Space Situational Awareness (SSA) research findings

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Abstract

Space Situational Awareness (SSA) is the foundation for space superiority and has become a national priority. Providing full SSA requires knowledge of space and ground assets along with communication links between these assets. It also requires an understanding of potential events and threats that may affect these assets. This paper summarizes the findings resulting from a research environment established to explore SSA issues. Non-traditional data sources available on the internet are identified along with methods to mine relevant data. Algorithms to augment this data with value added processing were evaluated and key features are presented. These include all-on-all conjunction analysis utilizing analytical distributed processing approaches and maneuver detection utilizing an approach described in the AMOS 2007 paper "Satellite Maneuver Detection Using Two-line Elements". Data fusion techniques are presented which were utilized to evaluate space launches, enhance maneuver detection capabilities, characterize events and determine possible intent. Several visualization approaches were explored and the key features/limitations are discussed to include performance consideration, event models between visualization components, and data needs at the tactical, operational, and strategic levels. Data dissemination approaches utilizing a Service Oriented Architecture (SOA) are highlighted along with challenges such as Multiple Levels of Security associated with the data. Dependencies between visualization and dissemination that impact the system's performance are discussed. Alternatives to balance system performance and application of a User Defined Operational Picture (UDOP) are explored.

1. Introduction and Background

Space-based capabilities have become an integral part of the United States' infrastructure and provide the U.S. military with an asymmetric advantage during times of conflict. This has not gone unnoticed by adversaries who are developing systems to negate our advantage. Achieving Space Situational Awareness (SSA) is the first step in enabling protection of our country's space assets and ensuring space superiority for our military. The SSA Services and Fusion Internal Research and Development (IRAD) (SSFI) investigates fundamental technologies for SSA and space protection by exposing mission critical data sources via a net-centric methodology. Space Situational Awareness and Space Protection operators require access to this pool of potentially relevant data which includes: 1) space objects, 2) status, 3) activities, 4) threats, 5) environment. This data can then be used to assess system and satellite status and facilitate courses of action development. Current approaches require highly skilled people to manually gather and correlate a necessarily limited subset (given time and resource constraints) of the available data in pursuit of SSA to make informed decisions. The SSFI presents this information to operators at the tactical, operational and strategic levels and makes it available in a machine-to-machine interface for further processing and analysis. Fig. 1 conveys the SSFI end-to-end concept.

2. Data Sources

All of the data utilized by SSFI was gathered from open source sites accessible on the Internet. As a result, our data ingest approaches had to deal with conflicting and/or incomplete data sources. These issues can best be seen with the launch data. Our team was unable to identify an authoritative launch schedule data source capable of providing a complete and accurate set of information. Further, the various launch schedule data sources do not provide the same data fields causing specific information to only be available from a single site. SSFI utilized a voting approach, where majority vote rules, to adjudicate conflicting data sources. As launch schedule updates occurred due to delays, our system would mine the information from multiple data sources and reflect the change once the majority of sources agreed. Given this approach, a tie is possible when all sources disagree or one source is incomplete (a launch event is not found in that source). To resolve ties we established a relative priority among the data sources. The data source with the higher priority is considered a more authoritative source.

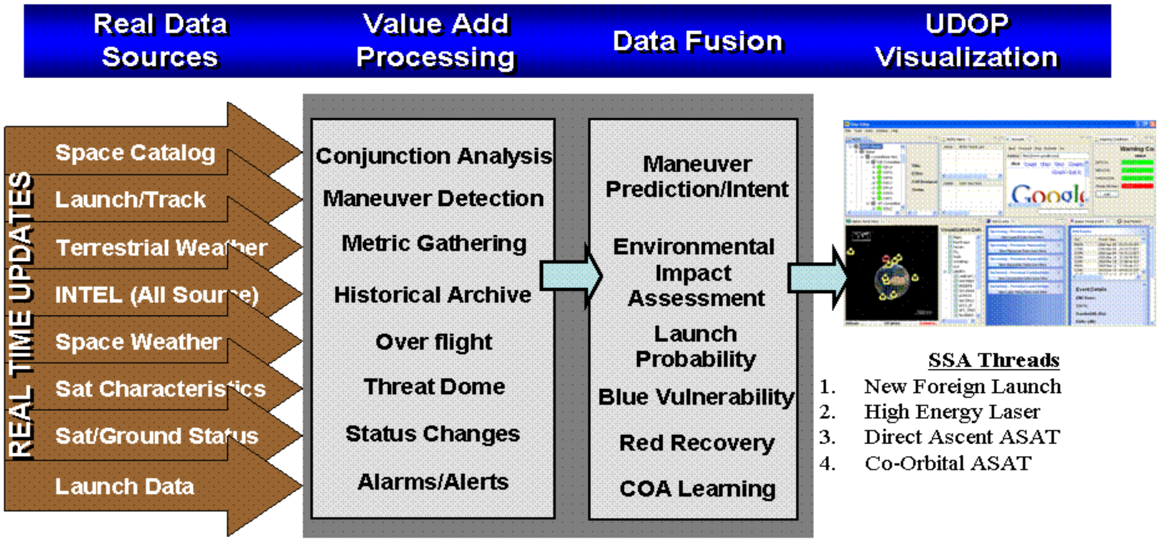


Fig. 1: SSA IRAD End-to-End Concept.
Uncovered lessons learned to solve performance, scalability & integration issues

Many of the data sources exist in the form of a web page. To ingest the information and make the data available via a machine-to-machine interface required mediation approaches to parse the html from the various web pages and extract the pertinent data items. The extracted information was stored in a relational database allowing the creation of web services to expose the collected data.

Much of the launch schedule information found comes from sources in which the data is manually entered. This results in inconsistent representations of the same information. An example could be these three representations of the same launch location data: Vandenberg, Vandenberg USA, and Vandenberg AFB. all representing the same launch location. To address this issue the SSFI team created a launch facility table in the database and established a relationship between the launch facility and launch schedule tables. When the foreign key did not match we utilized a best fit approach to ensure consistent data. The best fit approach compared the name from the data source to the name located in the launch facility table to identify the closest match. The data retrieved from the external source would be saved with the closest match launch location name.

3. Value Add Algorithms

Exposing information from various data sources provided the opportunity to algorithmically provide additional data. This was referred to as value-added processing and covered several topics shown in fig. 1. Much of this processing resulted from our ability to propagate satellite orbits forward and evaluate geometric relationships. The SSFI team utilized Two- Line Element (TLE) set data coupled with the Analytical Graphic Incorporated (AGI) product, Dynamic Geometry Library (DGL) [1], to propagate orbits and analyze geometric relationships.

Conjunction Analysis

Within our environment we have explored approaches for conducting conjunction analysis. Currently, approximately 11,500 objects are tracked. Performing an all-on-all analysis requires the analysis of ½(n**2 – n) pairs or ~66 million pairs. As the number of objects increases because of new launches and improvements in our tracking systems, the number of evaluation pairs will also increase. This analysis could become so computationally intensive that it would be impossible to produce a timely report on a daily basis. Our research focused on analytical approaches to reduce the computations and was inspired by the theories presented in [2].

The first approach was our spherical approximation. This was a pre-filter that examined the apogee/perigee of the two objects to determine if that pair could be discarded from further analysis. By looking only at the orbits' apogees and perigees, it can be established if it is possible for the two objects to have a conjunction. This simple analysis can eliminate almost 1/3 of all pairs.

The age of the TLE was also examined. The conjunction analysis was conducted each day. However, not all TLEs are updated every day. When both TLEs for a given pair have not been updated since the last time the conjunction analysis completed, the pair need only be evaluated for the final day. The results from the previous day's analysis are still valid and would not have changed.

The final approach utilized an elliptical approximation. Each orbit forms an ellipse in 3D space with the Earth at one focus. The orbital ellipse lies on a plane. Given a pair of objects will result in two orbital ellipse planes. The intersection of these two planes forms a line that passes through the Earth. Each orbital ellipse will intersect the line at 2 points, one on each side of the Earth. The distance between the points on the line represents the closest possible approach of the two objects for a given revolution. We established a threshold of 50 km and conducted further analysis when it was possible for the objects to pass within the threshold. When filtering pairs utilizing this elliptical approximation approach we had to account for an exception condition referred to as the coplanar exception. This exception resulted when both orbital planes lie on or near the same plane and the resulting intersection is no longer a line but rather a plane. In this case, we did not filter the pair with this method.

The SSFI conjunction analysis is executed once per day starting at 9 pm. This time was selected to provide the analysis maximum use of the computer resources. Complete all-on-all analysis was completed by distributing the problem across four dual core machines and one virtualized dual-core machine. The total run time varies from night to night based on the number of pairs filtered, but will typically complete between 2:30 and 3 am or 5.5 to 6 hours. As the space catalog grows the SSFI conjunction analysis could be further decomposed and distributed over additional machines. Efforts are currently underway to further improve the efficiency by filtering additional pairs to provide more timely results.

The use of TLE data to perform this analysis introduces uncertainty in the relative position of the two objects, also known as covariance. Several approaches to compute this covariance associated with a given TLE have been developed and each approach has shortcomings and limitations. The MAESTRO approach [3] compares the accuracy of the TLE data to the observation data used to generate the TLE. This was not practical for the SSFI team because the observation data is not generally available and the calibration source was not independent. The COVGEN approach [4] compared TLEs to each other to determine how the predictions change with the propagation interval. Although this approach makes some assumptions regarding TLE prediction errors, all the necessary information was available to the SSFI team. By computing the covariance for the time of closest approach the SSFI team was able to compute the conjunction probability utilizing a Gaussian calculation. The ability to estimate the covariance is crucial in computing the probability and is an area of continued research.

Maneuver Detection

Identifying maneuvers of space objects in a timely fashion provides useful information for track custody and can provide insight into vehicle status. Although performing maneuver detection utilizing TLE data as the primary input is prone to false alarms or missed detections caused by measurement uncertainty, the SSFI team implemented an approach which focused on minimizing false alarms. The algorithm was tuned such that everything identified as a maneuver was in fact a maneuver and was identified in a timely manner for the purpose of providing valid inputs into the data fusion processing. The SSFI team utilizes the approaches described in [5] and [6] as a starting point and augmented the approaches with lessons learned to meet the goal of minimizing false alarms.

Typical satellite maneuvers take on two forms. In-plane maneuvers change the orbital energy resulting in eccentricity and altitude changes to the orbit. In-plane maneuvers manifest as abrupt temporal changes in the mean motion, semi-major axis and/or eccentricity. Out-of-plane maneuvers result in abrupt changes in inclination. The Kelecy/Hall [5] approach had the advantage of apriori knowledge of maneuver and TLE data for the life of the vehicles under study. This approach compared adjacent segments of smoothed data to detect these abrupt changes and focused on LEO vehicles. The Abbot/Wallace [6] approach inputted radar and optical sensor data to a Bayesian network to detect changes in state of GEO vehicles. Changes in the Longitude of the ascending node (LAN) were the primary element used to determine changes in state.

The SSFI team utilized the entire space catalog to detect maneuvers in all orbital regimes. To accomplish this we first categorized each object in the catalog into an orbital regime to include: LEO, MEO, molniya, polar, sun synchronous, tundra, GEO, inclined GEO, HEO, and graveyard GEO. For each orbital type the SSFI team gathered TLE data over several days to arrive at a covariance over time. The maneuver detection algorithm would compute the delta for each orbital element between yesterday and today. These deltas were compared against the expected covariance associated with the delta time between the TLE epochs. Deltas which fell outside of the expected covariance were flagged as candidate maneuvers. The set of candidate maneuvers were provided to a Bayesian network to further evaluate the state of the object and arrive at a maneuver set for the day. The set of maneuvers uncovered by this approach typically would have taken place over the past 24 hours. To arrive at the estimated time of the maneuver, today's TLE was propagated backwards and yesterdays propagated forward to locate the time in which these orbits came the closest. The time of closest approach between the two TLEs was deemed the maneuver time and the information recorded in the maneuver log.

The maneuver detection algorithm executes once per day and is detecting approximately five maneuvers each day across all orbital regimes. Once the algorithm started executing efforts were made to verify the detected maneuvers. Satellite maneuver information is either not reported or difficult to locate on the internet. When it is reported, it is typically buried in event log data for a specific vehicle or constellation. The ability of the SSFI maneuver detection algorithm to detect maneuvers was confirmed based on data extracted from event logs [7] and [8]. This analysis also pointed out that our data smoothing approach was not sufficient causing some false alarms. The SSFI team implemented additional data filters to compensate. The first was deemed the manual adjustment filter. Occasionally the delta time between adjacent TLEs would be very small, but the orbital elements would jump significantly. These were flagged as manual updates by the operator. The second was referred to as the insufficient observation filter. As the delta time between adjacent TLE epochs became large we observed a much higher false alarm rate. We flagged these as being based on insufficient observations and required additional evidence in the Bayesian network. Because it was our goal to minimize the number of false alarms, we acknowledge many maneuvers are going unnoticed. Our current approach would greatly benefit from utilizing unprocessed sensor data over TLEs, and could be tuned to increase the number of detections while keeping the false alarm rate low.

4. Data Fusion Techniques

Given the exposed data sources and value add processing, sufficient information was available to the SSFI team to draw new conclusions utilizing data fusion techniques. Two approaches were implemented: conducting data fusion during the data ingest phase and invoking a data fusion engine as a web service call. We learned that some products are not well suited to be invoked within a web service and execute better as stand alone products. We also discovered the value of having live data coming into the system on a daily basis. This provided a rich and varied set of data to train the system. It also provided real world examples of inconsistencies in the data that would rarely be found in generated data.

Maneuver Prediction and Intent Characterization

As the history of maneuver information builds up over time, patterns or trends along with the magnitude of the maneuvers begin to appear. When this information is coupled with additional data, such as vehicle telemetry, data fusion techniques could be utilized to predict when maneuvers could be expected and the absence of a maneuver can be used as a potential vehicle anomaly indicator. Further, by examining characteristics of a given maneuver, it could be characterized and the intent of the maneuver could be suggested.

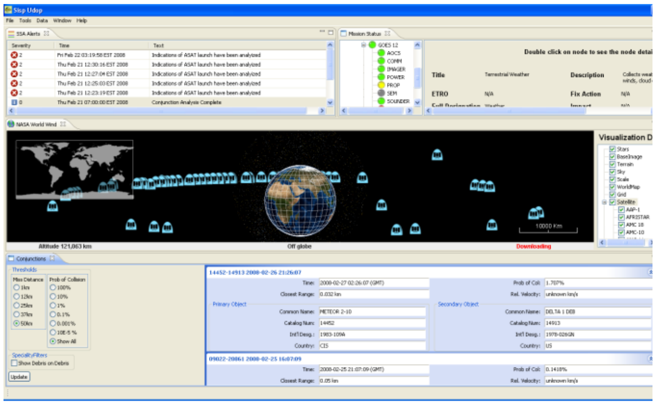
The SSFI team took advantage of the THEMIS constellation event log and Ephemeris data [7] as the inputs into a Bayesian network for maneuver prediction. The mission plan for this constellation requires frequent large maneuvers making it ideal. The telemetry data was available in real time and maneuver history was available in the event log. We utilized the event history information as training data for the Bayesian network and we recorded the real time telemetry data leading up to maneuvers. The long term history found in the event log provided patterns and trends that heightened awareness of upcoming maneuvers. The telemetry data provided more conclusive indications. The sequence of changes in the telemetry leading up to a maneuver resulted in an identifiable signature for the data fusion algorithm. Although the SSFI team was able to predict maneuvers in the THEMIS constellation, the lead time was fairly short. The THEMIS constellation telemetry data updates when the vehicle is in contact with a ground antenna. The maneuver indications would be observed in the same contact window in which the maneuver occurred. Thus, the maneuver prediction conclusion would be produced minutes prior to the maneuver event.

Space Launch

The Space Launch Schedule information mined from the internet proved to not accurately reflect actual space launches. The SSFI team examined data fusion approaches to augment the schedule information in an attempt to improve the presented schedule. The team pulled launch history information covering three years along with terrestrial weather for the given launch locations. The launch history data identified delays do to weather. This information was used to train our data fusion algorithm. Forecasted weather data was then fused with the launch schedule information to conclude the likelihood of the launch.

5. Visualization Approaches

Data that is ingested and exposed within the architecture is made available to consumers through a wide range of visualization tools. Depending on the user viewing the data and the type of data being viewed, the operator can select from four visualization methods. The four visualization methods are as follows: 1) User Defined Operational Picture (UDOP) plug-ins, 2) Portlets, 3) thin-client applications, and 4) standalone thick-client applications. Although each has its drawbacks and benefits, all selections promote interoperability and extensibility by relying on net-centric, standards-based data exchange and storage mechanisms.



Severity	Time	Text
2	Fri Feb 22 03:19:58 EST 2008	Indications of ASAT launch have been analyzed
2	Thu Feb 21 12:30:16 EST 2008	Indications of ASAT launch have been analyzed
2	Thu Feb 21 12:27:04 EST 2008	Indications of ASAT launch have been analyzed
2	Thu Feb 21 12:25:03 EST 2008	Indications of ASAT launch have been analyzed
2	Thu Feb 21 12:23:19 EST 2008	Indications of ASAT launch have been analyzed
0	Thu Feb 21 07:00:00 EST 2008	Conjunction Analysis Complete

GOES 12
- AOCS
- COMM
- IMAGER
- POWER
- PROP
- SEM
- SOUNDER

Double click on node to see the node detai

Title: Terrestrial Weather
Description: Collects wea winds, cloud
ETRO: N/A
Fix Action: N/A

Miss Distance: ○ 1km ○ 12km ○ 25km ○ 37km ● 50km
Prob of Collision: ○ 100% ○ 10% ○ 1% ○ 0.1% ○ 0.001% ○ 10E-5 % ● Show All
SpecialtyFilters: ☐ Show Debris on Debris

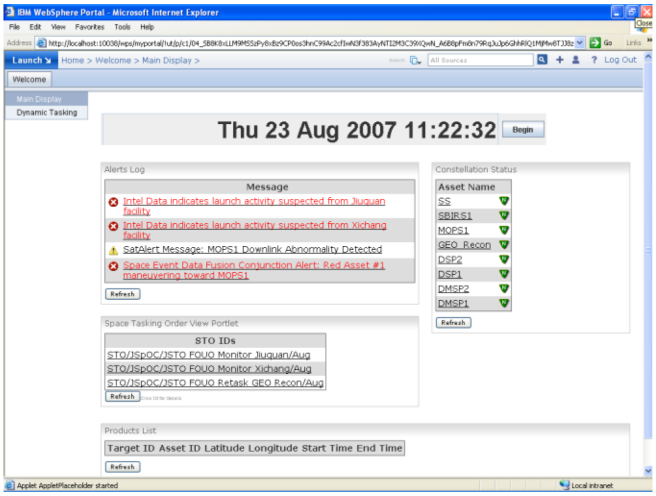
14452-14913 2008-02-26 21:26:07
Time: 2008-02-27 02:26:07 (GMT)
Closest Range: 0.032 km
Prob of Coll: 1.707%
Rel. Velocity: unknown km/s
Primary Object
Common Name: METEOR 2-10
Catalog Num: 14452
Int'l Desg.: 1983-109A
Country: CIS
Secondary Object
Common Name: DELTA 1 DEB
Catalog Num: 14913
Int'l Desg.: 1978-026GN
Country: US

09022-20861 2008-02-25 16:07:09
Time: 2008-02-25 21:07:09 (GMT)
Closest Range: 0.05 km
Prob of Coll: 0.1418%
Rel. Velocity: unknown km/s

Fig. 2: Eclipse Framework UDOP
Modular plug-ins provide a flexible approach.

UDOP Plug-ins

The SSIF team developed a User Defined Operational Picture (UDOP) to visualize the Space Situational Awareness data being created and exposed. The UDOP is built on Eclipse, a flexible, modular Java-based plug-in framework currently utilized on several SMC prototypes to include the JSpOC Situational Awareness Response System (JSARS) and the Single Integrated Space Picture (SISP). Eclipse is built on an event model that allows each plug-in to communicate and share data with the other plug-ins in the framework. Using this event model, the SSIF team was able to harness the processing power and data storage capabilities of client hardware, while maintaining extensibility to support rapid SSA prototyping.



http://localhost:10038/wps/myportal/!ut/p/c1/04_SB8K8xLLM9MSSzPy8xBz9CP0os3hnC99Ac2cfIwN3f383AyNTI2M3C39XQwN_A6B8pFm8n79RqJuJp6GhhRlQ1MjMw6TJJ8z

Thu 23 Aug 2007 11:22:32

Alerts Log

Message
Intel Data indicates launch activity suspected from Jiuquan facility
Intel Data indicates launch activity suspected from Xichang facility
SatAlert Message: MOPS1 Downlink Abnormality Detected
Space Event Data Fusion Conjunction Alert: Red Asset #1 maneuvering toward MOPS1

Constellation Status

Asset Name
SS
SBIRS1
MOPS1
GEO Recon
DSP2
DSP1
DMSP2
DMSP1

Space Tasking Order View Portlet

STO IDs
STO/JSpOC/JSTO FOUO Monitor Jiuquan/Aug
STO/JSpOC/JSTO FOUO Monitor Xichang/Aug
STO/JSpOC/JSTO FOUO Retask GEO Recon/Aug

Products List

Target ID	Asset ID	Latitude	Longitude	Start Time	End Time

Fig. 3: Portal-Based Visualization.
Portal-based visualization support high-level status and drill-down capabilities for SSA.

Eclipse also supports the integration of AGI's 4DX technology [1], which provides high quality, interactive 2D/3D visualizations of static and temporal data. AGI's visualization approach is highly suitable for many SSA applications in which watching data over time is critical. The Eclipse Framework UDOP developed by the SSIF team is depicted in fig. 2.

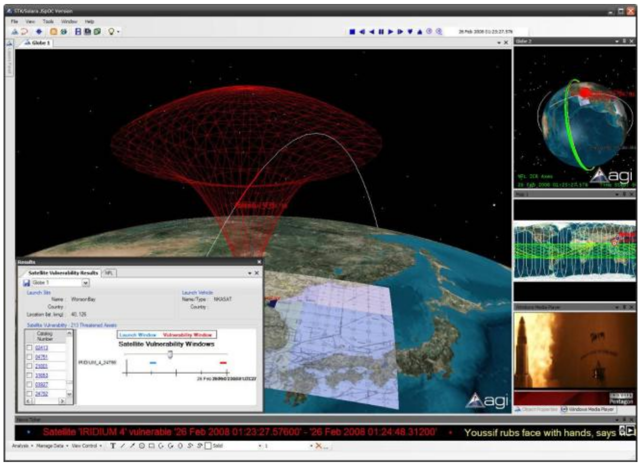
Portlets

The SSIF team developed a portal-based solution for SSA in a Direct Ascent ASAT scenario. The team developed portlets, and accompanying web services, for the visualization of constellation status, active Space Tasking Orders (STOs), high level alarms/alerts and other related data.. Data items are visualized through a collection of discoverable portlets integrated into a user-customizable, standards-based solution. The ability to customize the portal, and to discover new portelts as they are developed make this solution, depicted in fig. 3, a lightweight UDOP.

The portlets we have developed are compliant with WSRP 1.0 and JSR-168. Although our specific portal solution is based on IBM Portal Server, by adhering to industry standards we can ensure cross-compatibility with a variety of commercial portal servers.

Thin-client Applications

Thin-client solutions such as web applications, while not as extensible as a UDOP or portal solution are useful in their own right. Web applications allow for a consistent, intuitive, user interface without requiring custom server software, client-side processing, or extensive development time. One typical limitation of web applications is that a user must know the application exists in order to access it. To avoid this limitation, we have employed an approach in which all web applications are registered within the Systinet registry. User wishing to discover data exposed within the enterprise can browse web services, data feeds, and web applications side-by-side in a single location.



Satellite 'IRIDIUM 4' vulnerable '26 Feb 2008 01:23:27.57600' - '26 Feb 2008 01:24:48.31200' • Youssif rubs face with hands, says

Fig. 4: Thin-client Application
High quality 2D/3D visualization produced from AGI component technology.

Web applications are often viewed as being best suited for the visualization of tabular data. However, we leveraged AGI component technology to bring high quality 2D/3D visualization to the web browser alongside tabular data. Fig. 4 depicts two flavors of web applications that support SSA.

Standalone Thick-client Applications

Although standalone thick-client implementations are often not net-centric, interoperability with 3rd party visualization tools can be accomplished through compliance with RSS, KML, and GML standards. Standards-based data feeds are discoverable in the registry, and can be ingested directly into applictions such as Google Earth or AGI STK with no additional development.

The SSFI team has developed launch site location KML data feeds. This location data was rendered with the 2525B symbology and combined with open source data about launch locations. Fig. 5 depicts our visualization implementation.

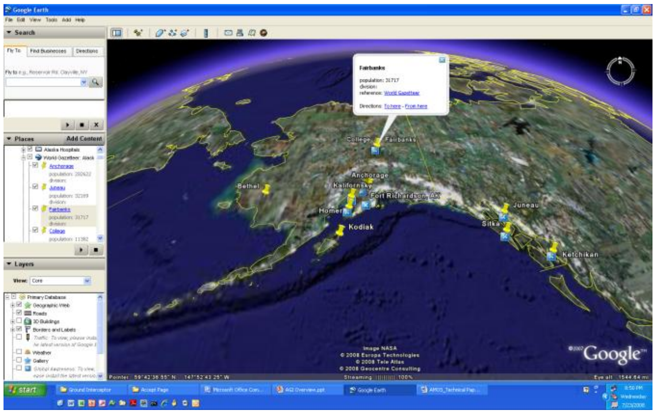


Fig. 5: Google Earth Visualization.
Third-party COTS Products can provide capability at little cost.

6. Data Dissemination

Two levels of web services have been created to allow for machine-to-machine data dissemination: information services and business logic. Information services expose the data obtained directly from internet data sources. The business logic services exposed the value-added processing and data fusion results. The SSFI team controlled access to the data by requiring security information in the Web Service (WS) security extension to the web service calls. The IBM DataPower device was used to extract the security relevant data from request messages. Authentication and Access Authorization was performed utilizing the IBM Tivoli Access Manager. For performance reasons, the Web methods were created to allow users to access multiple pieces of information in a single service request. The creation of the Web Services was done utilizing object oriented methods and this proved to simplify our ability to enhance the system capabilities.

7. Future Research

The SSFI team's use of live data sources produced a greater understanding of the SSA problem space. Future work will focus on additional data source that might provide vehicle status and anomaly data. In the value-added processing area work will focus on approaches to role-up vehicle status to arrive at constellation and mission status with the understanding that each constellation will require a unique approach. Data Fusion work will explore anomaly causal analysis, and visualization updates will focus on approaches to convey data fusion results that offer summary data and allow drill down into the details as well as the temporal aspects of the SSA domain.

8. Acknowledgements

The development of the SSIF was conducted by the Lockheed Martin Information Systems and Global Services (IS&GS) Space Situational Awareness Internal Research and Development Team. Many of the concepts build upon papers presented at previous proceedings and were implemented by the SSIF team. To successfully implement many of the algorithms, the SSIF team utilized a bailment copy of the AGI products 4DX and DGL. Our security architecture utilize bailment copies of IBM products to include DataPower and Tivoli Access Manager.

9. REFERENCES

1. Analytical Grapics Incorporated, Component Products, http://www.stk.com/products/components/main.cfm
2. T.S. Kelso and S. Alfano, "Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES), American Astronautical Society Proceedings paper AAS 05-124, January 2005
3. Denis A. Kaya and Daniel E. Snow, "Element Set Prediction Accuracy Assessment", AAS 99-425, AAS/AIAA Astrodynamics Specailist Conference, Girdwook, AK, August 1999
4. Glenn E. Peterson, Robert G. Gist, Daniel L. Oltrogge, "Covariance Generation for Space Objects Using Public Data", AAS 01-113, AAS/AIAA Space Flight Mechanics Meeting, Santa Barbara, CA February 2001
5. Tom Kelecy, et al., "Satellite Maneuver Detection Using Two-line Element (TLE) Data", AMOS Technical Conference Proceedings, Wailea, HI, September 2007.
6. Richard I. Abbot and Timothy P. Wallace, "Decision Support in Space Situational Awareness", Lincoln Laboratory Journal , Volume 16, November 2, 2007
7. The THEMIS constellation event log data were downloaded from the University of California, Berkley web site found at http://soleil.ssl.berkeley.edu/ground_systems/request_planning.themis.txt
8. The GOES constellation weekly operations plan were downloaded from NOAA Satellite and Information Service web site found at http://noaasis.noaa.gov/cemscs/goeswkly.txt