Advances in Satellite Conjunction Analysis

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ABSTRACT

Previous works have documented improved abilities to rapidly perform full-catalog (i.e., "all on all") satellite conjunction analysis. This paper explores the use of operational methodologies for appropriately thinning the resultant large data sets in a tailorable, meaningful way based on operator needs. A web services architecture is proposed to deliver relevant information on conjunctions and present operators with actionable maneuver plans for the purpose of mitigating threatening conjunctions.

1. INTRODUCTION

Optimal safety of flight requires robust satellite catalog knowledge. This includes detailed understanding of all objects, including operational, non-operational, spent rocket bodies and other debris – items that are maneuverable and non-maneuverable. This also includes knowledge of events of interest in space, which include things like new launches, direct-ascent ASAT threats, co-orbital ASAT threats, conjunctions and re-entries. From a conjunction standpoint, this includes routinely performing "all-on-all" conjunction analysis – performing a full-catalog conjunction analysis that looks for close approaches between *any* two space objects.

In the past, there has been some debate regarding the necessity of performing all-on-all conjunction assessment (CA), compared to performing all-active-on-all CA. Some feel that the additional computations and potential analysis of the additional debris-on-debris conjunctions could be unnecessary since there are no mitigation options and present approaches are throughput-constrained and cannot handle the additional processing. Predictive event analysis, however, specifically *a priori* knowledge of debris-generation events (including debris-on-debris conjunctions), is critical to overall safety of flight. Owners of high-value assets need to be aware of such potential events in order to allow for course of action planning. Operators of surveillance sensors should have the opportunity to anticipate debris-generation events rather than be 'blind-sided' by them.

In addition to the prediction of certain events, it is also necessary to provide true course of action planning. This includes providing potential mitigation and avoidance strategies when a conjunction includes at least one maneuverable satellite.

In an environment where all of the necessary catalog data is freely shared, such course of action planning could be performed on the operator side of the system. If the sharing of all information is not practical or possible, then recommended mitigation and avoidance strategies and inputs to the courses of action must be provided by the center with access to the required data. Individual operators can then analyze and act upon those recommendations.

2. CHALLENGE

Rapid all-on-all conjunction assessment has already been successfully demonstrated using commercial and government software tools and commercial PC hardware [1, 2, 3]. This paper describes a method in which the process can be, and has been, set up to periodically run automatically. Details of the current performance of this all-on-all system are shown in Table 1 below.

Table 1. All-on-All Performance Metrics

Catalog size	~14,600 objects (public catalog)
Source data	Ephemeris files
CA look-ahead	5 days
Software used	AGI CAT components
Hardware	Dell dual hex-core desktop PC (~$5500)
Execution time	35 min

The result of this process is a set of descriptive data for every conjunction found. The number of conjunctions identified with the current size of the space catalog is prohibitive in terms of manual analysis. The addition of SBSS to existing sensor systems will result in the discovery of new orbiting objects. The advent of the new Space Fence in a few years will result in an order of magnitude increase in the size of the catalog. Although this increase will consist of mostly non-operational and/or debris objects, the operational catalog is also expected to grow significantly [4]. Taken together, these items underscore the need for future operational CA systems to be scalable and utilize an automated concept of operations (CONOPS), which requires minimal manual intervention. The issue is how to analyze all of the CA data in such environments.

3. CONJUNCTION ASSESSMENT PROCESSING

For an operational deployment of full-catalog CA, the most accurate conjunction source data is high-precision ephemeris data. Prototypes have been developed that have explored the use of the GP catalog, in the form of two-line element (TLE) sets, for rapid pre-filtering. However, the problems with the accuracy of the existing TLE data sets have been well documented, and relying on them for CA pre-filtering is seen as problematic [5]. The catalog ephemeris required to drive conjunction assessment will be generated by processing all possible sources of tracking data as shown in Figure 1.

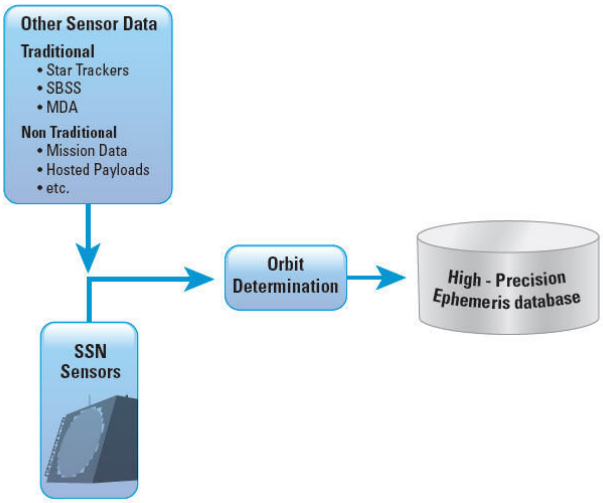


Fig. 1. Ephemeris Generation Flow

For the most accurate results, this ephemeris database must leverage owner/operator ephemeris data, derived via their cooperative tracking systems. Such an inclusion allows the overall system to have more precise orbital knowledge of these satellites, minimizes the chances of cross-tagging by a non-cooperative tracking system, and also allows for the system to evaluate the planned position of operational satellites as they maneuver, since the source ephemeris from the owner/operators includes their maneuver planning effects. In principle, these are the reasons behind the Space Data Association's Space data Center (SDC). The goal would be to synthesize the SDC data with the high-precision data for the rest of the catalog. Reference [6] contains more detailed information about the SDC.

The frequency at which all-on-all conjunction knowledge is updated will be driven by the availability of new ephemeris solutions and the selected CONOPS. In addition to the source ephemeris, satellite specific proximity thresholds are used to define conjunctions of interest. The resulting events are archived in a conjunction database containing references to the source information and descriptive information such as the miss distance, time of closest approach (TCA) and probability of collision (Pc). Given appropriate points of contact for operational spacecraft, the CA process includes automatic notifications to owner/operators when conjunctions are found involving their satellites. As presently implemented by AGI, the entire conjunction database is available as a web service for consumption by users. This overall flow is shown in Figure 2. It is worth noting that many operators desire a probability of collision, but such a computation is only valid with realistic covariance. Such dynamic realistic covariance is only available if the orbit determination process models all appropriate forces and their associated uncertainties [7].

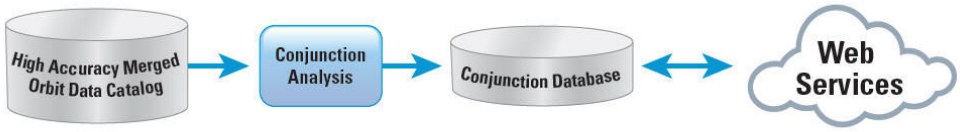


Fig. 2. Automated Conjunction Assessment Flow

As presently implemented by AGI, the entire conjunction database is available as a web service for consumption by users. Any authorized user can access data from the server using a front-end query for filtering the conjunction data according to their interests. Filtering by mission, country, orbit class or even by conjunction geometry is possible, as shown in Figure 3. Note that this implementation is for example purposes only, and can be tailored to satisfy the CONOPS requirements of the operations center involved.

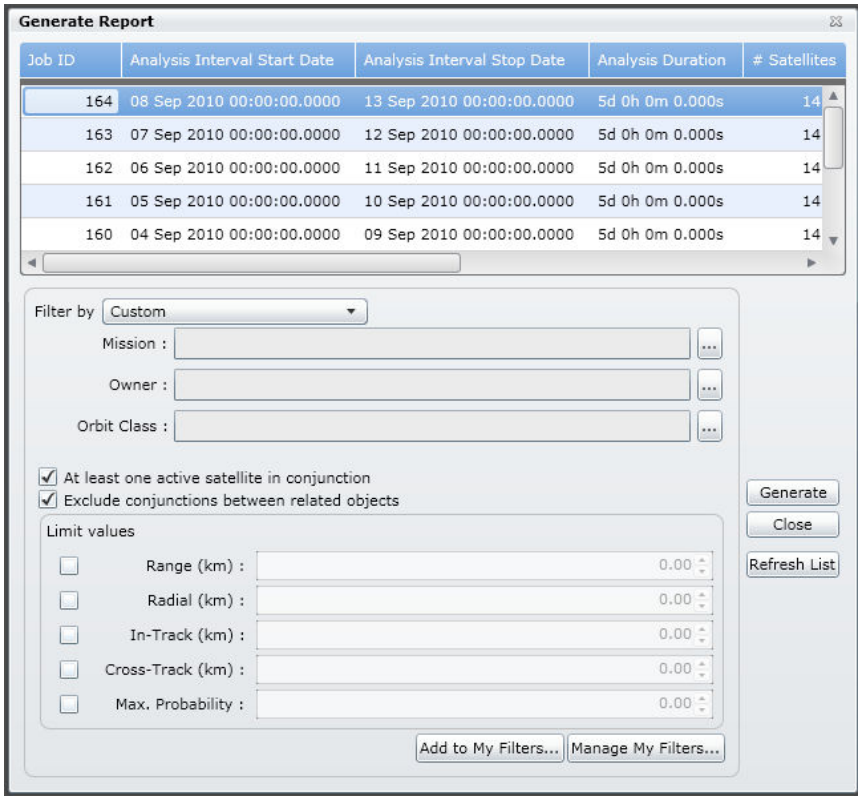
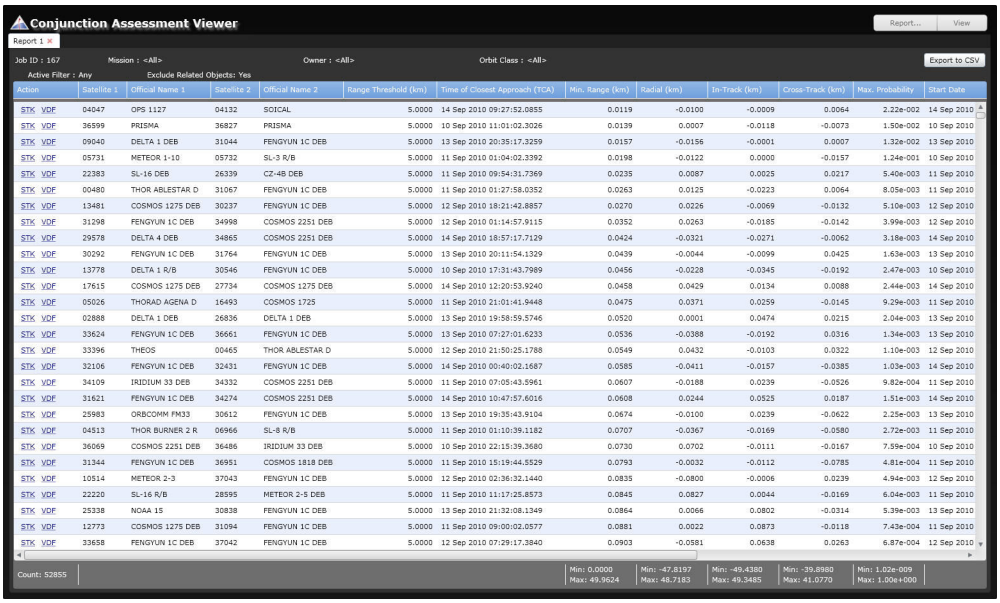


Fig. 3. Conjunction Assessment Web Service Interface

An example of the data returned by such a query is displayed in Figure 4. Note that the present set of data computed for each conjunction is broader than what is shown in the figure.



Conjunction Assessment Viewer

Report 1

Job ID : 167 Mission : <All> Owner : <All> Orbit Class : <All>

Active Filter : Any Exclude Related Objects: Yes

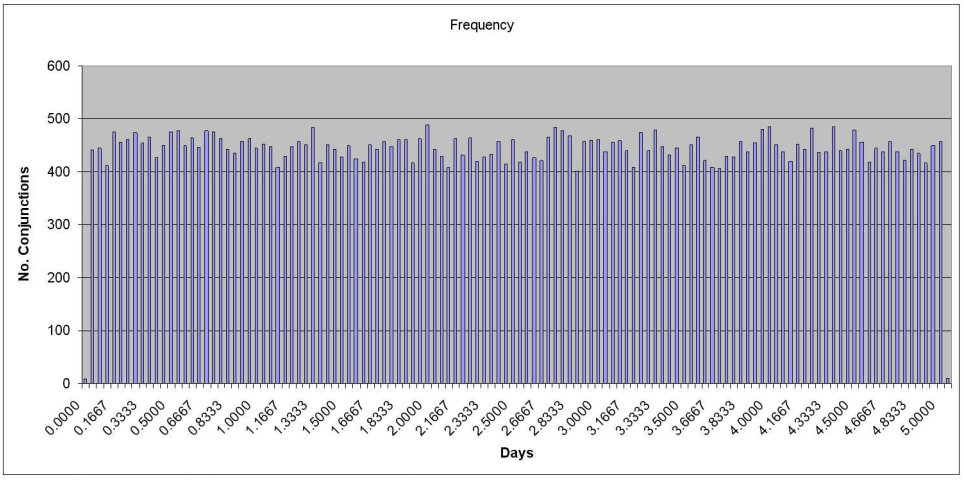
Action	Satellite 1	Official Name 1	Satellite 2	Official Name 2	Range Threshold (km)	Time of Closest Approach (TCA)	Min. Range (km)	Radial (km)	In-Track (km)	Cross-Track (km)	Max. Probability	Start Date
STK VDF	04047	OPS 1127	04132	SOICAL	5.0000	14 Sep 2010 09:27:52.0855	0.0119	-0.0100	-0.0009	0.0064	2.22e-002	14 Sep 2010
STK VDF	36599	PRISMA	36827	PRISMA	5.0000	10 Sep 2010 11:01:02.3026	0.0139	0.0007	-0.0118	-0.0073	1.50e-002	10 Sep 2010
STK VDF	09040	DELTA 1 DEB	31044	FENGYUN 1C DEB	5.0000	13 Sep 2010 20:35:17.3259	0.0157	-0.0156	-0.0001	0.0007	1.32e-002	13 Sep 2010
STK VDF	05731	METEOR 1-10	05732	SL-3 R/B	5.0000	11 Sep 2010 01:04:02.3392	0.0198	-0.0122	0.0000	-0.0157	1.24e-001	10 Sep 2010
STK VDF	22383	SL-16 DEB	26339	CZ-4B DEB	5.0000	11 Sep 2010 09:54:31.7369	0.0235	0.0087	0.0025	0.0217	5.40e-003	11 Sep 2010
STK VDF	00480	THOR ABLESTAR D	31067	FENGYUN 1C DEB	5.0000	11 Sep 2010 01:27:58.0352	0.0263	0.0125	-0.0223	0.0064	8.05e-003	11 Sep 2010
STK VDF	13481	COSMOS 1275 DEB	30237	FENGYUN 1C DEB	5.0000	12 Sep 2010 18:21:42.8857	0.0270	0.0226	-0.0069	-0.0132	5.10e-003	12 Sep 2010
STK VDF	31298	FENGYUN 1C DEB	34998	COSMOS 2251 DEB	5.0000	12 Sep 2010 01:14:57.9115	0.0352	0.0263	-0.0185	-0.0142	3.99e-003	12 Sep 2010
STK VDF	29578	DELTA 4 DEB	34865	COSMOS 2251 DEB	5.0000	14 Sep 2010 18:57:17.7129	0.0424	-0.0321	-0.0271	-0.0062	3.18e-003	14 Sep 2010
STK VDF	30292	FENGYUN 1C DEB	31764	FENGYUN 1C DEB	5.0000	13 Sep 2010 20:11:54.1329	0.0439	-0.0044	-0.0099	0.0425	1.63e-003	13 Sep 2010
STK VDF	13778	DELTA 1 R/B	30546	FENGYUN 1C DEB	5.0000	10 Sep 2010 17:31:43.7989	0.0456	-0.0228	-0.0345	-0.0192	2.47e-003	10 Sep 2010
STK VDF	17615	COSMOS 1275 DEB	27734	COSMOS 1275 DEB	5.0000	14 Sep 2010 12:20:53.9240	0.0458	0.0429	0.0134	0.0088	2.44e-003	14 Sep 2010
STK VDF	05026	THORAD AGENA D	16493	COSMOS 1725	5.0000	11 Sep 2010 21:01:41.9448	0.0475	0.0371	0.0259	-0.0145	9.29e-003	11 Sep 2010
STK VDF	02888	DELTA 1 DEB	26836	DELTA 1 DEB	5.0000	13 Sep 2010 19:58:59.5746	0.0520	0.0001	0.0474	0.0215	2.04e-003	13 Sep 2010
STK VDF	33624	FENGYUN 1C DEB	36661	FENGYUN 1C DEB	5.0000	13 Sep 2010 07:27:01.6233	0.0536	-0.0388	-0.0192	0.0316	1.34e-003	13 Sep 2010
STK VDF	33396	THEOS	00465	THOR ABLESTAR D	5.0000	12 Sep 2010 21:50:25.1788	0.0549	0.0432	-0.0103	0.0322	1.10e-003	12 Sep 2010
STK VDF	32106	FENGYUN 1C DEB	32431	FENGYUN 1C DEB	5.0000	14 Sep 2010 00:40:02.1687	0.0585	-0.0411	-0.0157	-0.0385	1.03e-003	14 Sep 2010
STK VDF	34109	IRIDIUM 33 DEB	34332	COSMOS 2251 DEB	5.0000	11 Sep 2010 07:05:43.5961	0.0607	-0.0188	0.0239	-0.0526	9.82e-004	11 Sep 2010
STK VDF	31621	FENGYUN 1C DEB	34274	COSMOS 2251 DEB	5.0000	14 Sep 2010 10:47:57.6016	0.0608	0.0244	0.0525	0.0187	1.51e-003	14 Sep 2010
STK VDF	25983	ORBCOMM FM33	30612	FENGYUN 1C DEB	5.0000	13 Sep 2010 19:35:43.9104	0.0674	-0.0100	0.0239	-0.0622	2.25e-003	13 Sep 2010
STK VDF	04513	THOR BURNER 2 R	06966	SL-8 R/B	5.0000	11 Sep 2010 01:10:39.1182	0.0707	-0.0367	-0.0169	-0.0580	2.72e-003	11 Sep 2010
STK VDF	36069	COSMOS 2251 DEB	36486	IRIDIUM 33 DEB	5.0000	10 Sep 2010 22:15:39.3680	0.0730	0.0702	-0.0111	-0.0167	7.59e-004	10 Sep 2010
STK VDF	31344	FENGYUN 1C DEB	36951	COSMOS 1818 DEB	5.0000	11 Sep 2010 15:19:44.5529	0.0793	-0.0032	-0.0112	-0.0785	4.81e-004	11 Sep 2010
STK VDF	10514	METEOR 2-3	37043	FENGYUN 1C DEB	5.0000	12 Sep 2010 02:36:32.1440	0.0835	-0.0800	-0.0006	0.0239	4.94e-003	12 Sep 2010
STK VDF	22220	SL-16 R/B	28595	METEOR 2-5 DEB	5.0000	11 Sep 2010 11:17:25.8573	0.0845	0.0827	0.0044	-0.0169	6.04e-003	11 Sep 2010
STK VDF	25338	NOAA 15	30838	FENGYUN 1C DEB	5.0000	13 Sep 2010 21:32:08.1349	0.0864	0.0066	0.0802	-0.0314	5.39e-003	13 Sep 2010
STK VDF	12773	COSMOS 1275 DEB	31094	FENGYUN 1C DEB	5.0000	11 Sep 2010 09:00:02.0577	0.0881	0.0022	0.0873	-0.0118	7.43e-004	11 Sep 2010
STK VDF	33658	FENGYUN 1C DEB	37042	FENGYUN 1C DEB	5.0000	12 Sep 2010 07:29:17.3840	0.0903	-0.0581	0.0638	0.0263	6.87e-004	12 Sep 2010

Count: 52855 | Min: 0.0000 Max: 49.9624 | Min: -47.8197 Max: 48.7183 | Min: -49.4380 Max: 49.3485 | Min: -39.8980 Max: 41.0770 | Min: 1.02e-009 Max: 1.00e+000

Fig. 4. Conjunction Assessment Results Example

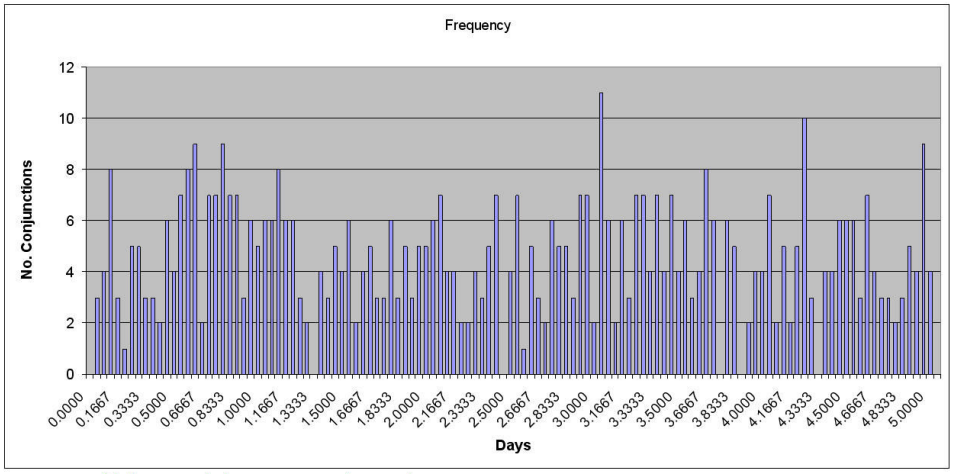
4. CONJUNCTION ANALYSIS

As mentioned previously, the full-catalog CA produces large quantities of data. The current catalog is reported to contain more than 22,000 objects [8]. For the public catalog of approximately 14,600 objects, the five day look-ahead finds approximately 53,000 conjunctions based on the use of a 50 km threshold for GEO objects and a 5 km threshold for all others. This represents a rate of approximately 446 conjunctions per hour, or one conjunction every 8 seconds. Clearly manual analysis of each conjunction is not possible. In order to reduce the data to manageable amounts, an automated system could 'thin' it by identifying thresholds on additional measures of risk. An example of this would be to only analyze conjunctions where the predicted miss distance is less than 1 km and where the radial miss distance is less than 200 meters. [This is for example purposes only. Any such limiting requires further analysis beyond the scope of this paper to justify the limits selected. In particular, limiting the data based on radial miss distance is potentially problematic – the assumption that the tracking sensor is providing a highly accurate assessment of orbit radius at any time is not necessarily true.] Operationally shrinking the threshold from something like 5 km to 1 km infers that the level of comfort with the orbit estimation and orbit covariance is improved; to gain such confidence probably requires the use of a filter-based approach to generate realistic covariance. Thinning the data in such a way cuts the number of conjunctions needing further analysis by two orders of magnitude, to approximately 550. This is one conjunction every ~780 seconds, which, although much better, is still not manageable via manual processes, especially considering the expected growth in the size of the catalog. Histograms of the original data set and the 'thinned' data set are shown in Figures 5 and 6. In these figures each bar in the histogram represents one hour.



Note – each bar represents one hour

Fig. 5. Hourly Conjunction Rates using 5 (50) km Threshold



Note – each bar represents one hour

Fig. 6. 'Thinned' Hourly Conjunction Rates

There are many other possible operational considerations for reducing the data. One possibility would be to specify different thresholds for operational spacecraft versus debris. For example, provided realistic covariance is available with the orbit data and true probability can be computed. A higher threshold of Pc for debris-on-debris events could be used compared to events where operational spacecraft are involved.

Another technique to quickly assess risk is to examine the trend of the conjunction. With each successive orbit update, the epoch of the orbit solution gets closer to TCA, lessening the effect of force modeling errors on the predicted miss distance. Conjunction information should, therefore, become more reliable with each orbit update. Using today's prototype, analysts simply call up a conjunction trend plot to visually inspect it. Instances that show a diminishing predicted miss distance combined with an increasing probability require more detailed analysis. Those with the opposite trend can most likely be set aside. These two cases are illustrated in Figures 7 and 8.

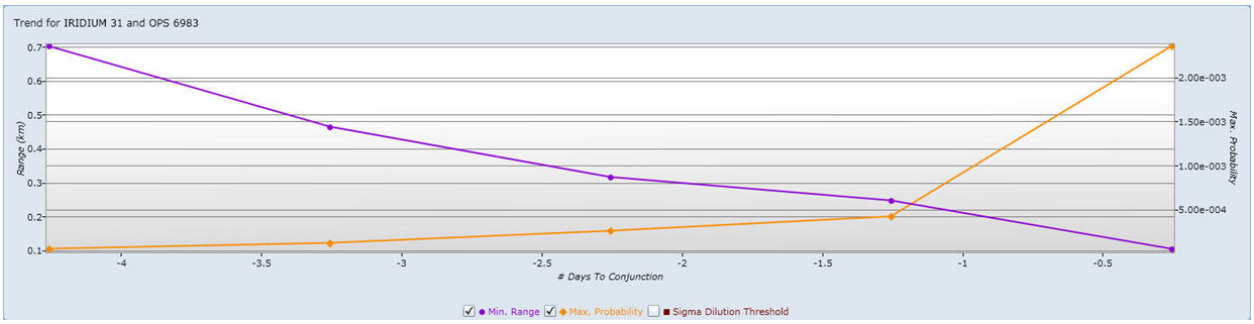


Fig. 7. Degrading Conjunction Trend – Range Decreasing, Probability Increasing

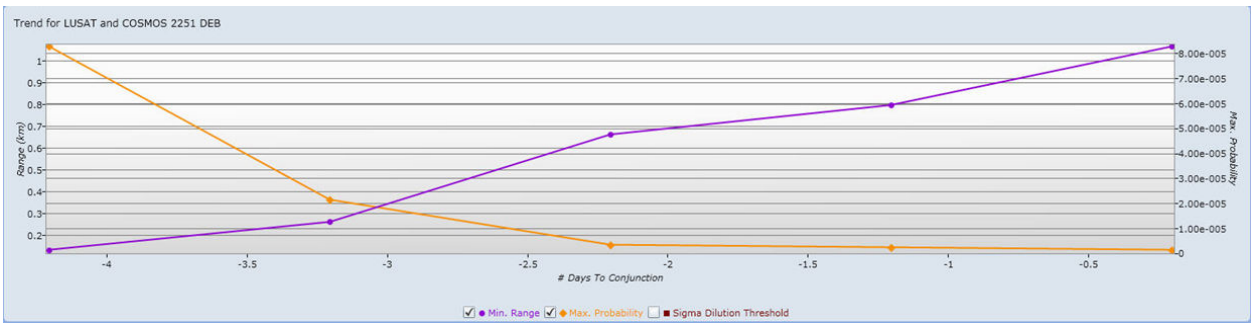


Fig. 8. Improving Conjunction Trend – Range Increasing, Probability Decreasing

Conjunctions which represent significant risk may be deemed worthy of more detailed monitoring. Improved knowledge of a particular conjunction can only be obtained through the addition of information on the orbits of the two objects. The most obvious method for increasing orbit knowledge is to take more observations. Proposed sensor tasking should, however, be evaluated in terms of potential reduction of uncertainty at the time of the conjunction to avoid wasting of sensor resources. A tracking data simulation capability such as the simulator tool in AGI's Orbit Determination Toolkit (ODTK) technology can be leveraged for this purpose. For the period between the time of the analysis and some terminal time prior to TCA (after which response to further analysis would not be possible) a parametric analysis of potential network tracking opportunities would be performed and the resultant predicted covariance at TCA evaluated. A graphical example showing potential SSN tracking opportunities for evaluation is shown in Figure 9.

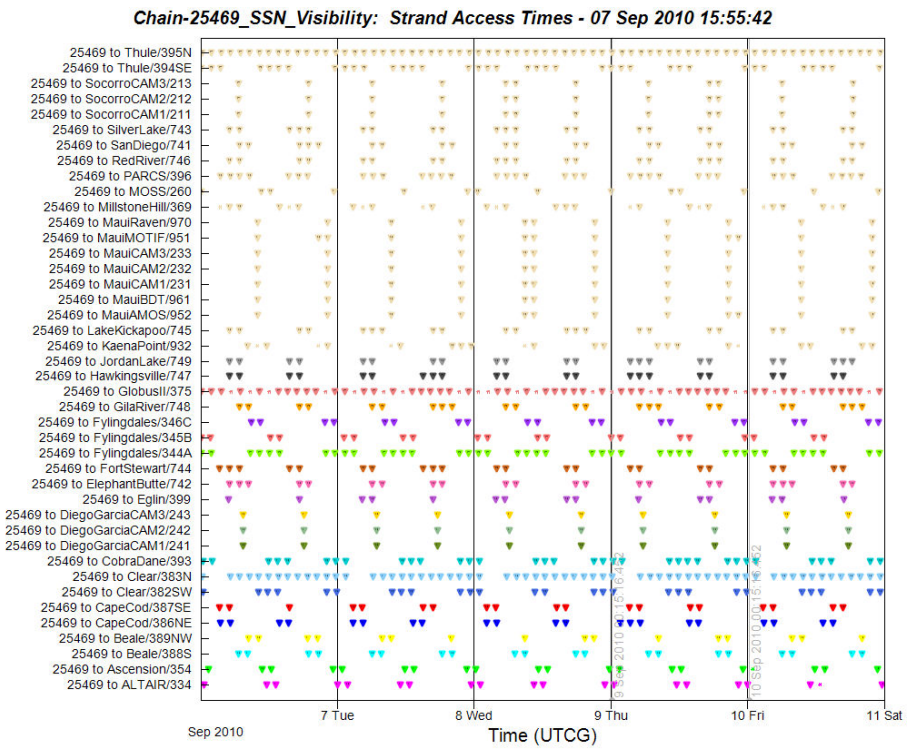


Fig. 9. Example SSN Tracking Opportunities for Evaluation

The goal would be to select the tracking scheme that best shrinks the combined covariance at TCA. This information would be fed to an overall scheduling engine for network sensor tasking. Figure 10 depicts the example geometry at TCA.

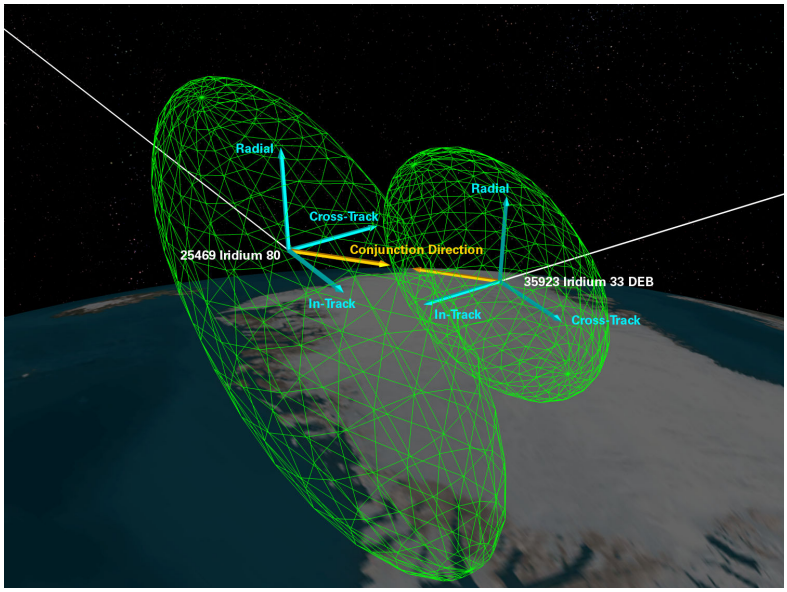


Fig. 10. Example Conjunction Geometry at TCA

While most conjunction events will require no more than routine monitoring, a small number of conjunctions will exist involving maneuverable spacecraft for which the risk of collision is too high and mitigation options are desired. Optimally, all required information could be made available to the satellite operator for course of action planning. In scenarios where such data sharing is not possible, the operations center with access to the full catalog

has the best information on the conjunction; it is in the best position to assess mitigation strategies. This is done in a generic sense, with regard to the orbital geometry of the conjunction but without regard to the individual spacecraft involved or their mission constraints. Using either miss distance or probability as the metric, a varying scale of maneuver time (measured in time prior to TCA), magnitude and direction is computed. Direction is evaluated in each of three axes individually. Once a time is chosen, the potential effects of combing direction axes are evaluated. The results are made available in a series of 2D plots or a 3D depiction. The development of mitigation and avoidance strategies has been previously documented in [9]. Figures 11, 12 and 13 show example output of this analysis in 1D, 2D and 3D respectively.

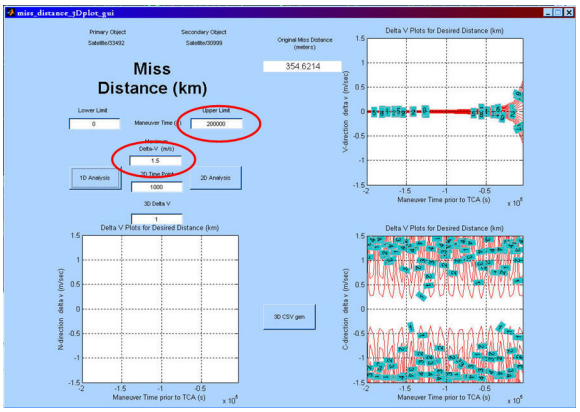


Fig. 11. Mitigation Maneuver Assessment in 1D

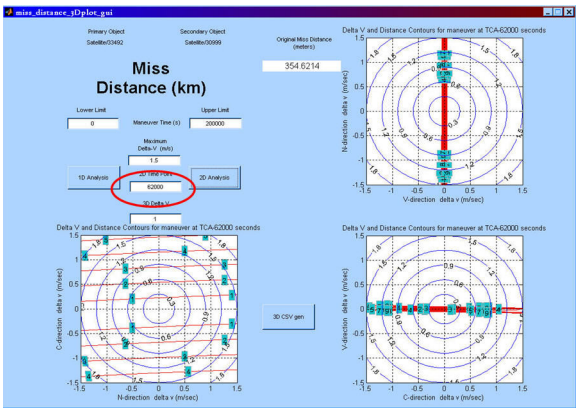


Fig. 12. Mitigation Maneuver Assessment in 2D

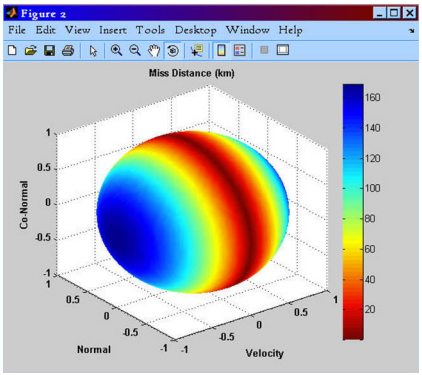


Fig. 13. Mitigation Maneuver Assessment in 3D

The results of the conjunction analysis process, including the mitigation maneuver assessment along with the high-quality ephemeris solution for the conjuncting object are provided to the satellite owner/operator. The owner/operator now performs course of action planning, first deciding if the computed conjunction requires action or additional analysis. If the risk is unacceptable to the operator, the maneuver assessment is used as an input to actual spacecraft maneuver planning. At this point, the owner/operator can evaluate mission requirements, including payload planning, communications opportunities and stationkeeping strategies. All of these are considered along with the particular spacecraft's propulsion system capabilities and consumables. There may be very valid reasons why an operator cannot or doesn't want to perform the 'optimum' maneuver suggested by the mitigation planning, but can still use that guidance to execute a maneuver consistent with the mission which drops the conjunction risk to an acceptable level.

As potential mitigation maneuvers are planned and evaluated, an integral part of this process is to assess the planned post-maneuver orbit ephemeris with the initial conjuncting object. This is the reason why it is essential for the owner/operator to receive that data along with the conjunction information. The owner /operator's course of action planning is only complete when the chosen mitigation maneuver is demonstrated, via a subsequent one-on-all CA, to acceptably mitigate the initial conjunction and is also shown to not result in any new additional conjunctions.

5. CONCLUSIONS

The overall system described is shown in Figure 14 below. Many of the necessary processes or building blocks are already running in automated fashion, and are shown in green in the figure. Some of them are automatically running in operational environments, such as the automated OD process, or have been successfully demonstrated with prototypes that continue to run automatically every day. The main areas needing further work to automate such an architecture are:

- Analysis, automation and configuration of the Conjunction & Orbit Analysis block.
  The current system allows operators to perform much of this manually via web services, but this is not scalable for large-scale applications. The good news is that the necessary work is highly automatable, and can be made flexible based upon particular operational rules or CONOPS. Certainly there will be some situations, for example where manned spaceflight objects are concerned, where analyst insight is desirable. The intent here is not to propose a heuristic, artificial intelligent system, but rather to automate the work to the fullest extent possible in order to maintain scalability. Future study is required here to investigate how to best achieve this, perhaps using a combination of miss distance, probability, orbit quality assessment, and conjunction trending.
- Integration of some of the building blocks to deploy a comprehensive system.

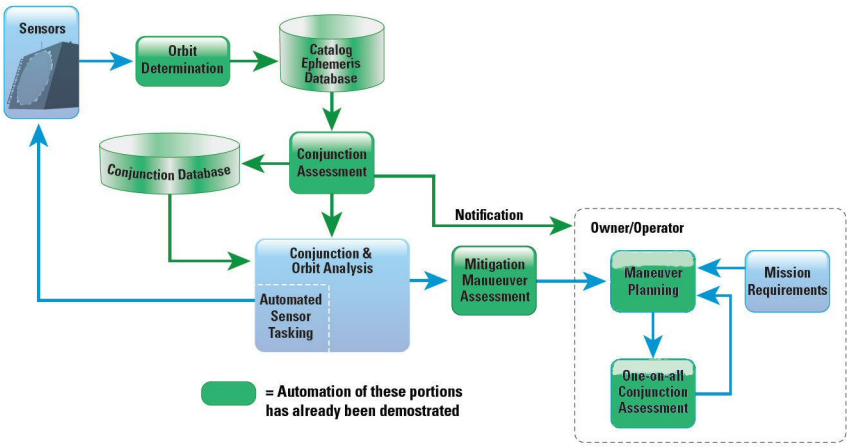


Fig. 14. Conjunction Assessment & Mitigation System Architecture

The resulting benefits of deploying such a system will be:

- Full-catalog CA processing
- Automatic owner/operator notification
- Assessment of the severity of conjunctions
- Automated feedback to the sensor tasking algorithms for improved CA
- Course of action planning information provided to owner/operators.
- Increased worldwide safety of flight
- Improved Space Situational Awareness

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