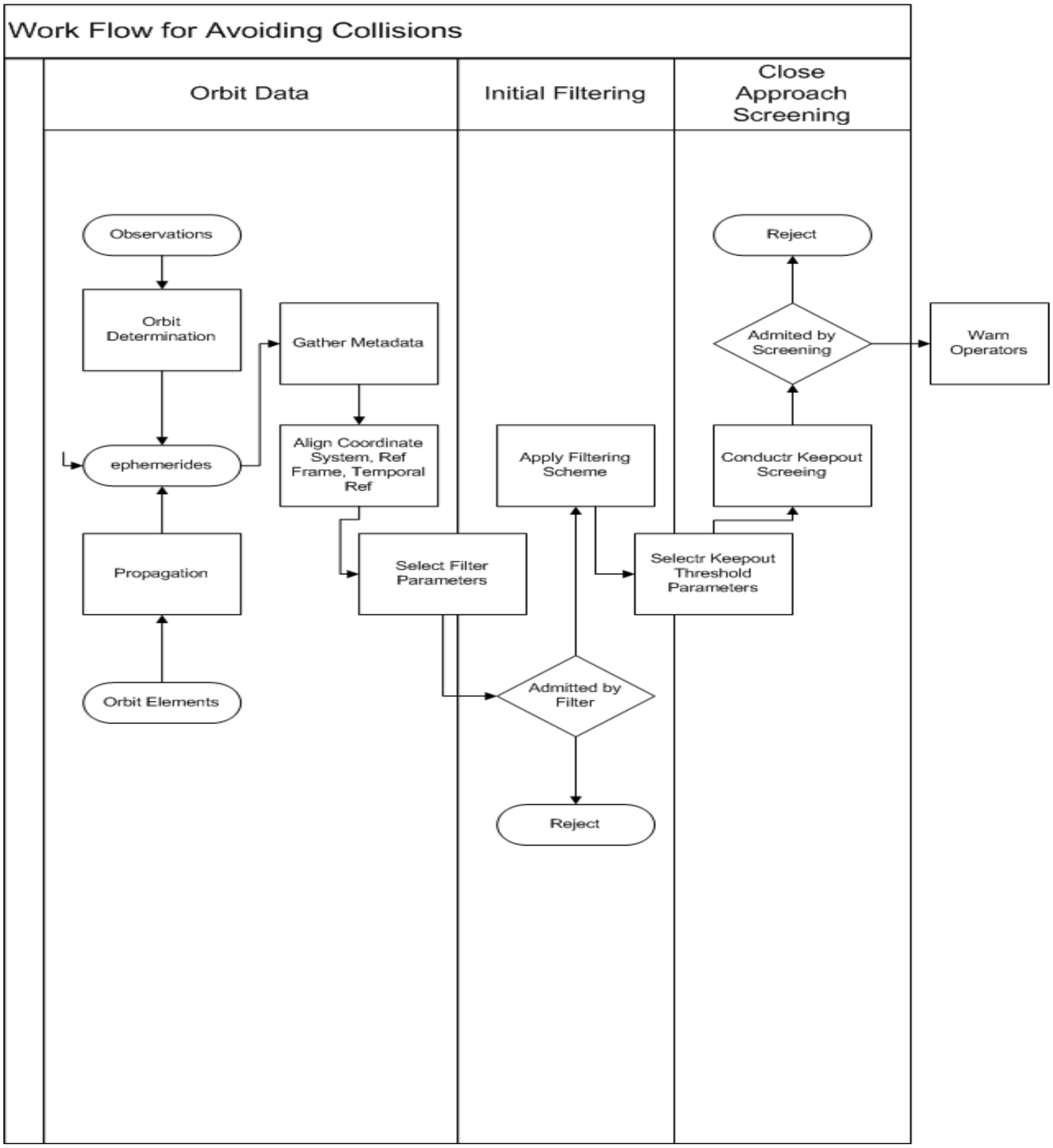

Figure 3: Representative collision avoidance work flow.

3.1 Highly Accurate and Precise Satellite Orbits

Owner/operator observations and ephemerides are the best representations of the states of their satellites. Operators employ techniques they trust and which have enabled reliable resource management. These techniques have evolved unique to constellations or even individual satellites. They are not uniform even among constellations controlled by a single operator. Operators acquire satellites on orbit that were previously controlled by others. Some organizations, such as Intelsat, operate satellites for other service providers.

There are many techniques for developing orbit estimates from observations. Most are described in ISO DIS 1123[8]. They are also enumerated in Vallado's text.[9] They include a variety of statistical filters, least squares, and differential correction of recent orbit estimates. The SDC can employ most of the alternatives but trustworthy conjunction estimates require that output ephemeris products from both conjunction partners be consistent and compatible.

The SDC has demonstrated the ability to ingest and apply consistently ephemerides in many forms and to produce consistent representations of the orbit estimates and their uncertainties. The SDC has also demonstrated advantages of predictive filters, but it can ingest the outputs of any other orbit determination approaches that users prefer.

3.2 Estimate and Report Conjunctions

SDC principals have developed internationally recognized requirements for CA from their SDC experience.

Conjunctions are close approaches among satellites. They are not collisions. Different operators have different judgment of what constitutes a close approach. The SDC accommodates criteria the operators establish as opposed to what might be convenient for the SDC. The most important requirement is that perceived conjunctions include as many high probability collisions as possible. The SDC has established a mathematically rigorous approach to determining close approach thresholds sufficient for individual operators' risk tolerance.

Conjunction assessment can be computationally intensive. Starting with the entire catalog, the possibilities are first thinned with a filtering technique, which eliminates satellite pairs virtually impossible to lead to close approaches. The surviving pairs are screened more precisely, reducing the number that must be examined intensively to estimate collision probability. ISO CD 16158[10] enumerates widely used filtering and screening techniques. Any approach that a user prefers could be employed.

The SDC exercises unique diligence in assuring actionable conjunction assessments. CSSI experts have defined requirements for actionability.[11] These include considering the age of orbit estimates included, the reference frames and coordinate systems of contributing data, the time span in which observations were gathered, the force models employed in owner/operator generated ephemerides, the reliability of owner/operator maneuver plane, and many other factors.

By now all seriously involved in conjunction assessment recognize that the task demands orbit estimates much more accurate and with uncertainty much better characterized than any other satellite operational task. Even proximity operations can be quantifiable collision risks.

One criterion for response is that there is sufficient time to plan and execute evasive maneuvers with minimal expenditure of stored energy. Kelso and Oltrogge have confirmed that accurate orbit estimates about two days into the future are required to facilitate operator action.[12] CSSI has developed maneuver planning tools that estimate the energy required, the thrust vector, and the time required to reduce collision probability to a safe value.[13]

Owner/operators also plan maneuvers and estimate ephemerides for different time spans in the future. These are operational imperatives unique to the satellite and mission. The SDC has developed procedures to bring orbit estimation time spans for conjunction pairs into a common time span. There are several ways to do this, for example truncating all ephemerides to the shortest time span among them or using ephemerides provided to extend orbit estimates to a longer time span using trusted orbit determination techniques.

Data alignment is important since different owner/operators conduct operations in a variety of reference frames and potentially different time scales. Absolute time from a common past reference is critical since it determines Earth Orientation Parameters (EOP) necessary to correlate observations from an Earth fixed, rotating reference frame to the inertial reference frame in which satellite orbits are determined and in which stellar references reside. The correlation between coordinated universal time and time expressed in Earth orientation and rotation angle is a key concern. Therefore, the time scale and the reference frame are interdependent. The variety of reference frames and alternative orbit element formulations in operational use today is astounding. Sometimes operators themselves do not realize what reference frame their software uses. Even if they do, reference frame descriptions change with time and using an old version can mislead interpreting ephemerides. SDC principals have devoted significant effort to reference frame-related forensics data analysis prior to including data into the SDC.

Reporting conjunction perceptions is much more than sending an email. Essential elements of information must be included, both data and metadata. Operators whose satellites are in jeopardy must be able to trust and to confirm conjunction assessments. The SDC accomplishes this through data provided by SDC subscribers on their own satellites, quality controlled and timely use of the public catalog, databases of subscriber satellite characteristics, and very active contribution to international standards for such exchanges such as Orbit Data Messages[14] and Conjunction Data Messages[15].

The SDC maintains continuous vigilance for close approaches to all subscriber satellites, screening with user-specified thresholds in a neighborhood watch, and immediately transmits conjunctions with notable close approach. The usual format is that provided in the SOCRATES free web service. Prudently, the SDC does not presume to manage evasive maneuvers, which are best dealt with collaboratively by the parties involved. The timing of close approaches, relative velocities, and close approach distances in the SDC format are ultimately verifiable, since orbit data, force models, propagators, and other essential elements of analysis are well described and easily accessible.

Our diligence in characterizing orbit determination and propagation techniques is widely recognized and well documented. We were principal authors of normative standards and best practices.[16,17] . We can employ almost any widely used schemes and force models. We have examined the effects of different force models, representations of the atmosphere, multibody effects, and influences of solar and other radiative fields.[18] The SDC operators examine the accuracy and precision of owner/operator ephemerides quarterly[19]. Accuracy is how well orbits match a reference. Do we determine the satellite's state consistently with independent ground truth? Precision is the dispersion of repeated measurements or estimates. We have demonstrated that Two Line Element sets (TLE) can be inaccurate as well as imprecise.[20]. Semi-analytic theories such as those embedded in TLEs do not explain all of the inaccuracies and imprecisions in orbit estimates. Even numerical orbit determination schemes have as yet unexplained issues. Often there is no truth. Observations themselves are imprecise. It is very important that the imprecision be understood and characterized. Imprecision is represented by dynamic variances and covariances. As previously stated, covariances are the most important element of conjunction and collision assessment.

The issue of a realistic covariance matrix cannot be overemphasized, and in fact, it has received considerable discussion over the last few years. Batch least squares techniques produce a covariance matrix as a result of the estimation process and the additional state parameters included—solve-for parameters, track weighting, etc. This technique has been used for many years, but may experience difficulties when non-conservative forces introduce significant error into the solutions. Using a statistical Filter such as a Kalman Filter that incorporates mathematically derived process noise has the advantage of not being constrained by the fit span, and the limitations that imposes on dynamic variables in the solution. However, the filter solution may not model the mean long term behavior in prediction as well as batch least squares methods, although various fading memory approaches can be used to adjust bias and drift uncertainty. [21]

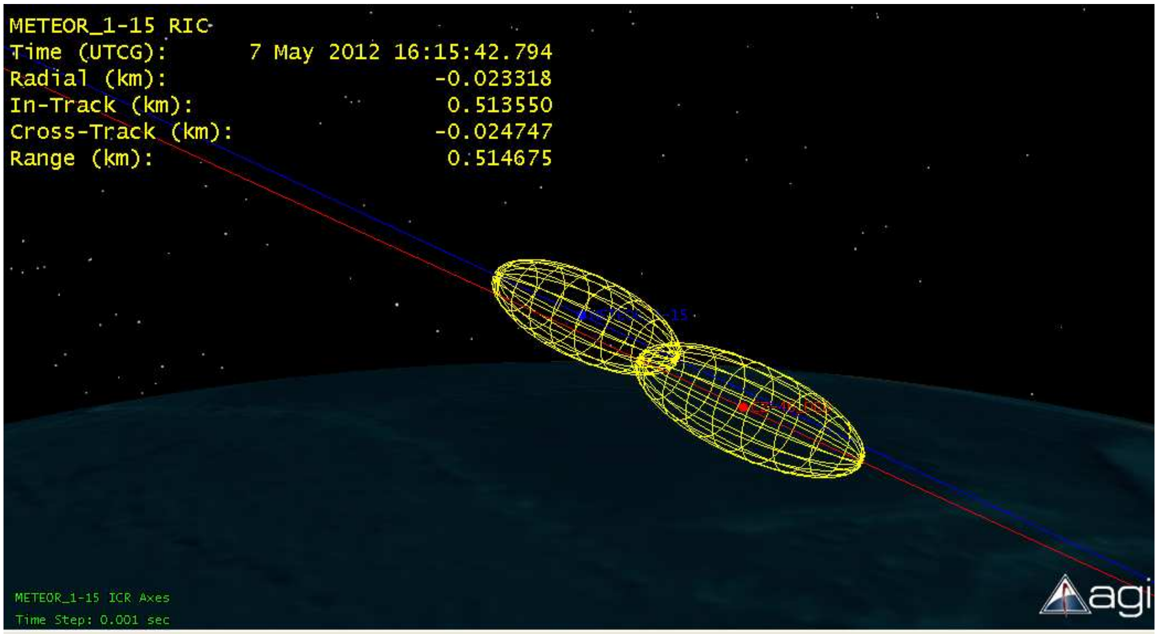

Figure 4. Conjunction Encounter Geometry

The figure shows a generic close approach scenario. Each satellite has an associated velocity and covariance. The combined error ellipse is simply the summation of each individual covariance and the relative velocity vector is used to define the encounter plane. The sigmas (n) should be the same for each error ellipse. (STK image courtesy of AGI)

For orbit propagation, maneuver detection, and tracking, the covariances must be a consistent product of orbit propagation. Covariances that are scaled or otherwise manipulated independent of the mathematical orbit determination or propagation processes should not be used to estimate collision probabilities. We are very serious about covariance realism and consistency.[22]

3.6. Quality Control and Database Maintenance and Assurance

The CelesTrak service has been for nearly 30 years the most widely used and trusted value added source of orbit data, including extensive and searchable historical records. CelesTrak is the paradigm for SDC operations. The SDC scrutinizes publicly available orbit data, usually providing the first and only detection of cross-tagging (associating an orbit estimate with the wrong satellite, missing data, and other anomalies). The SDC maintains current databases of points of contact among subscribed operators and satellite characteristics important for orbit estimation such as satellite mass and ballistic coefficients. The integrity of sensitive orbit and satellite data is exquisite and spotless with state of the art distributed server reliability and web services, including physical security that critical revenue sensitive operations require.

4. Operational Experience and Value Added

The SDC is also the source of new standards and operational practices. It is pioneering fusing owner/operator data with independent observations. It has enabled advances in track association, choosing safe keepout volumes, and understanding the advantages and deficiencies of existing public satellite catalogs. There is no substitute for doing the job. That experience was gained over eight years, beginning with SOCRATES.

This experience has contributed much to recent international and national standards. For example, the diversity of reference frames, coordinate systems, and time scales among satellite operations was astounding. Operators should control what coordinate systems, reference frames, and time scales are best for their operations. However, in order to communicate essential data to those who must collaborate, for example to avoid collisions, these physical constructs must be completely described to others or they should conform to standard approaches that are widely accepted and documented. Orbit and conjunction data message international standards facilitate this. Such standards are based in great measure on SDC experience and direct participation of SDC principals.

The utmost importance of trust among collaborators and the ability to verify mission and revenue critical data is one of the most important SDC legacies. Conjunction reports and assessments are estimates based on past information. The time of closest approach, minimum separation between satellites, and relative velocity are imprecise to a degree determined by the imprecision and inaccuracy of contributing orbit estimates. The uncertainty can be such that dangerous situations might not be identified or safe passage is confused with danger. Evasion and mitigation are planned and executed by affected operators based on their best mutual understanding of each other's kinematic states. This is generally not the same data that was used to detect danger or issue warnings. Commercial operators are reluctant to accept without confirmation another's estimate of the risk to the operator's assets and revenue. Those with sufficient resources must have information for them to verify conjunction warnings. Those who operate few satellites or are disadvantaged must have ultimate confidence in those they rely on. The SDC provides the fullness of information to subscribers and potentially others who are at risk. The SDC has earned the confidence of many who operate few satellites or who lack resources or skills to verify independently. These principles are reflected in international best practices for avoiding collisions currently being developed with SDC leadership.[23]

It is important to separate operations from maintenance and development while maintaining close connection is very important. The SDC has demonstrated the ability to sustain reliable operations while developing new capabilities and resolving operational problems. Having separate but identical servers has been critical. The SDC has an independent "sand box" for offline development.

5. Plans and emerging capabilities

One should use the best orbit data, data transfer, and supporting databases to help perceive, locate, and mitigate electromagnetic interference with critical Comsat operations. The SDC is well along developing this capability. We have demonstrated the value of more precise orbit data in classical TDOA, FDOA, and cross-correlation geolocation. The SDC can host member data spanning operational contacts, satellite electromagnetic characteristics, reference emitters, and transponder coverage for subscribers. It is charged by the SDA to enable the commercial RFI warning process.

No space surveillance capability is ubiquitous. None are required to be because the requirement is to obtain a sufficient number and distribution of observations to estimate orbits consistent with satellite missions and avoiding collisions among them. This can be approached with a spectrum of observation locations and capabilities from which the most appropriate set can be created. Presently the SDC has only subscriber observations and orbit data, and USAF two line element sets. While the USAF has putatively the best orbit estimates for debris, which is the greatest threat in LEO, it does not enjoy competition sensitive subscriber orbits, which the SDC has. We support and hope for an industry-government collaboration.

Lacking that, the SDA seeks independent sources of trustworthy observations and independently reliable orbits of debris objects in orbit in order to minimize the risks to subscribers. An initial announcement in Madrid in 2011 was followed by a more substantial set of requirements and solicitation at the first SDA Users Meeting during Satellite 2012. Several institutional and industrial observation organizations have responded. The US National Oceanic and Atmospheric Agency employs SDC services. The diligence of SDC orbit determination, quality control, data assurance, and security makes incorporating these sources of information straightforward.

New value added capabilities are developed continuously. One of the most important is a mathematically and physically sound way to balance the probability of correctly identifying a potential collision with the probability of incorrectly including false alarms among pairs of satellites potentially at risk. The technique guides determining consistently filtering and keep out/screening criteria. It is described in recent conference papers[24] and best practice documents[25].

Conclusion

Nearly 300 satellites participate in SDC work flows, this includes more than 60% of geostationary communication satellites. Their operations span numerous operational software suites and operational concepts. Combining these was a monumental task. The entire operation and capability cost a very small fraction of member operational expenditures or what a comparable Government sponsored project would cost.

The SDC demonstrates that competitors who face a common risk can collaborate to mitigate the threat to all. Competitors and other participants reside in many nations, industries, and governments. While the policy and diplomatic communities deliberate confidence building and transparency, the civil and commercial cohorts have accomplished these. This demonstrates the feasibility and wisdom of national space policies that encourage or even mandate furtherance of commercial capabilities.

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