IMPROVED CONJUNCTION ANALYSIS VIA COLLABORATIVE SPACE SITUATIONAL AWARENESS

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ABSTRACT

Satellite operators are becoming increasingly aware of the threat of on-orbit collisions—between satellites or with orbital debris. Successful conjunction monitoring and collision avoidance activities require accurate orbital information for as many space objects as possible. Current sources of orbital data are of low fidelity, as a result of how those data are generated, and are of limited value to conjunction analysis. However, satellite operators have much better data for their own satellites. When that data is shared among operators, overall space situational awareness can be significantly improved. This paper will demonstrate the potential improvements and discuss an operational implementation—SOCRATES-GEO—which uses operator data to improve conjunction monitoring.

1. INTRODUCTION

Recent events in Earth orbit, such as the 2007 Chinese anti-satellite (ASAT) test, the 2008 intercept of USA 193, and the need to maneuver the International Space Station (ISS) to avoid pieces of debris from the 2008 breakup of Cosmos 2421 [1], have highlighted the need for better space situational awareness (SSA). While there are many aspects to SSA, tracking objects in orbit in order to determine their positions over time is a key requirement.

For over half a century, the need to maintain orbits for not only operational satellites, but dead satellites, rocket bodies, upper stages, and the ever-increasing debris resulting from a variety of causes, has lead the US to develop and operate the Space Surveillance Network (SSN)—a network of radar and optical sensors distributed across the globe. This network has the advantage of being able to track everything in Earth orbit—within the individual sensor capabilities—whether it is operational or not.

But this *non-cooperative* tracking network also has its limitations. In particular, non-cooperative tracking is not as accurate as cooperative tracking, such as active ranging or the GPS receivers now used by many satellite operators. It also has no reliable way to know when maneuvers might occur and is reactive in correcting an orbit once a maneuver has been performed. This is the price of needing to track everything in Earth orbit, whether it can—or even wants to—be tracked.

What if there were an easy way to improve tracking, particularly for that class of objects which are the most difficult to track—operational satellites? These satellites are the most difficult to track because they frequently maneuver to maintain orbits consistent with their mission requirements. The delay in detecting and processing a maneuver—even without other problems due to weather or equipment malfunctions—can result in positional errors on the order of hundreds or even thousands of kilometers. These delays can even result in an inability to associate new observations with an object's track—or what is referred to as a 'lost' satellite. Obviously, operational satellites, even under the best of conditions, will require increased SSA resource allocation to maintain their orbits.

As it turns out, however, the good news is that there is a better way. Each operational satellite has its orbit maintained by a satellite operator, in order to allow the operator to plan state-of-health contacts, anomaly support, thermal and power management, attitude maintenance, and periodic orbit adjustments. And, of course, the satellite operator knows when maneuvers are planned to be conducted and what the post-maneuver nominal orbit should be.

While these orbital data are generated in a wide variety of data formats, coordinate frames, and time systems, the ability to share these data via a common framework would go a long way to improving SSA and reducing the resources required for tracking operational satellites. In fact, this realization was the genesis of the data center concept proposed by Intelsat in mid-2007 and now implemented by the Center for Space Standards & Innovation (CSSI). The current consortium of satellite operators who contribute to the data center includes Intelsat, Inmarsat, EchoStar, SES (Astra, New Skies, Americom), NOAA, Star One, and Telesat (with several other satellite operators expressing interest) and covers 117 satellites with another 24 pending. That's about 32 percent of the active geostationary (GEO) satellite population, with another 6 percent coming soon.

The data center is already being used to support collaborative conjunction analysis among members of the consortium, via an automated process known as SOCRATES-GEO. Before discussing how that process works and the benefits of the collaboration, let us first take a look at some already available public sources of data and what the potential improvements might be.

2. ANALYSIS

As it turns out, there is an increasing availability of operator-provided orbital data available to the public via the Internet. The biggest challenge here is finding the data, decoding the data format, and then using the data—with the appropriate propagation model—to generate usable satellite ephemerides. Because many astrodynamics analysis packages don't have the ability to use this variety of data natively, we first undertook to 'convert' the native data to NORAD two-line element sets (TLEs) by fitting it with the SGP4 orbital model, since most packages do implement this propagator. We call these *supplemental* TLEs since they are generated as a supplement to the normal TLEs produced by NORAD.

One of the best test cases to examine the performance of these supplemental TLEs is the orbital data for GPS. One alternate source of orbital data is the GPS almanacs, which contain basic data used by GPS receivers to determine preliminary satellite locations in the process of obtaining a location fix. This data is transmitted by the GPS constellation (at a very low data rate) but is also now available online. In fact, some GPS systems now use this online data to quickly initialize their GPS receivers. While the data isn't of sufficient quality for navigation purposes, it is far better than the orbits obtained from non-cooperative tracking data, as we are about to see.

Of course, GPS is closely tracked by a network of highly accurate sensors around the globe and the positions of each satellite in the constellation are routinely calculated to accuracies on the order of several centimeters. Both the US National Geospatial-Intelligence Agency (NGA) and the International GNSS (Global Navigation Satellite Systems) Service (IGS) process this data into precise ephemerides (PE), assess its accuracy, and provide it to the public via the Internet.

That provides our first opportunity to perform some analysis showing the relative accuracy of orbits generated from non-cooperative and cooperative tracking data. The PE, which are accurate to the centimeter level, will serve as our truth data. For this case, we will take the TLEs released on the Space Track web site at 1300 UTC on 2007 Dec 31 along with the SEM almanac released that same morning at 1515 UTC (all test data is available on CelesTrak at http://celestrak.com/NORAD/elements/supplemental/). The SEM almanac data was converted to ephemerides in accordance with the specifications in IS-GPS-200D from the Time of Applicability (TOA) of the data (2008 Jan 2 at 16:44:34 UTC) for 24 hours. Those ephemerides were then fit to a TLE using the SGP4 propagator in Satellite Tool Kit (STK). This process was done for all 30 operational GPS satellites. The almanac ephemerides and the original and supplemental TLEs were then compared to the PE obtained from NGA for 2007 Dec 31. The results are shown in Figs. 1 and 2.

Fig. 1 shows that the SEM almanacs (green), even when propagated backwards several days, provide considerably better accuracy than the original NORAD TLEs (red). In this case, the NORAD TLEs had a mean error (difference from the NGA PE) of 7.544 km and a maximum error of 32.449 km. The SEM almanacs had a mean error of 1.292 km and a maximum error of 3.073 km.

Fig. 2 shows that, interestingly enough, the supplemental TLEs can produce even better accuracy, for certain propagation intervals. Since the IS-GPS-200D orbit propagator is a fairly simple two-body propagator, fitting the almanac to a TLE and using the higher fidelity SGP4 propagator produces less error at the time of our test case. As a result, the mean error for the supplemental TLEs (blue) is only 0.872 km and the maximum error is 2.366 km. The supplemental TLEs reduce the mean error by 88 percent and the maximum error by 93 percent.

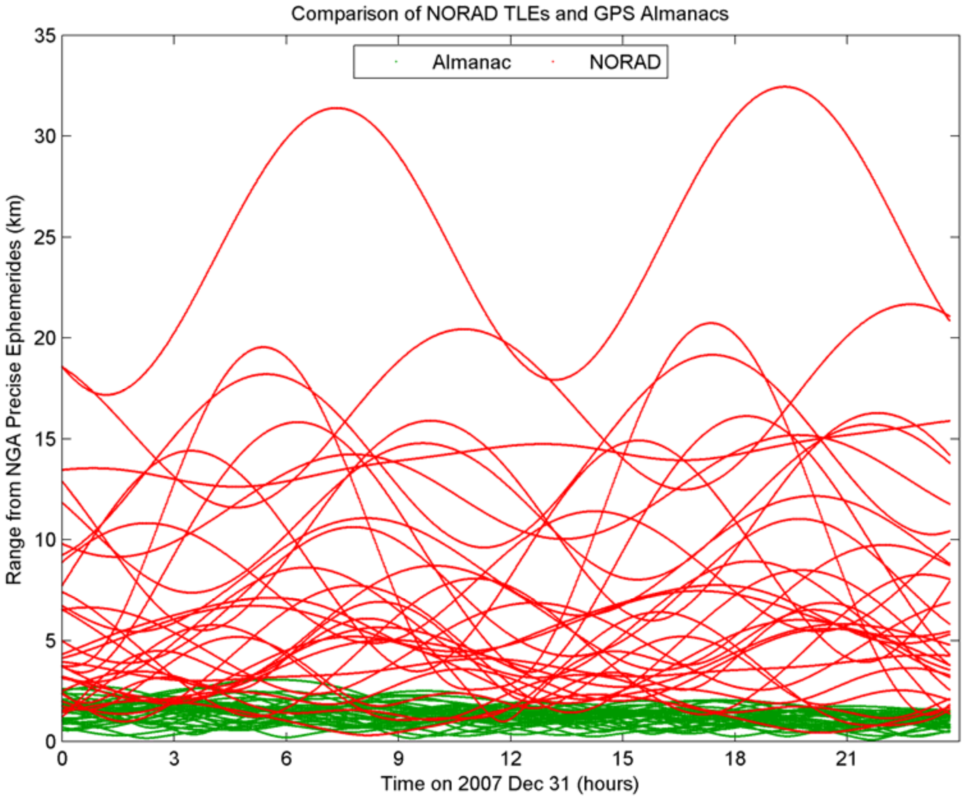

Figure 1. Comparison of NORAD TLEs and GPS Almanacs

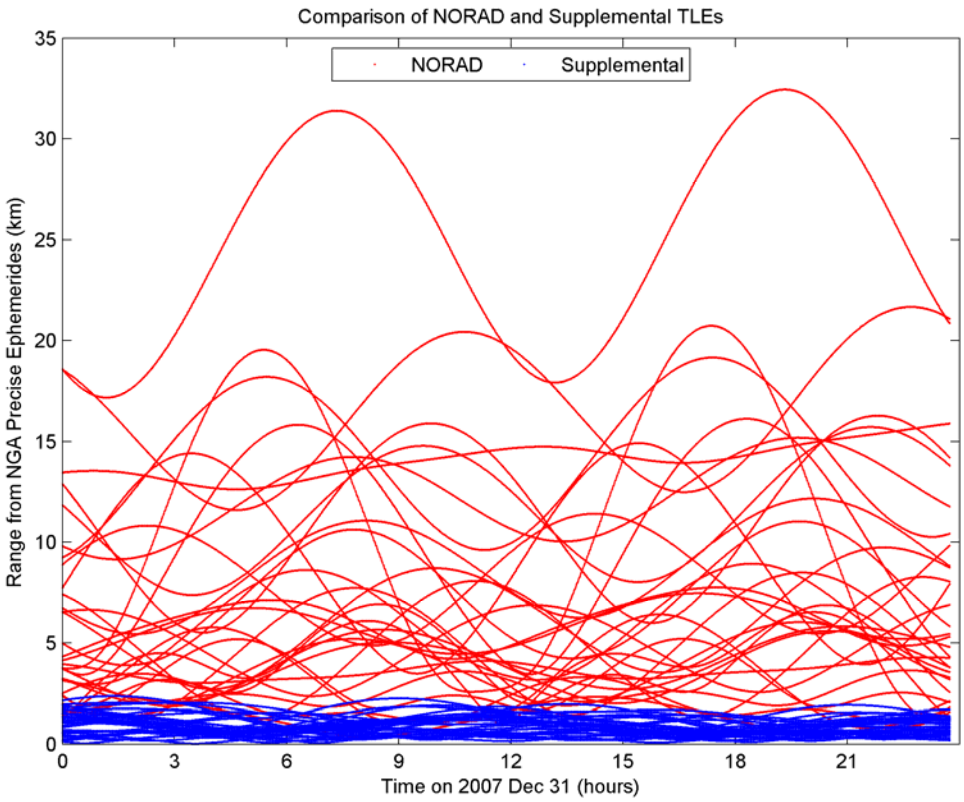

Figure 2. Comparison of NORAD and Supplemental TLEs for GPS

If we apply this same process using the Rapid Precise Ephemerides provided by the Russian Space Agency's Information-Analytical Centre (RSA IAC) for GLONASS, which is provided in the standard SP3 data format, we see similar results, as shown in Fig. 3. In this case, we compare the NORAD TLEs released on the Space Track site at 1300 UTC on 2008 January 25 to the supplemental TLEs generated from the GLONASS Rapid PE released at 1311 UTC the same day for the 14 satellites then active. The truth orbit in this case is the GLONASS Final PE, which is accurate to at least the meter level.

Here we see a mean error for the original NORAD TLEs (red) of 3.301 km and a maximum error of 9.388 km compared to a mean error for the supplemental TLEs (blue) of 201 m and a maximum error of 539 m. The supplemental TLEs reduce both the mean and maximum error by 94 percent.

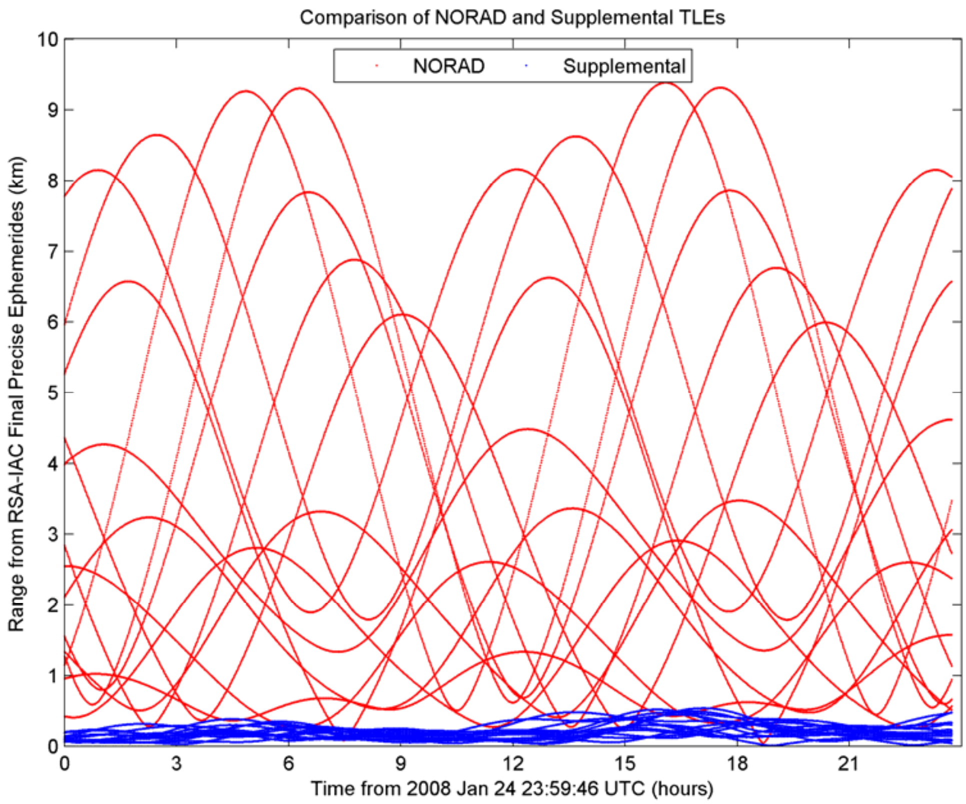

Figure 3. Comparison of NORAD and Supplemental TLEs for GLONASS

Our final test case examines three Intelsat satellites to illustrate the relative performance of various orbital data sets. Since we had not only the Intelsat-provided ephemerides (which have been independently determined to be accurate to at least 500 m), but also the 11-parameter data Intelsat provides via their public web site, we could assess performance of not only these data but supplemental TLEs generated from the 11-parameter data, along with the NORAD TLEs. We did this for Intelsat 3R, 6B, and 11, since these satellites were close to each other at the time of the analysis.

Fig. 4 shows these four orbital data types, for each of the three satellites, by showing the orbits for two days starting on 2008 February 13 at 0000 UTC, in the Earth-fixed frame. The Intelsat ephemerides are in green, the Intelsat 11-parameter data are in yellow, the supplemental TLEs derived from the 11-parameter data are in orange, and the NORAD TLEs are in red. For the most part, the 11-parameter data agrees quite well with the Intelsat ephemerides, except for the IS-6B case, which was due to a data synchronization issue between the data that was provided directly to the data center and that posted on the Intelsat web site.

It is clear, however, that that the NORAD TLEs do not agree well with the Intelsat ephemerides. Not only is the relative order of the three satellites switched, but a potential conjunction is shown between IS-6B and IS-3R, when those two satellites are not close together, and a potential conjunction between IS-3R and IS-11 is made to look unlikely. It also appears that the maneuver at 23:11:27 UTC on 2008 February 3 may have thrown off the orbit determination for IS-11.

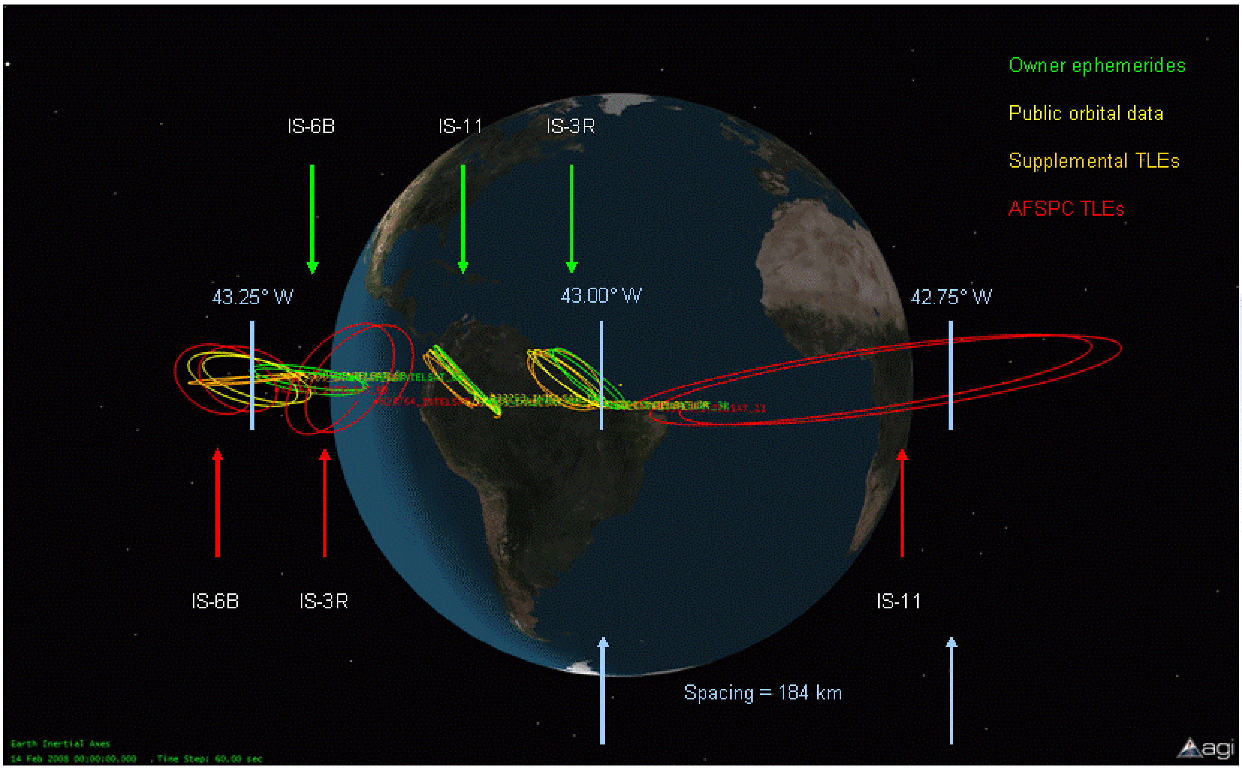

Figure 4. Comparison of Orbital Products for Intelsat 3R, 6B, and 11

It should be noted that each of these test cases were randomly selected and do not represent worst-case results. The criteria for selecting the particular date simply happened to be the time when the analysis was performed, so the results should be representative. The primary difference in the accuracy is due to the inherent limitations of non-cooperative tracking, which is used for full-catalog orbit maintenance.

These three test cases should highlight the potential advantages of the data center concept. Not only is it possible to dramatically improve accuracy and, thereby, reduce the false-alarm rate for conjunction analysis, but it is possible to do this without large expenditures and delays resulting from acquiring new sensors. In addition, having planned and actual maneuver information can further improve overall SSA by avoiding the delays in determining new orbits. As a result, tracking requirements for operational satellites could be reduced considerably, even if unsure of the data quality for some satellites, since it would be far easier to simply verify a reported position than to rely solely on non-cooperative tracking.

3. APPLICATION

Now that we've seen the potential benefits of collaborative SSA, let's look at the process we've implemented at the data center to perform conjunction analysis—SOCRATES-GEO (SG).

SG, like its predecessor SOCRATES [2], manages the process of selecting orbital data, conducting conjunction analysis using STK, and then reporting out the results of that analysis via CelesTrak. The primary difference with SG is that it uses the best available data sources, whenever possible, instead of TLEs. For the most part, that means using the satellite operator-provided ephemerides that come into the data center or other public satellite operator-provided data sources.

We have consciously decided to restrict this phase of the larger SOCRATES effort to the more limited environment around GEO, where the roughly 360 operational satellites are a significant proportion of the total 1,300 objects (for which we have public data) that come within 250 km of GEO altitude. It is also easier to make the case for collaboration since the potential benefits are more apparent and the operators in this orbital regime all understand the potential risk for everyone if there is even one collision.

Since the amount of participation in this effort is fundamental to its success, we want to encourage as many satellite operators to participate, as possible. As such, any operator that provides data has full access to the analysis products generated by SG. To protect the data, SG is restricted to those satellite operators that provide their orbital data to the data center and access is restricted by user authentication and communication is protected using secure HTTP (Secure Socket Layer).

Each organization can designate their data, operator, and administrative points of contact (POCs) via their online profile, as well as specifying their individual notification criteria. Data POCs are notified automatically of any anomalies in the data provided, such as missed updates or outdated ephemerides. Operator POCs are automatically notified of any conjunctions which violate their specified criteria (e.g., range less than 10 km or maximum probability greater than 1 in 100,000) for any satellite in their Satellite Watch List—whether it is one of their satellites or not. A sample operator notification message is shown in Fig. 5. Operator POCs are also sent links to Neighborhood Watch plots, which show the range between any pairs of satellites for which they want to continually monitor. A sample Neighborhood Watch plot is shown in Fig. 6.

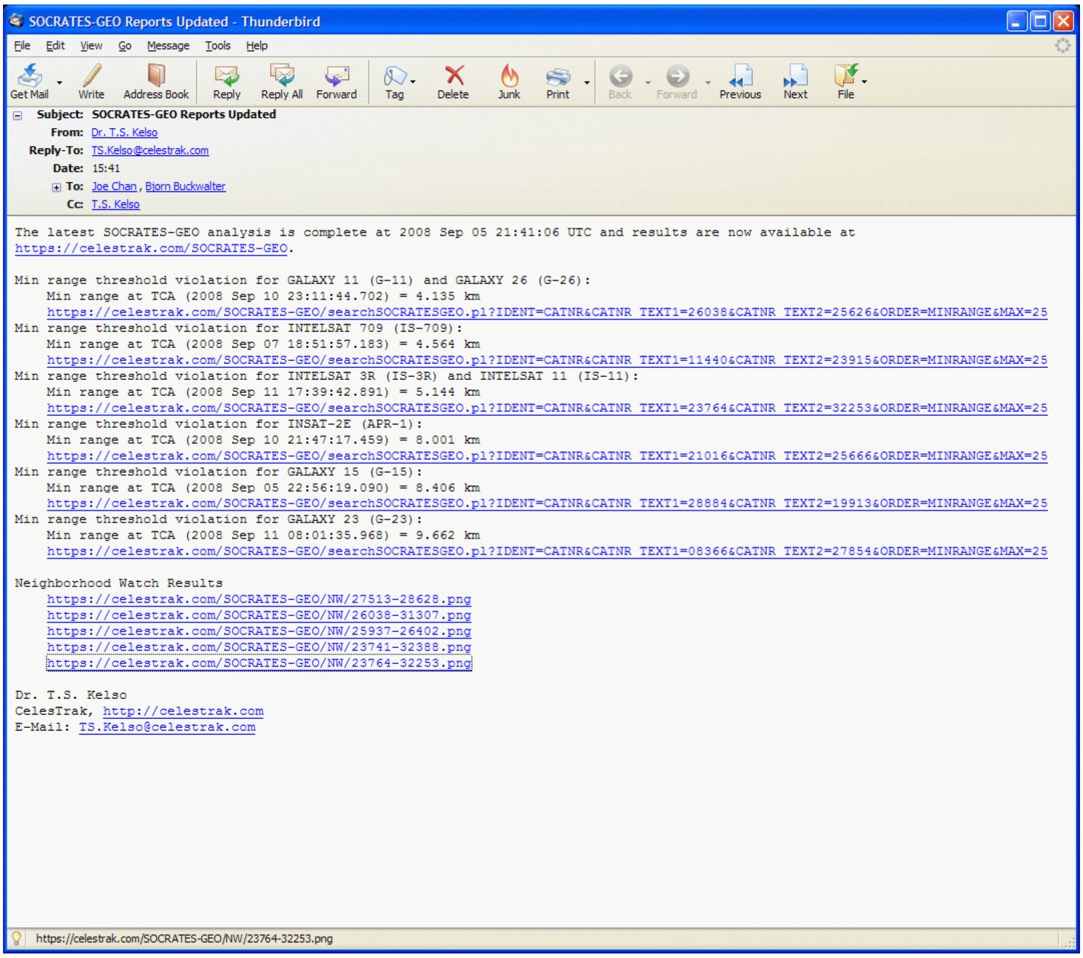

Figure 5. Automatic Operator Notification Message

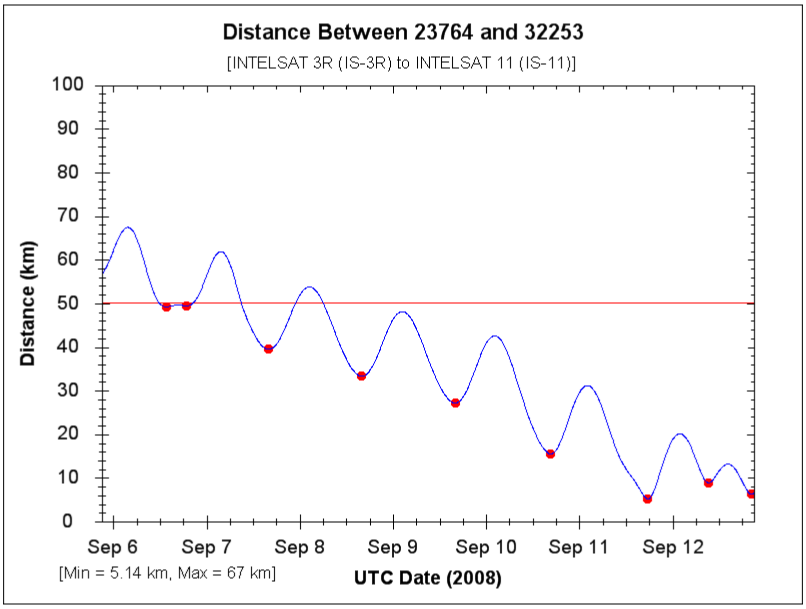

Figure 6. Neighborhood Watch Plot

CSSI has made participation easy. Rather than requiring conformance to standard data formats, coordinate frames, and time systems, CSSI works directly with the satellite operator to accept the data in whatever format their legacy software generates it. Of course, that means close attention must be paid to understanding the data format, units, coordinate frame, and time system and that additional validation must be performed to ensure that understanding. CSSI and Intelsat welcome additional participation in the data center and SOCRATES-GEO.

This flexibility does not, however, obviate the need for standards. Satellite operators are still faced with the need to be able to interchange orbital data products provided by SG for their additional analysis. However, CSSI stands ready to help satellite operators to adopt these standards to make this process successful. CSSI is also working with AGI (its parent organization) to implement the ability to directly import many of the public data sources in upcoming releases of STK, including: GPS almanacs (both SEM and Yuma), SP3a and SP3c ephemerides, Intelsat's 11-parameter data, and the Consultative Committee for Space Data Systems (CCSDS) Orbit Ephemeris Message (OEM) and Orbit Parameter Message (OPM) formats.

4. SUMMARY

The first six months of operation of the data center have proven to be quite successful. Not only does the data center already routinely collect data for 30-40 percent of all the operational satellites in GEO, but the members of the consortium are working more closely together and learning how to make the SG process work even more effectively. In particular, members are realizing the need to be able to interchange data products via standard formats which use clearly defined coordinate frames and time systems, thereby ensuring that everyone involved in working a conjunction has the same understanding of the data. Finally, by working through the data center, everyone has access to the latest data, ensuring that a common baseline is used for decision making.

It should be obvious that this approach could be quickly and easily expanded to include not only all operational satellites in GEO, but for all Earth orbit regimes. Doing so could substantially reduce SSA resource requirements to maintain these orbits and allow these resources to be applied to better tracking orbital debris which represents a threat to all operational satellites. The key to success is promoting an understanding of the value of sharing the best data and analysis through a common data center.

5. REFERENCES

1. The NASA Orbital Debris Program Office. (2008). "ISS Maneuvers to Avoid Russian Fragmentation Debris," *Orbital Debris Quarterly News*, **12**(4), 1–2.
2. Kelso, T.S. and Alfano, S. (2005), "Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES)," presented at the 2005 AAS/AIAA Space Flight Mechanics Conference, Copper Mountain, CO, 2005 January 23–27.