Current State of Conjunction Monitoring for Satellite Operators and the Steps Forward

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Abstract: The paper will discuss the current state of conjunction monitoring for the satellite operators. We will go over the different conjunction monitoring systems being offered and the development of a satellite operators and owners self-managed space data association (SDA). In this presentation we will present in general the different practices of close approach monitoring processes being implemented by the different operators. We will discuss our experiences on satellite conjunctions and the risks for the current systems including the many false alerts and missed conjunctions. We will also discuss the lesson learn and other ideas for moving forward including (1) acquiring independent data to validate orbit uncertainties, (2) data fusion to improve orbit solutions accuracies and uncertainties, (3) different conjunction detection techniques and selection of thresholds to provide more reliable and actionable assessments and (4) techniques to monitor miss distances to help validate potential close approaches.

Keywords: *Collision monitoring, Conjunctions, Close approaches*

1. Brief History of Close Approach Monitoring Services

In 1999 Aerospace Corporation via the Space Operation Support Office (SOPSO) started offering to satellites operators close approach monitoring service. The Aerospace Corporation developed a fully automated two tier program that determined satellite close approaches based on miss-distances and conjunction probabilities. The initial detection was based on the publicly available Two Line Element sets (TLE). Once a potential conjunction was identified Aerospace Corporation would request the more accurate special perturbation (SP) ephemeris data on the behalf of the satellite operators from the Air Force to confirm the conjunction. The Aerospace Corporation shut down the SOPSO office abruptly in November 2002 and the support was terminated. About the same time MIT Lincoln Lab offered similar services to satellite operators to perform close approach analysis. It was a semi-automated system and the conjunction detection was based on miss-distances only. Because MIT had a contractual relationship with the Air Force, and therefore direct access to the observations from the deep space surveillance network, the conjunction monitoring was based on a single tier process. However, the monitoring was restricted to non-active passive space objects. This restriction was due to the difficulties in detecting past maneuvers and predicting future maneuvers of active satellites and thus invalidated longer term close approach predictions. The US government was providing a service to satellite operators via. the CFE program. In this program the satellite operators could send in a request for close approach screening. This process was a pilot program and at that time it was a relatively long process. The CFE program was replaced with the service currently provided by the Join Space Operation Center (JSpOC). The current process is a great improvement and more structured than the CFE program. Dr. Kelso has been providing a public service to monitor close approaches for the entire catalog using TLE vs TLE. This is a comprehensive all-on-all monitoring tool and is named SOCRATES. In 2006, Intelsat and two other geostationary (GEO) satellite owner/operation Inmarsat and SES approached Dr. Kelso to create a prototype data center to be managed by satellite owner/operator. This led to the creation of SOCRATES-GEO. SOCRATES-GEO employs the ephemeris data form the owner operators and TLE for close approach screening. In this case when close approaches are detected an alert will be issued to the concern parties. Finally in 2010 the satellite owners/operators got together and created a legal non-profit entity named the Space Data Association (SDA) to provide active screening for satellite operators. SOCRATES-GEO was migrated to the new operation center, Space Data Center (SDC) under the management of SDA. This data center is an interactive repository for commercial satellite orbital, maneuver and frequency information. Satellite operators would routinely deposit their fleet information into the trusted third party Data Center, SDC and retrieve information from other member operators when necessary. The Data Center would allow operators to augment existing TLE data with precision orbit data and maneuver plans from the operator's fleets for close approach monitoring. This type of data sharing tries to address the need to share information for safety of flight and the security and company proprietary concerns. The Data Center is managed by the satellite operators and being a not-for-profit organization providing services to the satellite operators.

2. Different Models of Current State of Close Approach Monitoring

There are different implementation of close approach monitoring tools developed by different software vendors and satellite operators. Unfortunately due to limitation of reliable ephemeris data the different models are limited in the reliability and efficiency.

The most common type is the conjunction monitoring based on TLE and the owner operator precision ephemeris data which contains the maneuver information. In most cases the conjunction detections are based on a combination of the miss-distances of the two satellites or an assigned probability of conjunction. There difficulties is in the computation of conjunction probability which requires the knowledge or an estimate of the uncertainties of the TLE. This model, named the in-house model, is limited by the accuracies of TLE. There are drawbacks in this close approach monitoring process. In addition to lack of standards of TLE propagators, TLE data do not have the required accuracy for credible collision detection. An operator that is forced to rely on TLE data must increase the calculated collision margin to avoid potential close approaches. In most cases, threats identified using the basic TLE data are downgraded after coordination with other operators or further evaluation with more precise orbital data. In addition to the inaccuracies of the TLE data, these data also lack reliable maneuver information. This limits the usefulness of the TLE for longer term predictions, since maneuver information is necessary to properly predict the ephemeris for active satellites. The lack of this data becomes increasingly problematic as more satellites employ ionic propulsion systems and are, essentially, constantly maneuvering. This is a two tier model require further evaluation and validation of a conjunction threat using TLE data with more authoritative data, either the ephemeris data from another operator or the more precise special perturbation (SP) ephemeris from the Joint Space Operation Center (JSpOC).

With the creation of SDA the members are able to share data for close approach monitoring. One advantage is that the conjunctions resulted from the screening among member ephemeris are actionable since the close approach analysis is based on precise satellite owner/operator data including the planned maneuvers. The conjunction detection is based on miss-distance and the miss-volume is configurable by the member per satellite. There are plans in SDA to add the probability of collision to the detection criteria. A few difficulties include building a mechanism for the members to upload their covariance for the ephemeris and the uncertainty estimates for the non-active and non-cooperative satellites. Unfortunately it still has the drawback when close approaches involve non-member satellites or non-active space debris. In these situations, the alerts are based on TLE and once received the alerts it still require a 2nd step to validate the conjunction with more authoritative data.

In the recent years the JSpOC has provided a service for satellite operators who has signed a tailor agreement. The service provides active-on-all conjunction screening. The criteria for close approach are based on miss-distances and are configurable by the users. JSpOC will issues both email alerts for potential conjunction in the next 3 days and the conjunction summary message (CSM) or the conjunction data message (CDM) to the users. The CSM/CDM is available on the JSpOC spacetrack.org.

The take away is that most of the current available close conjunction monitoring systems is based on a two tier process. The risk for a two tier process is that is not sufficient and inefficient. The alerts come out from the system are not actionable immediately and it takes additional steps to validate the conjunction with more authoritative data. In many situation this will take away valuable time if avoidance maneuvers are needed. In addition, because of this, most operators would increase their alert thresholds to minimize the risks of missed conjunctions and this lead to "false" warnings. Unfortunately this added workload to the operators to analysis "false" alarms and there are still risks of missed conjunction.

3. Concerns with Two Tier Conjunction Monitoring Process

Table 1. showed a typical alerts Intelsat receives in 12 months with a fleet of 75 GEO satellites.

Conjunction based on SP vs. SP	Conjunction based on Ephemeris vs. TLE	Conjunction based on Ephemeris vs. SP	Avoidance Maneuver Performed
175	142	25	5

Table 1. Detected Conjunctions for a period of 12 Months

Most of the detected conjunctions using TLE and SP data only were downgraded with more accurate ephemeris data and when maneuver information was included in the conjunction assessment. The number of detected conjunctions using Ephemeris and SP data is based on JSpOC's missed distance criteria. Majority of the detected conjunctions for our fleet are with non-active highly inclined satellites. The predicted conjunctions occur near the equator crossing of the two satellites. This type of conjunction is very sensitive to alongtrack components of the orbit, which is also the least certain orbit component due to the characteristic of ranging geometry. It is therefore interesting to improve the overall uncertainties for both operational and non-active objects to validate potential close approaches. . The results highlight the concern of a two tier process and the importance of obtaining the most authoritative data and maneuver information for active satellites for credible conjunction assessment. Majority of the avoidance maneuvers are planned by shifting the start times and adjust the delta-v of the already planned E/W station-keeping maneuvers to minimize propellant usage. Based on our experience a running monitoring between 7 to 10 days is optimal. Monitoring conjunction over 10 days become unreliable as the predicted orbit may change due to modified maneuver plans and/or variations in the planned maneuver performances. A monitoring window less than 7 days will result in not providing sufficient time for analysis and decision making and planning of avoidance maneuvers if necessary.

Table 2. showed a case of missed conjunction for an active satellite (XXXX) and a rocket body (YYYY).

Creation Date: 2013-10-23 09:24:34 UTC (3.4 hours ago)	
Upload Time: 2013-10-23 11:47:47 UTC (1.0 hours ago)	
Conjunction for XXXX and YYYY	
CSM vs. CSM	TCA: 2013-10-26 08:31:43.139 UTC, **7.567** km
Ephemeris vs. CSM	TCA: 2013-10-26 08:32:08.832 UTC, **3.343** km
Ephemeris vs. TLE	TCA: 2013-10-26 08:32:08.802 UTC, **3.425** km

Table 2. Example of Missed Conjunction

The case "CSM vs. CSM" was a conjunction detected using SP data for both objects. The analysis showed a missed distance over 7 km. However, if the active satellite ephemeris data were used both conjunction analysis using either SP or TLE data for the rocket body showed a missed distance of about 3.5 km. The results seem to show there may be inconsistent in the SP data for the active satellite. This may be due to a recent maneuver not accounted for in the SP solution or maneuver planned in the future not accounted for in the conjunction analysis.

Table 3. showed another interesting case of missed conjunction involving an active satellite (SatA) equipped with low thrust thrusters which performs multiple maneuvers daily and an inactive drifter (SatB).

In this case the conjunction analyses using either "SP vs. SP" or "Ephemeris vs. TLE" did not show any conjunction and the calculated missed distance in both cases were above 10 km. When the operator ephemeris for SatA and the SP data for SatB were used in the analysis it showed a missed distance of 600 meter.

Screening	SatA	SatB	Separations (km)	Notes
SDA	Ephemeris	TLE	14.0	Bad SatB TLE
JSpOC	SP	SP	> 10	SatA SP did not include planned maneuvers
Request	Ephemeris	SP	0.6	SatA ephemeris included planned maneuvers
Request	Ephemeris	SP	3.9	Cancelled loaded maneuvers
JSpOC	SP	SP	3.3	Additional Tasking (~ 12 hours) and cancelled loaded maneuvers

Table 3. Example of Missed Conjunction involving an active satellite equipped with electrical propulsion system

This is an interesting case. It seemed the issues were that the SP data did not include the maneuvers for SatA and the TLE data for the drifter were not incorrect leading to a false close approach analyses performed using those data. As seen from the table above once the planned maneuvers was cancelled for SatA the missed distance was increased to about 4 km. This was validated separately with the updated SP data after about 12 hours of additional tasking.

The above examples illustrated the potential risks with a two tier system.

4. Lessons Learned and Going Forward

It is no doubt that there is an increase in awareness in the risks of satellite conjunction recently. The formation of SDA with members willing to share data in a secure manner and the increase in support from JSpOC are evidences of that. In fact most operators in both commercial and government sectors have taken steps to improve communication with each other and are more willing to share orbital data and maneuver information. As we rely on the data provided by different satellite operators for conjunction monitoring and mitigation it is very important to have a clear definitions of the reference frames and time systems that are used to represent the orbit data and maneuver information. In addition, it is important to have good calibrations of the sensors and a thorough understand the quality of the orbit solution which depends on the characterization of the entire system including measurement model, force model and systemic effects. This will impact directly the conjunction models that depend on conjunction probabilities which are derived from the knowledge on the uncertainty estimates of the ephemeris data. One way to achieve this is to acquire "third party" data which allows for independent sensor calibrations and improve the orbit solutions if the data are fused together properly. Sabol [1], Chan [2] and many different studies have shown the feasibility and improvement of orbit accuracy with data fusion via simulation and actual observation data but unfortunately it has been little sharing of "third party" data to support routine orbit determination activities. It is also important to note that having more data does not necessary lead to better quality orbit solution by default. One must be careful when fusing data from different sources as each data source will contain different error characteristics. These errors need to be accounted for and each data type needs to be properly weighted in order to result in an "optimal" solution which will improve orbit accuracy and produce realistic covariance. Different data calibration techniques have been proposed based on simulation data by different authors but experiment with real measurement data are need to validate the results. For example, Chan [3] proposed a data weighting technique using subset solutions to provide optimal orbit solution and realistic orbit uncertainties by fusing different measurement types from different sources based on simulated data. In order to improve the orbit and uncertainty knowledge the industry to work together to share data. We need to find ways to improve data sharing and at the same time balance the need for security and proprietary concerns.

There are basically two types of conjunction detection indicators: (1) miss distances and (2) conjunction probabilities. The conjunction probabilities was proposed by Ken Chan [4] and the implementation of maximum probability by Sal Alfano [5] to take into account that the realistic orbit uncertainties estimates may not always be available. Unfortunately each technique has its limitations. Based on our experience we find it is most useful to use a combination of miss distances and orbit uncertainties in the three orbital components. The risk defined by the conjunction probability alone does not easily provide a physical interpretation to the collision geometry and it seems arbitrary to set a threshold probability. The concept of using probability for conjunction detection is valid since there are uncertainties associated with the orbit solutions and one needs to account for the orbit uncertainties to provide a proper conjunction risk assessment. To do this, one will need realistic orbit covariance and a technique to include that in conjunction detection algorithm to provide a physical interpretation of the conjunction event. We have seen increased cooperative environment in sharing orbit data among operators but it is still lacking behind in sharing orbit covariance data. In some cases the covariance derived from orbit solutions are too unrealistic. One of the goals to improve data sharing is to increase the awareness and sensitivities among operators the importance in providing realistic orbit covariance in addition to orbit and maneuver information. In most cases the decisions to perform avoidance maneuvers are very manual processes due to lack of well-defined parameters to easily characteristic the risk of the potential conjunctions. Different techniques have been proposed by different investigators. John Conner [6] proposed that for a fixed miss distance one can use the radial component of the inter-satellite separation between two objects as a mean to compute the upper bound risk of collision. Ryan Frigm [7] investigated the use of a single matrix for conjunction assessment. These are interesting initial studies addressing this difficult but important topic for conjunction monitoring that deserve more attentions.

One approach to refine the miss distances between the two objects during close approaches is to consider the relative distances between the two objects. Traditionally the miss distances are computed by differencing the orbits of the two objects obtained from two different orbit determination solutions potentially using different software and different measurement sources. The idea is that if one is to measure the two objects using the same sensor simultaneously and compute the orbit using the same orbit determination software most of the modeling and systemic errors in the orbit determination process may cancel out thus reducing the uncertainties of the relative distances of the two objects. There may still have a relatively large error for the absolute positions of the objects but the result will have a much tighter uncertainty of their relative distances. An improved knowledge of the relative distance and its error estimates are useful in assessing a conjunction and decision making. This is illustrated in Fig 1.

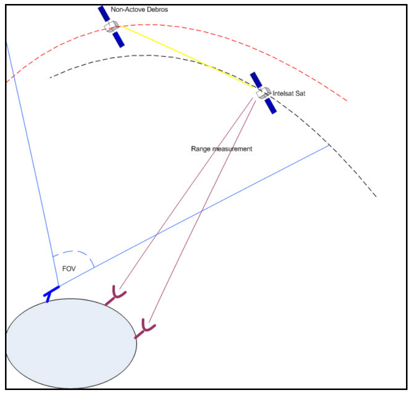

Fig 1. Close Approach Monitoring with Relative Position Measurement

5. Conclusions

Although there has been an increase in cooperation among operator to share data, based on our experiences the current two tier process with SDA, JSpOC and operator's in-house monitoring tool it is not efficient in responding to potential conjunctions and we must find ways to improve cooperation and eliminate the need for the current two tier process. Based on our experience the majority of detected conjunctions are with non-active high inclination objects for GEO satellites and currently the only reliable source of the orbit elements of non-active objects are provided with JSpOC via. TLE. Unfortunately the orbit accuracies for TLE are not sufficient for reliable conjunction monitoring and for planning avoidance maneuvers. We need additional sources to improve the accuracy of orbital elements for the non-active space objects other than TLE. We also discussed the benefits of acquiring independent source of data for active objects to improve orbit solutions and to derive realistic orbit covariance through data fusion. In addition, the independent data can potentially be used for routine sensor calibrations. This becomes more important as different operators start sharing orbit data for conjunction monitoring. We also discussed the need for longer lead time in providing credible alerts for potential conjunctions as we have found that it requires more time to plan and execute avoidance maneuvers with satellites equipped with fuel efficient low thrust thrusters. The current process for conjunction assessment and decision making for avoidance maneuver is very manual as we are still searching and developing clear conjunction detection indicators and the criteria for avoidance maneuvers. We have proposed an approach to refine the monitoring of two approaching objects by considering relative position data once potential conjunction is detected.

6. References

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