ORBIT DETERMINATION RESULTS FROM OPTICAL MEASUREMENTS

EUROPEAN SPACE ASTRONOMY CENTRE (ESA/ESAC), MADRID, SPAIN
3 – 6 MAY 2010

David A. Vallado(1), Vladimir Agapov (2)

(1) Center for Space Standards and Innovation, Colorado Springs, Colorado, 80920, USA. Email:dvallado@agi.com
(2) Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences, Russia,
Email:vladimir.agapov@gmail.com

ABSTRACT

Operations in geosynchronous orbit are important for many aspects of commerce. Avoiding conjunctions in an ever increasingly crowded geosynchronous – environment is therefore becoming more important especially in light of the Iridium 33 / Cosmos 2251 collision. SOCRATES-GEO has combined owner operator numerical ephemerides with Two-Line Element (TLE) set information for over 2 years. Unfortunately, the TLE information is of limited quality, and obtaining high quality ephemerides is often difficult. Previously we explored how we could replace the TLE data for those objects for which we do not get operator data (non-participating SOCRATES-GEO operational satellites or debris). The International Scientific Observing Network (ISON) resource provides high-quality optical observations on numerous GEO satellites. This paper introduces additional orbit determination results of optical data and seeks to understand what observation mix is necessary to meet certain accuracy requirements.

1. INTRODUCTION

Since May 2004, CSSI has been providing daily reports of likely conjunctions for the upcoming week for all objects in earth orbit using the full catalog of unclassified NORAD TLEs available to the public. The program is called Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES) [1]. The information is publicly posted at http://www.celestrak.com/SOCRATES/.

SOCRATES-GEO grew from the initial SOCRATES effort and began operations in December 2007 focusing on geosynchronous satellites. The emphasis on GEO is because over 25% of the total known population is comprised of operational satellites, where we can obtain data directly from the operators. These satellites represent an important region because it's a limited resource, close locations are desired for many satellites, existing space surveillance is not very good, and any debris created from a collision would impact hundreds of additional satellites for many decades. At the time of this writing, we are processing 184 of the satellite owner-operator satellites, with several more in work. This is over 50% of the active geosynchronous satellite population. Each of the owner ephemerides includes all maneuvers, whether planned or already executed. The maneuver information is arguably the most important and unique aspect of using this information.

Further expansion of SOCRATES-GEO occurred on April 12, 2010, when the Space Data Association Ltd. (SDA) selected Analytical Graphics, Inc. (AGI) to develop and operate its Space Data Center (SDC). The system is an automated space situational awareness (SSA) program designed to reduce the risks of on-orbit collisions and radio frequency interference. It is the satellite industry's first global operator-led network for sharing high-accuracy operational data to improve overall space situational awareness and satellite operations.

The SDA and SOCRATES-GEO efforts look at all objects that pass within 250 km of GEO, combining owner ephemerides and TLE information as available. The reports are similar to the regular SOCRATES reports, but also include the ability to directly use improved data sources (supplemental TLE's or independent ephemerides), getting standard reports, allowing for restricted access, and customizable user notification.

Our experience from SDA and SOCRATES-GEO shows us many more things than just the original intent of refining the conjunction processing for GEO satellites. The SDC concept conclusively demonstrates improvements to orbital accuracy, the ability to reduce search volumes for sensors, the reduction of false alarm rates for conjunctions, and even shows how SSA tracking requirement could be reduced (trust but verify).

Unfortunately, the TLE information is of significantly lower quality than the owner ephemerides, but a large improvement in the conjunction processing is still achieved over analysis using TLE information for both objects. With over 50% of the GEO operators already providing data, we seek ways to replace the TLE data for those objects for which we do not get operator data (non-participating operational satellites, or debris). The International Scientific Observing Network (ISON) is an excellent resource from which we can obtain high quality observations on satellites to support non-operational satellites and debris ephemeris generation.

Vallado and Agapov [2] showed some initial examples of successful integration of ISON observational data to replace TLE information. This paper extends the processing of additional observational data to provide more complete and accurate Space Situational Awareness (SSA) for conjunction operations. Using Analytical Graphics Inc. Orbit Determination Toolkit (ODTK), we process the ISON observational data. Details are provided to demonstrate the filter results of the orbit determination, and to give confidence in the overall processing.

We define SSA as the process by which an organization maintains a catalog of all objects in space, to some level of accuracy, and in a timely fashion. Several relevant attributes are discussed in Vallado [3]: complete and robust, timely and efficient, standardized and maintainable, accurate, and importantly, trusted.

The primary question we seek to investigate is **what observations and processing are needed to achieve a certain level of accuracy on a particular satellite, now, and at a future time?**

2. BACKGROUND

Beginning in about 2001, cooperation of optical observatories began, and by 2005 the International Scientific Optical Network (ISON) [4] was created. Additional observatories have been added to primarily study scientific and applied problems in space, notably in geosynchronous orbits. A great deal of modernization of equipment and software has taken place, and the Keldysh Institute of Applied Mathematics Russian Academy of Sciences (KIAM RAS) has been a principal scientific and organizational coordinator of ISON. By 2010, 33 telescopes at 23 observatories in 11 countries were operating around the world with over 90 researchers. The current tasks include regular GEO monitoring, new object discovery and tracking, and maintenance of as complete a catalog as possible. ISON is currently tracking 1467 objects in GEO compared to the TLE catalog of 1016 objects, and the observers track between 150 up to 800 individual objects each night. The data are stored at the KIAM Ballistic Center upon collection. The processing and analysis of information on space debris is also developed at the Center.

For the most part, the TLE data are regularly updated and made available electronically via the US Air Force Space Command (AFSPC) Space Track web site. That database is not fully comprehensive, however, because it intentionally omits those satellites deemed vital to US national security—a couple hundred payloads along with the associated rocket bodies and upper stages which delivered them to orbit. Even so, current orbital data is available for 14261 of 15618 (91 percent) cataloged by NORAD. Not all of these missing objects are for restricted objects, though. Some are considered lost since they have not been tracked for the past 30 days or longer. This database does not include those objects too small to be detected or regularly tracked by the US Space Surveillance Network (SSN).

Because the TLE information is of limited quality, we use public data such as GPS almanacs, GLONASS precise ephemerides, and the Intelsat 11-parameter data to supplement the TLE's. These data sources can all be imported into STK directly, or used to generate TLE's. We term the resulting data supplemental TLE's. An advantage is possible through the supplemental TLE's. Here, we process an external ephemeris (usually from a numerical orbit determination and subsequent propagation), and fit a TLE to this information. Because of the larger observation density, SGP4 is able to better model the orbit, and predictions from the resulting TLE's can be 10-20 times better than a comparable TLE developed from AFSPC processing of SSN observations [5].

The various options of data to use for conjunction operations are shown in Fig. 1. SOCRATES uses the TLE on TLE approach. SOCRATES-GEO takes advantage of each of the various options depending on what data is available. The status of the second satellite (active or not) influences the choices available for ephemeris information. There are many permutations when combining each of these data sources. The operator ephemeris vs operator ephemeris derived from observations results in the most accurate processing, and the TLE vs TLE is the least accurate.

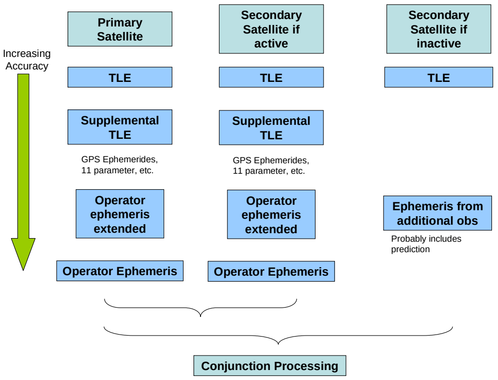

Figure 1. Conjunction Processing Options.

3. ORBIT DETERMINATION PROCESSING

We process additional observations to replace the TLE information with the Kalman filter in Analytical Graphic Inc's Orbit Determination Toolkit (ODTK).

Because the filter processes data differently than traditional batch least squares, we show 3 basic reports used to gain confidence in the results.

Optical observations present many challenges for the operator. We briefly discuss several topics.

The coordinate frame for optical measurements is generally topocentric, but some centers perform conversions to other coordinate systems. We also found that not all systems with the same names are the same as well. Initial test cases between organizations are essential to fully understand exactly what data is being transferred. In ODTK, we use the ICRF from the latest IERS conventions [6, 7].

The initial estimate is crucial to processing the data. Often, a TLE is not sufficient to initiate an OD process. We saw this with both satellites examined. The type of data can also affect our ability to arrive at an accurate initial estimate. Radar data generally produces a much more accurate initial estimate, while optical data generally requires additional processing (IOD and LS) to get the initial estimate.

The accuracy we obtain from observational data is a function of many variables including the number, type, and quality of the observations in a pass over a sensor, the location of the data within a pass, the total number of tracks, number of sensors, location of the sensors, the processing technique, etc. To obtain the best accuracy, we trade-off the merits of each of these aspects versus their costs.

Sensor observations will not always be available when needed. Maintenance, downtime, and tasking priority can affect the quantity of observations, and personnel actions can even influence quality and, in some cases, prevent the observations themselves from reaching the user. Unfortunately, we can’t reliably predict these effects. One solution is trying to gather as many types of data as possible, so we’ll have a backup whenever normal procedures fail. This is particularly challenging for space surveillance operations.

Closely related is the amount of data available for a satellite. Continuous data does not exist for most satellites (except for satellites with GPS receivers). If we observe only a small arc of a satellite’s orbit, it’s much more difficult to determine an accurate answer. This difficulty can lead to mismodeling of the orbit. Too little data can also result in our inability to estimate additional state (solve-for) parameters. Vallado and Carter [8] show we need more data if we want to solve for station biases in addition to the position and velocity vectors. This is especially true for eccentric, deep space, and drag perturbed orbits. Remember the solve-for parameters “soak up” any mismodeling in the force models, so we want to have sufficient data to accurately determine the effect of perturbations, and not just the dynamic mismodeling.

In general, more distinct tracking data should give better accuracy (Central Limit Theorem). However, this assumes that the biases are identified and removed, and that the relative accuracy (weighting) of each observation is known and used in the estimation process. If the orbit solution quality degrades with additional data, the model and the calibration are probably the cause. Additionally, suppose a sensor reports only two or three data points. Obviously most modern sensors receive much more data—often hundreds or thousands of points per pass. One approach to obtain more data could be to task more sensors to observe the satellite and report additional sparse sets of observations. Although that would give us a slight improvement, we could incorrectly conclude that sparse data from many sites permits highly accurate orbit determination. This is simply false because there is a trade-off between many variables, as mentioned at the beginning of this section. Quite often, denser data (even from single sites) can actually improve the quality of the orbits and reduce the overall sensor tasking when combined with accurate biases and proper numerical processing. Fonte [9] showed that dense, real-world observations from a single station could produce orbits accurate to less than 10 m for a 12-hour prediction on a satellite at about 800 km altitude. Sparse data (less than five observations per pass) even from multiple sensors can actually increase this error to over 400 m for the same satellites [10]. This suggests that dense observations (perhaps on the order of 50-100 per pass) can produce precise orbits (10 m to 100 m for many satellites).

The location of the measurements in a pass also affect the OD result. When the satellite is very low to the horizon, a small vertical (elevation) error can result in a large uncertainty about where the satellite is in its orbit—the along-track component. As the satellite travels over the site, a small horizontal (azimuth) error will become a large plane change or a cross-track error. This effect is magnified because the satellite is usually closest to the site at its maximum elevation, or culmination. If we combine these results, we get an error ellipsoid about the satellite. In general, along-track errors are greatest because of a lack of precise timing information and the uncertain nature of the local satellite environment (the non-conservative forces such as drag and solar radiation pressure tend to retard the satellite’s motion). Cross-track errors are usually smaller, typically resulting from a sensor’s misalignment. Radial errors are usually the smallest

A more practical concern is the format of the observational data. Most formats are densely packed files with little to no documentation. ISON can produce a .geosc format that is read directly by ODTK. Unfortunately, this format truncates the precision of the measurements, as most formats do. Although simple scripts can be written to convert the data to a useable form for input into ODTK, it may be better to adopt a new format that is a simple ASCII/XML form that permits various data types, precision, and includes enough information to specify what fields are being transmitted.

The system taking the observations must properly accomplish observations correlation and maneuvering, contend with co-located of satellites, process through continual E-W and N-S maneuvering, and minimize the number of lost satellites – usually about 10% of the catalog at any given time, or nearly 1400 objects! There is an important distinction in surveillance (searching to see what objects are visible) vs tracking (observing a known object at a certain time and location).

Small objects are very difficult to observe from the ground (think about 10 cm). Observability problems are particularly difficult for geostationary satellites as they have little relative motion with respect to ground sensors. The radial component is particularly difficult to observe. Sensors are usually limited, and coverage (gap) problems exist in some locations. Weather outages can easily hinder optical operations.

The Initial Orbit Determination (IOD) problem is often degenerate due to the lack of range information. Observations require proper selection of number per pass, where they are located in a pass, total observations available, the quality, how good the calibration values are, and others.

Finally, the perturbing forces present challenges. The third body and solar radiation pressure effects are reasonably well modelled, but not extensively understood. Recent discussion [11] has suggested that coulomb forces may even be partly responsible for some of the observed behaviors.

4. INTELSAT F3 (NORAD 4376) TESTING

This satellite is interesting because it is a large satellite (~90 m^2) and although it has been non-functional for many years, AFSPC last tracked it in 1971![1] ISON regularly tracks this object. Aside from the obvious conjunction implications, the ability of external sensor networks to provide observations where holes in coverage may exist is of great interest. Our ISON data included measurements from 01 Jan 2008 21:47:42.200 UTCG to 14 Apr 2010 15:39:15.830 UTCG.

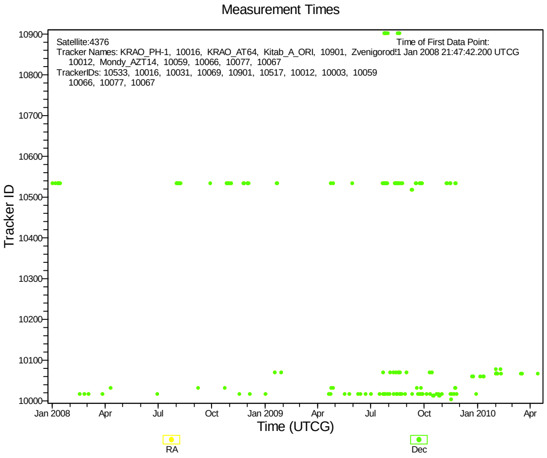

Figure 2. Measurement Times, satellite 4376.

The data spans several years and was not tasked specifically with the intention of obtaining a certain accuracy level to support conjunction operations. Rather, the data is simply routine measurements to enable future tracking. Knowing that "some" additional observations are needed to support any increase in accuracy for numerical processing, we chose several periods containing slightly more observations.

4.1 Data from 20 Apr 2009 19:30:25.5899999

Using the first three observations, the Gooding angle-only technique provides an initial estimate of the solution.[2] Orbital elements (a, e, i, Ω, ω, u) were as follows:

43068.754043 0.02043901 10.346662 320.734690 146.086260 185.820887

Inserting a Least Squares (LS) solution fro the data from 20-25 April (76 obs), we refine the solution to

42158.187976 0.00026464 10.235637 320.898468 320.026116 185.666411

We now process the data from 20-29 April because we don't want to end the filter where there is no data as it will give erroneous signatures in the FSC test. This is warranted because in actual operations, the solution would end precisely on the last observation taken.

The filter residual ratios (residuals divided by the noise) provide a normalized look at the results.

---

[1] We have done additional research to determine that this is indeed Intelsat F3 (4376) and plan a future paper to discuss our findings.

[2] The ability of angles-only techniques to accurately process GEO data is explored in greater detail in Vallado [12].

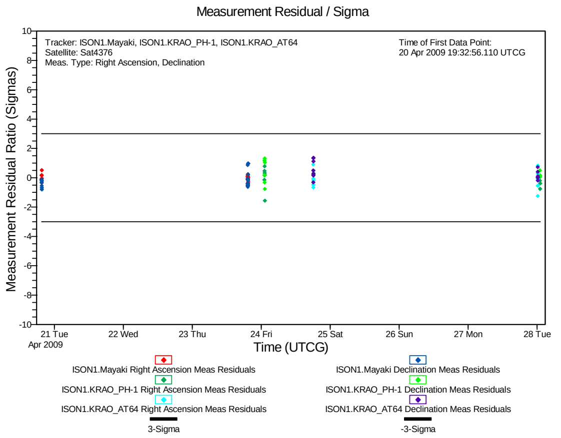

Figure 3. Filter Residual Ratios, satellite 4376.

Note that the observations are not extremely dense, but are well processed in the simulation. The smoother is then run to produce a position uncertainty.

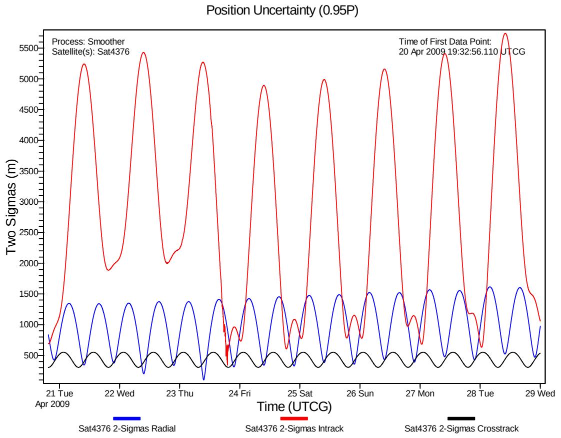

Figure 4. Smoother Position Uncertainty, satellite 4376.

Note that there is about a 5-6 km approximate uncertainty – a significant improvement from TLE data where differences are routinely many 10's of km.

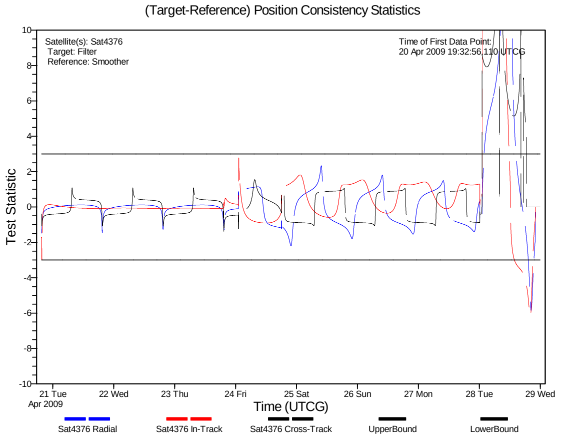

Figure 5. Filter Smoother Position Consistency Test, satellite 4376.

The FSC test looks reasonable. The last spike in the data occurs because we have data at the end of the processing, but then a large gap with no data for several days. We'll see additional cases of this in this paper.

4.2 Data from 21 Jul 2009 23:39:39.0500

The IOD provides the following initial estimate of the orbital elements.

39644.896537 0.04644448 10.108916 319.909300 174.721648 354.965378

Running the LS, the orbital elements are refined.

42150.669446 0.00018126 10.118728 320.494189 297.835103 352.760075

The residual ratios show more evenly spaced observations throughout the interval.

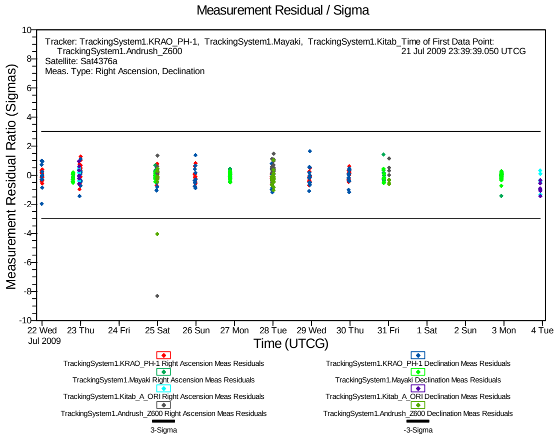

Figure 6. Filter Residual Ratios, satellite 4376.

The smoother position uncertainty is again about 6 km.

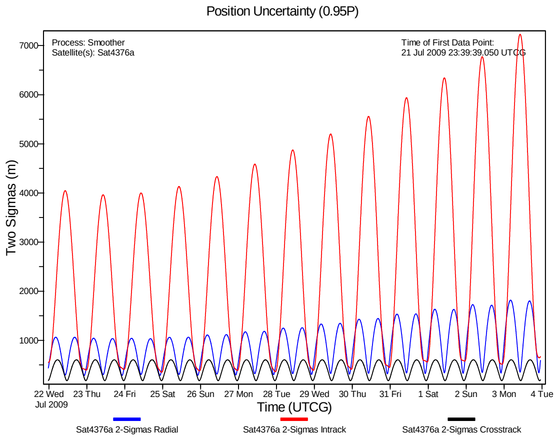

Figure 7. Smoother Position Uncertainty, satellite 4376.

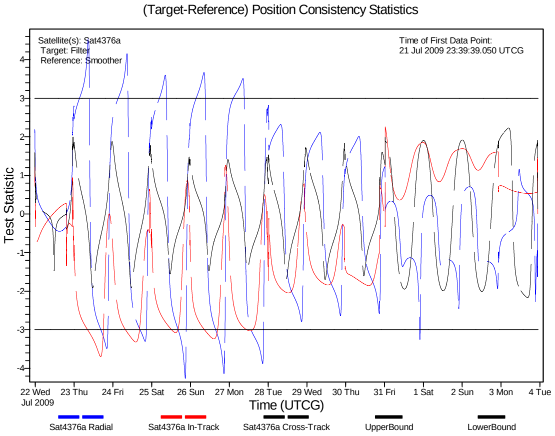

Figure 8. Filter Smoother Position Consistency Test, satellite 4376.

The FSC looks reasonable, although some additional work could be done to remove or reduce the couple of exceptions noted in the test.

From these few test, we conclude that the IOD when averaged (number of observations taken sequentially or in permutation) can get close, but the solution time may far from the desired epoch. The IOD seemed to work better taking obs separated in time (a few minutes) and then forming an initial estimate from there.

A Least Squares process was almost always needed right after the IOD because the solutions are just not close enough. Sometimes, a smaller fit span worked, but usually the results were better with 4-5 days of data (50-100 observations with no thinning). This worked well with the filter-smoother.

The best processing occurred with about 10-15 observations per day, and on subsequent days for 3-4 days.

When running the filter smoother, it's desirable to end after a set of obs, otherwise the FSC test can exhibit unusual behavior, and obscure the results from the portion where the data is being processed.

Overall, the results show the satellite is being tracked to an accuracy of a few km.

5. Transtage (NORAD 33509) TESTING

A GEO debris object (33509), this one had about 5084 observations from data from 19 Sep 2006 22:11:01.090 UTCG to 25 Apr 2010 15:50:15.170 UTCG. As in the previous case, note the long time period observations were available. Also note the date of the first TLE in Feb 2009 – an important consideration when determining the full extent of the catalog.

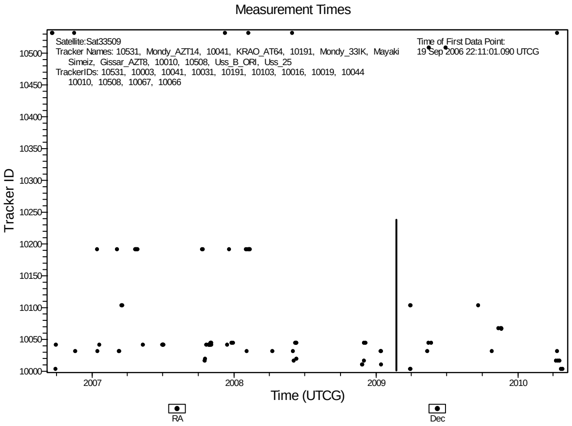

Figure 9. Measurement Times, satellite 33509.

We examine multiple test dates as before.

5.1 Data from 11 Oct 2007 00:40:22.01000

The IOD taken from observations spread through the first pass provides the following orbital elements.

41397.147065 0.00553558 10.145965 332.263304 241.509575 26.297631

The LS option refines this to the following.

41680.170365 0.00401170 10.130341 332.272258 308.934156 25.984515

The residual ratios look reasonable,

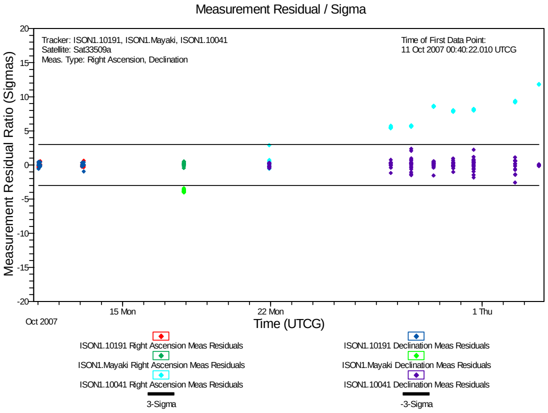

Figure 10. Filter Residual Ratios, satellite 33509.

And the position uncertainty and FSC look as we saw before.

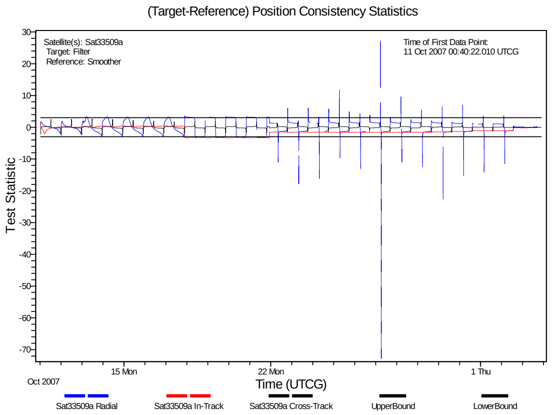

Figure 11. Filter Smoother Position Consistency Test, satellite 33509.

However, one sensor had incorrect information. Re-running, we find almost the same position uncertainty, but significantly better FSC (compare with Fig. 11).

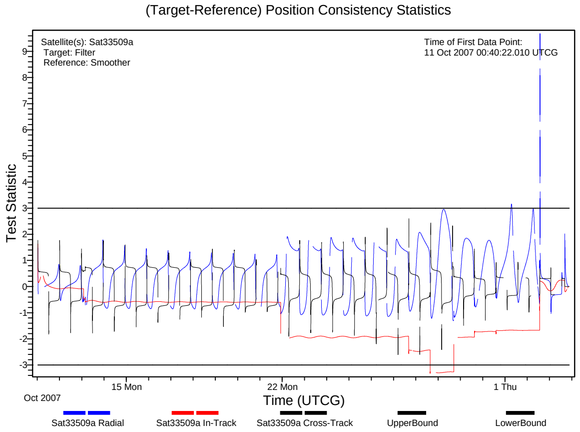

Figure 12. Filter Smoother Position Consistency Test, satellite 33509.

5.1 Data from 25 Nov 2008 18:20:30.67999

The IOD gives the initial orbital elements.

43500.368062 0.20864731 9.471354 322.488278 352.914587 82.671129

Running the LS for 2 days, we find refined orbital elements.

41677.347848 0.00566450 9.697247 330.150307 328.094569 75.127335

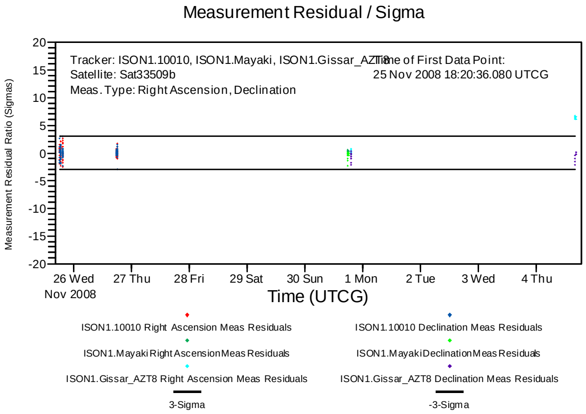

Figure 13. Filter Residual Ratios, satellite 33509.

Good results, but notice the long intervals without data. Because we have some noise or dispersion in the final observations, we will expect some variation in the FSC.

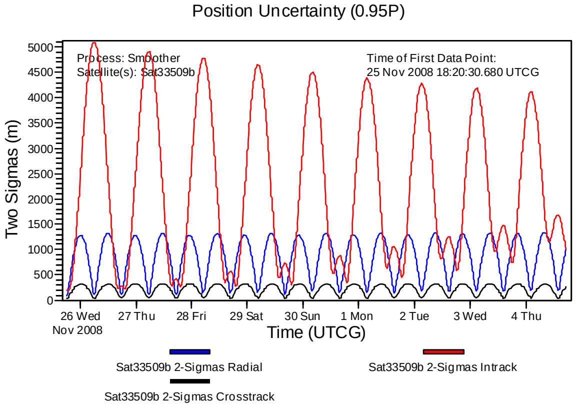

Figure 14. Smoother Position Uncertainty, satellite 33509.

The FSC shows the expected influence of the end observations on the interval.

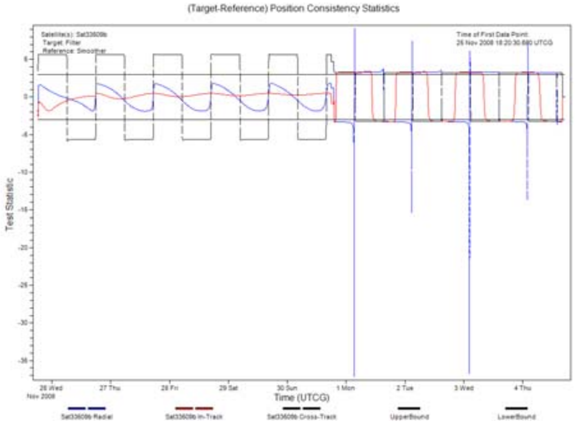

Figure 15. Filter Smoother Position Consistency Test, satellite 33509.

Although not acceptable for operations, as an initial estimate it serves our purposes.

6. CONCLUSIONS

We have examined the option of processing additional observations for satellites under consideration in conjunction screening to improve the quality of the existing TLE information. In particular, we examined geosynchronous satellites and the addition of data from ISON. Several strategies for processing routine observations were examined to determine what options could best support a given requirement for OD accuracy. All the resulting data was more accurate than the existing TLE information, but additional study is needed to completely quantify the necessary observations to support conjunction operations. The improved accuracy ultimately reduces the number of unnecessary avoidance maneuvers by better modelling the predicted conjunction. We discussed many of the data and formatting issues required to effectively add optical measurements into an OD process.

7. REFERENCES

1. Kelso, T. S., and S. Alfano. 2005. “Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES).” Paper AAS 05-124 presented at the AAS/AIAA Space Flight Mechanics Conference. Copper Mountain, CO.
2. Vallado, David A., T.S. Kelso, Vladimir Agapov, and Igor Molotov. 2009. Orbit Determination Issues and Results to incorporate Optical Measurements in Conjunction Operations. Paper presented at the 5th European Conference on Space Debris. Darmstadt, Germany.
3. Vallado, David A. 2007 *Fundamentals of Astrodynamics and Applications*. Third edition. Springer/Microcosm, Hawthorne, CA.
4. Molotov I., Agapov V. et al. 2008. International scientific optical network for space debris research, Advances in Space Research, Volume 41, Issue 7, 1022-1028.
5. Kelso, T. S.. 2007. Validation of SGP4 and IS-GPS-200D Against GPS Precision Ephemerides, Paper AAS 07-127 presented at the AAS/AIAA Space Flight Mechanics Conference. Sedona, AZ.
6. Souchay, Jean, and Martine Feissel-Vernier. 2006. IERS Technical Note #34—The International Celestial Reference System and Frame. IERS ICRS Centre, Paris.
7. Fey, A. L. and D. Gordon, C. S. Jacobs. 2009. IERS Technical Note #35— The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry. U.S. Naval Observatory
8. Vallado, David A. and Scott S. Carter. 1997. Accurate Orbit Determination from Short-arc Dense Observational Data. Paper AAS 97-704 presented at the AAS/AIAA Astrodynamics Specialist Conference. Sun Valley, ID.
9. Fonte, Daniel J. Jr. 1993. Implementing a 50 x 50 Gravity Field Model in an Orbit Determination System. M.S. Thesis, CSDL-T-1169.
10. Phillips Laboratory. 1995. 1995 *Success Stories*. Kirtland Air Force Base, NM: Phillips Laboratory History Office.
11. Agapov, Vladimir, and Moriba Jah. 2010. Personal discussions.
12. Vallado, David A. 2010. Evaluating Gooding Angles-only Orbit Determination of Space Based Space Surveillance measurements. Paper USR 10-S4.5 presented at the US/Russian Workshop. Maui, HI.