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VERIFYING OBSERVATIONAL DATA FOR REAL-WORLD SPACE SITUATIONAL AWARENESS

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In practice, Space Situational Awareness (SSA) requires precise knowledge of all objects in orbit. A complete, robust and accurate SSA system is necessary for accurate conjunction analysis (CA) and Radio Frequency Interference (RFI) determination. The Space Data Association fuses data from multiple sources to support state-of-the-art CA and RFI operations. Implementation requires significant work including a detailed verification effort to monitor and ensure interoperability and compatibility. This paper summarizes the various data assembly, conversion, and OD operations to support this effort. The attention to detail required at each step is shown, including the effect that time and coordinate systems have on a computed conjunction.

INTRODUCTION

Space Situational Awareness (SSA) requires precise knowledge of all objects in orbit. It is a basic requirement for conjunction analysis (CA), radio frequency interference (RFI) calculations, etc. I define SSA as the process by which an organization maintains a catalog of all objects in space, to some level of accuracy at epoch and at future times, and in a timely fashion. Several relevant attributes are discussed in Vallado (2007: 831-834): complete and robust, timely and efficient, standardized and maintainable, accurate, and importantly, trusted.

We build on the basic SSA principles to establish the conjunction and RFI analysis operations required to support the Space Data Association (SDA). The fundamental data currency for these analyses is the precise ephemerides and associated parameters and filters used for the operations. Because each owner operator system is unique, relying on different data sources, orbit determination schemes, ground sensors, etc., periodic evaluations are performed with the raw observational data from each owner operator to ensure the data is being used in the most efficient and accurate manner. This includes close and private communication with each owner operator should any anomalies be observed. The operation is a professional look at improving the overall system and further enhancing the safety of each owner operator's satellites.

This paper describes the processes for the routine OD evaluations including the activities required to assemble and process the data. The paper also explores the degree to which small changes can affect the overall results of the conjunction calculations.

SDA OPERATIONS AND BACKGROUND

Since May 2004, the Center for Space Standards and Innovation (CSSI) has been providing daily reports of likely conjunctions for the upcoming week for all objects in Earth orbit using the full catalog of

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unclassified NORAD TLEs available to the public. The program is called Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES, Kelso and Alfano 2005). 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. In GEO (actually ±250 km from GEO altitude), over 25% of the total known population is comprised of operational satellites, where precise orbital data is available 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 centuries. Owner ephemerides include 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 SDA is a non-profit organization that brings together satellite operators who value controlled, reliable and efficient data-sharing critical to the safety and integrity of the space environment and the RF spectrum. The SDA was founded in 2009 by Inmarsat, Intelsat, and SES—three of the leading global satellite communications companies. By collecting and analyzing its authoritative radio frequency, close approach, ephemeris and points-of-contact data, the SDA's Space Data Center performs Space Situational Awareness and threat mitigation analyses with previously unachievable accuracy and expedience. By mid 2011, the SDA membership spans both GEO and LEO regimes, and now provides CA processing for more than 60% of all operational satellites in GEO.

The SDA receives information from a variety of satellite owner operators. The ephemeris data sometimes adheres to International Standards (e.g. OPM, OEM from ISO/DIS 26900: 2011), but often includes a variety of unique formats and interpretations. Before using any of the data in the operational system, we must ensure the terminology, coordinate systems, and formats are understood, and that conversion to common standard reference frames is possible. This ensures consistency throughout the processing for conjunctions. In a simplistic view, we could import the data and treat it as being similar to an existing pre-defined system, or even require a specific format for operators to use. This is impractical, and invites the possibility for errors to creep into the process.

Just as satellite sensors must routinely re-calibrate against known satellite orbits, we must periodically recalibrate our processing against independent sources of data. One possible route is to compare the owner ephemerides processed through their own OD system, and take the same observations and process through an independent OD program. We use Analytical Graphics Inc. Orbit Determination Toolkit (ODTK) for this aspect of the processing. Because most of the owner systems employ batch Least Squares techniques, there is an added benefit of being able to examine the response of the processing of different mathematical techniques that ODTK offers.

GATHERING DATA

The first step is to gather the observations, sensor locations, maneuver information and formats. Scripts are used extensively to ease this work. However, initial development of the scripts can be time consuming, especially where standard practice (ANSI/AIAA Standard, 2010, ISO/DIS 2011, etc) are not followed, or are modified. For the larger satellite constellations, this step is crucial. Collecting the data can be time consuming as most systems are not designed to transmit the data. Security safeguards are used in the transmission.

Database considerations need to be considered when doing this on a routine basis. Essentially, you're creating a ground system to maintain and perform the OD function for the satellites.

A difficulty encountered that wasn't envisioned at first was trying to align the time intervals of the various observations and ephemerides. When the data arrive irregularly, you're receiving information in a snapshot form, rather than a continuous data stream. An important part of the process is the ability to compare results and note any trends from previous tests. However, ensuring that the ephemerides cover the same interval is important, but processing the "same" observations in both cases is very difficult as most operational systems are embedded, have a database for the holding and processing of observations, and determination of exactly which observations were used in a particular run can be obscured. Some systems have this information readily available.

However, we must also consider the type of OD processing because equal sets of observations will produce different answers when processed through different OD systems. This is due primarily to the fact that each OD system accounts for the uncertainty in the observations with different parameters, techniques, and fidelity.

PROCESS

The verification process relies on several steps. This is an iterative process, and although much of it is automated, there are numerous manual intervention points to ensure quality control.

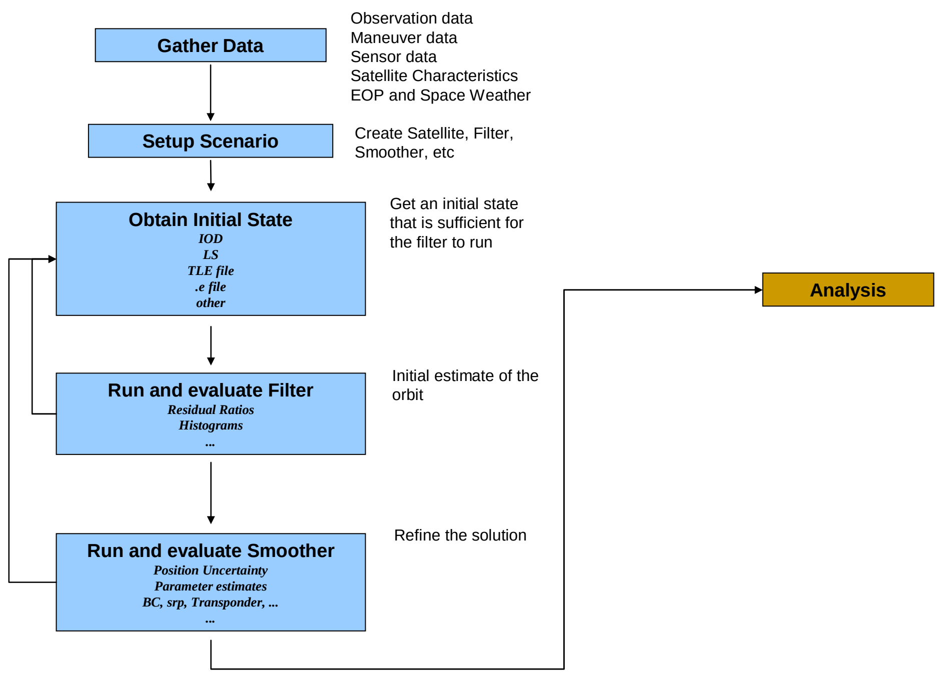

Figure 1. Overall Process. There are several steps in accomplishing the verification operation.

Several items are checked while the data is collected. For instance, each sensor location is verified through Google Earth to ensure the proper location is being used. Recognizing that Google Earth does not have precise geo-registration (Vallado and Griesbach, 2011), this is not exact. However, larger differences can be noted as shown below. When discrepancies are identified, the sensor locations are rechecked with the operator to determine if there is true location error or not. The largest variation seen so far has been about 1 km, and some sensors have been actually overloaded with other sensor numbers/locations.

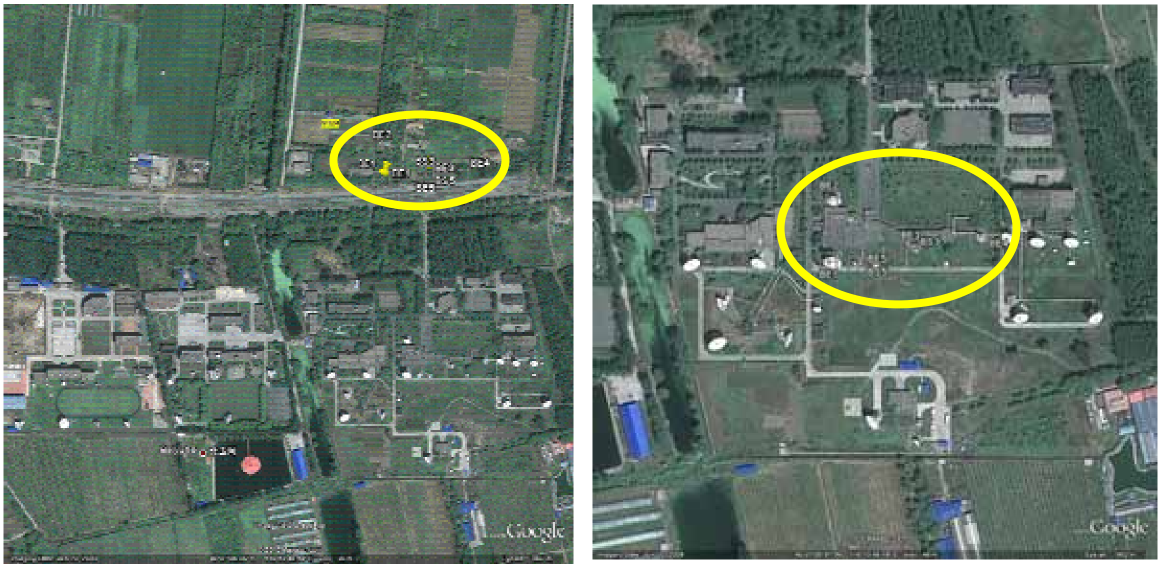

Figure 2. Sensor Location Checks. Before (left) and after (right) locations are shown. The difference in the coordinates is about 0.5 km. While mainly affecting the bias, correcting the sensor location serves to tighten up the overall processing.

Once the data is collected, the actual process is straightforward, and similar to other OD programs. The iterative process is not particularly well defined though, and each owner operator exhibits certain peculiarities. Once determined, these become part of the next evaluation.

ORBIT DETERMINATION EVALUATIONS

The most common OD process at the owner operators is generally Least Squares based, while ODTK is Kalman Filter (KF) based. The satellite physical parameters transfer between each. However, not all the solution parameters can be transferred directly. In fact, the sensor bias is really the only parameter that transfers reasonably well between programs. Once all the parameters are set, the iterative process to evaluate the filter-smoother results begins. Trying to precisely align OD programs is often significant additional work for little payoff. This is especially true as most if not all OD systems do not account for attitude in the determination of solar radiation pressure (SRP), so c_{srp} will certainly move around.

Sensor Parameter Modeling

The sensors are modeled depending on the type of mathematical technique used in the orbit determination process. For Batch Least Squares (BLS) system, the traditional bias and noise parameters enable the user to model the performance of the sensor as it gathers observations. BLS systems also use consider parameters to introduce additional uncertainty into the solution, but not as estimated parameters in the state space. KF systems also use the traditional bias and noise parameters, but can employ additional techniques to model short and long period effects in the dynamic behavior of the observations.

Proper modeling of the sensor observations is crucial to forming the correct weighting matrix. Generally, a simple bias and standard deviation is used to model the uncertainty in the observations. In addition, there are time-varying behaviors that can be modeled (Fig. 3).

There are numerous approaches to modeling dynamic variations in the sensor biases. ODTK models these as a stochastic process using a Gauss-Markov or Vasicek model. The Gauss-Markov model uses a bias sigma and half-life to solve for a dynamic correction to a constant bias. In the absence of observations, the correction decays exponentially to zero. The Vasicek model is similar with a short term correction that behaves like the Gauss-Markov model. However, it has an additional long-term correction that does not decay and allows the model to capture long-term trends in the bias.

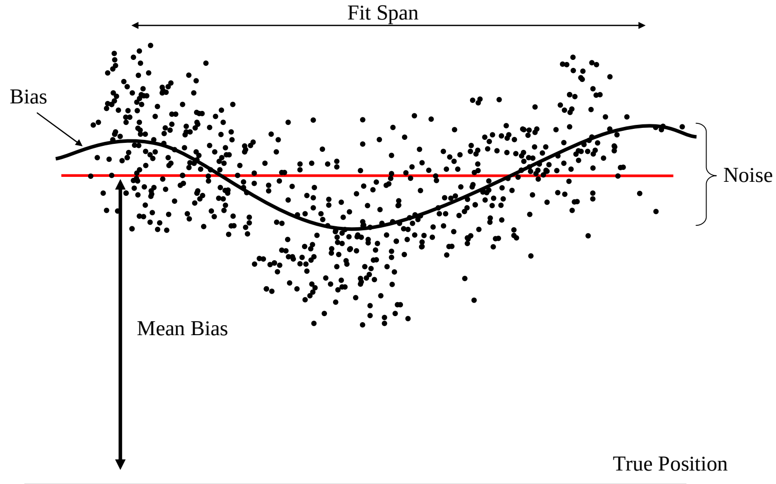

Figure 3. Depiction of Bias Parameters for Sensor Measurements (LS). The mean bias is a constant offset from the true position – the average of a dynamically changing bias over the fit span. The noise represents the average variation about the mean bias.

A KF has a similar depiction, but because the observations are processed individually, the values will be different. Notice that the bias correction changes continually as observations are processed. In Fig. 3, the mean bias estimate is the average over the entire fit span whereas in Fig. 4 it's the value the filter has estimated up to each observation time. If the initial bias is zero, then the average of the bias corrections will be an estimate of the constant bias. I've found that a single iteration to find this value works quite well in most cases.

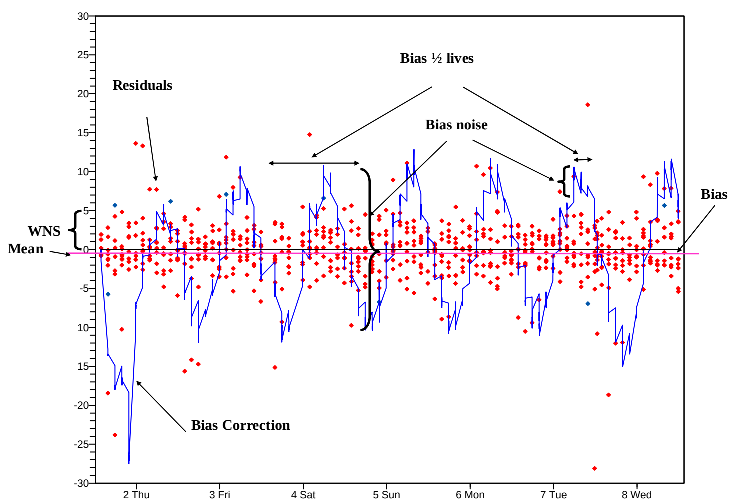

Figure 4. Depiction of Bias Parameters for Sensor Measurements (KF). The bias is the average of the individual bias corrections from the filter, assuming an initial zero bias. In this case, it is very close to zero. The noise (also called white noise sigma, WNS) represents the average residual variation about the mean. The bias parameters consider the behavior of the mean and noise over some interval of time.

Setting the Statistical Parameters

The bias and standard deviation are inherent characteristics of each sensor (Hough, 2011). A complete stochastic bias representation in ODTK is given by,

$$a = a_C + a_{GM} \tag{2}$$

where a_C is a user-specified static ***bias*** (a constant offset between a predicted value and an observed value) which is not estimated, and where a_{GM} is an estimated time-varying Gauss-Markov offset. Computing the expectation, $E(X(t_{k+1})X(t_k))$, reveals that σ^2_w is the steady state variance of a_{GM} (in the absence of measurements). For a_{GM}, the user must specify the ***bias sigma*** (σ_w) and the so-called ***bias half-life*** ($\tau_{½}$ for a_{GM}). A ***white noise sigma*** is also required to describe the random measurement noise.

For GEO orbits, we use a bias sigma slightly larger than the bias, and a half-life of about 1 day.

Observability

Observability is generally tested by examining the rank of the information matrix ($\boldsymbol{H}^T\boldsymbol{H} > 0$). For a KF, you can examine the sigma (from the diagonal elements in the covariance matrix) of the parameters you estimate and if they are reduced as the filter processes observations, the parameter is observable. Consider a single sensor ranging of GEO with little longitudinal separation between the satellite and sensor. Because the range observations tend to be very accurate (sometimes being averaged making their variation and resulting covariance even smaller), the residuals will be good. However, with little to no relative motion between the satellite and sensor, along-track and cross-track directions will be poorly observed and the satellite position uncertainty will reflect the larger uncertainty.

Force Models

Setting the force models is generally an easy process – gravity, third body, solar radiation pressure. The forces are generally well understood, but sometimes individual systems use variations. For instance, solar radiation pressure is extremely dependant on the precise exposed cross sectional area to the Sun, yet few programs accommodate this feature. The usual variation is seen a a variation in the solar radiation pressure coefficient, but it can also affect the position uncertainty. Another variation is the gravity field. Modern gravity fields have little real difference when working in the GEO region and with accuracies in the 100-1000 m range. However, older fields used coefficients which produce very different results. Consider the case shown in Fig. 5 in which the GEM-6 gravity field was used. The difference is about 1.5 km.

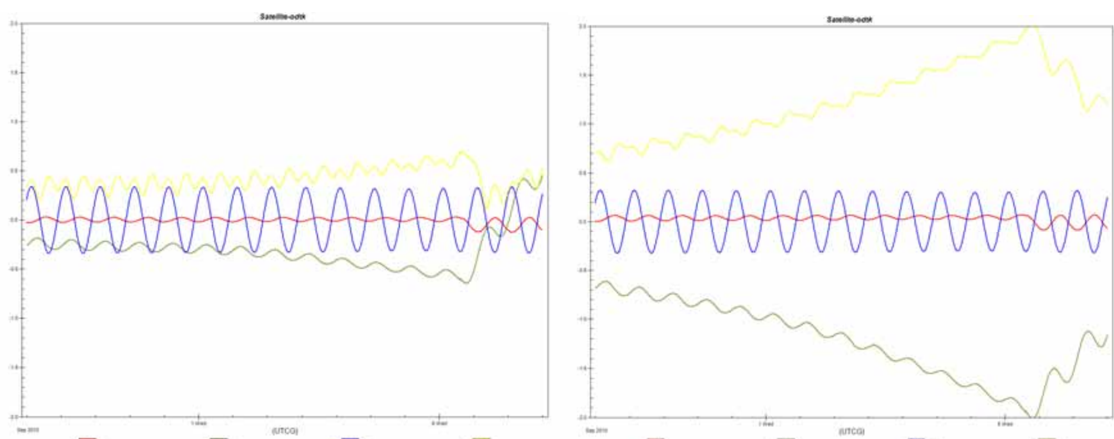

Figure 5. Gravity Models. Processing was accomplished using GEM-6 (left) and EGM-96 (right) gravity fields. Comparisons were made to an ephemeris using GEM-6. Note the discrepancy in the results, about 1.5 km.

What the OD Should Look Like

Three primary reports are useful – residual ratios, position uncertainty, and position consistency. The residual ratios are simply the residuals, divided by the standard deviations. This effectively normalizes the results and permits different types of observations to be viewed on a single graph (for instance, range, azimuth and elevation).

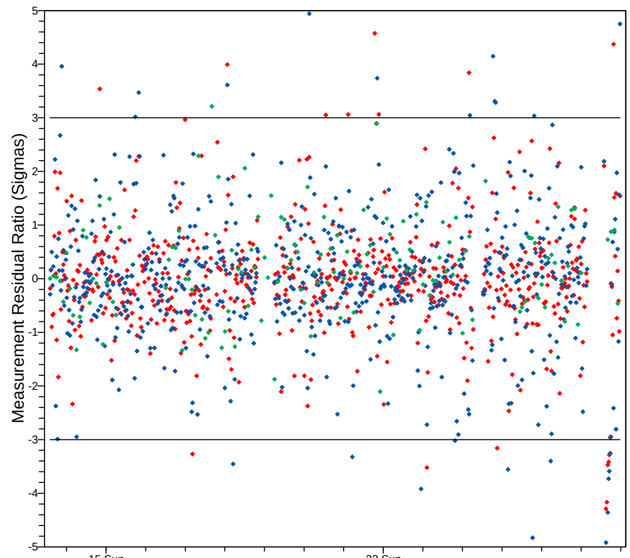

Figure 6. Residual Ratios. The residuals are divided by the standard deviation. This normalizes the results and permits different observational data types to be drawn on the same plot.

If the residuals ratios are too tightly packed, you may want to decrease the sensor white noise sigma some (for example 5 m to 3 m) and this will "expand" the residual ratios.

The position uncertainty is the uncertainty in the estimate as the filter process through the observations, and as the smoother processes the observations in reverse order. The smoother should be less than the filter uncertainty because the observations have been processed twice in the smoother.

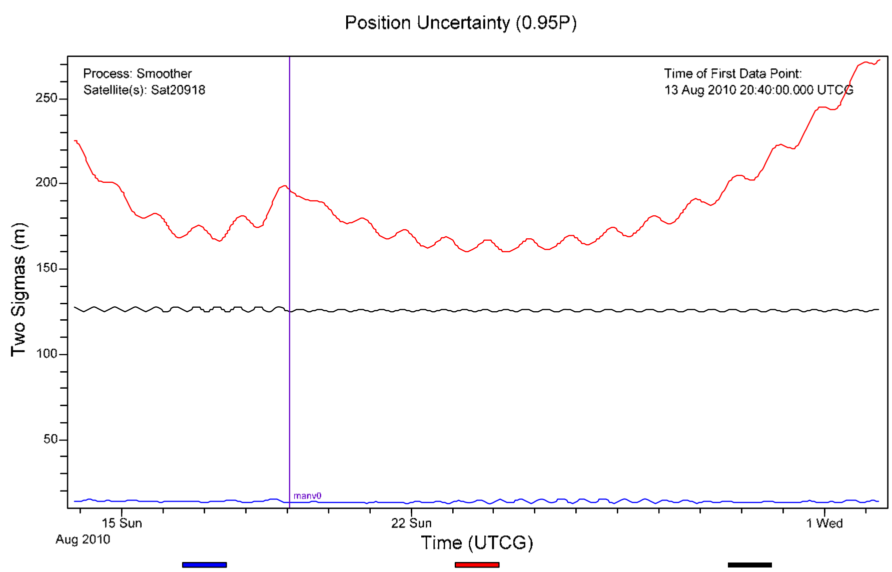

Figure 7. Smoother Position Uncertainty. The smoother should show a slight bathtub like shape, with larger uncertainties at the ends of the observational data that is processed. Maneuvers also insert additional uncertainty.

ODTK uses a filter-smoother consistency (FSC) test that is useful for general model validation. It's based on a proof that the difference between the filtered state (X_f) and smoother state (X_s) is normally distributed in n dimensions (assuming n is the size of the state-difference vector), and the uncertainty of the state-difference vector are equal to the filter covariance subtracted from the smoother covariance. Plotting this difference vector over time creates a population that should be normally distributed. If the result is abnormal, this is interpreted as incorrect settings in the filter-smoother model. ODTK provides a graphical method of examining filter-smoother consistency of each state element. For the single-state case, the filter-smoother state differences (X) are divided by the filter-smoother variance differences ($\sigma^2_f - \sigma^2_s$).

$$consistency = \frac{X_f - X_s}{\sqrt{\sigma_f^2 - \sigma_s^2}}$$

Filter-smoother consistency is generally claimed when this metric stays within ± 3 over the data interval. This single-element test provides the user with a very powerful diagnostic tool as this test is equally applicable to simulated and real data scenarios. Typical examples of problems are an initial state outside the radius of convergence, incorrect mass/area/other satellite parameter, out-gassing and momentum dumps that are not modeled correctly. Sometimes the cause of the mis-modeling is unrelated to a specific force model or parameter, at which time an un-modeled acceleration can be introduced for solution.

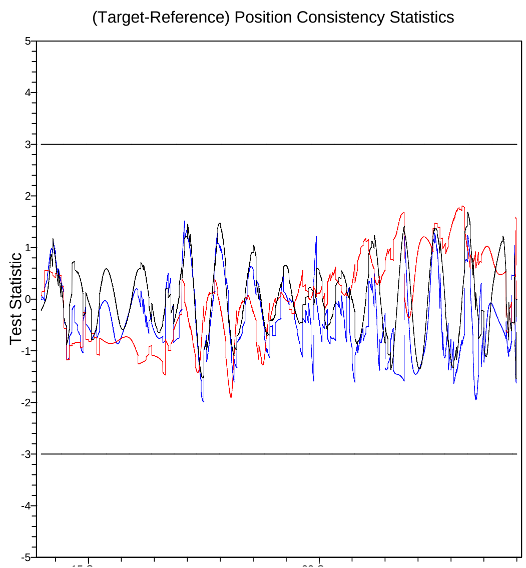

Figure 8. Position Consistency Test. The difference of the filter and smoother are compared statistically to generate a consistency test. Results should fall within the +-3 limits.

Much of the operation is automated, including the initial scenario setup, maneuver input, initial states, observations files, etc. Scripts handle the initial setup and produce PowerPoint (PPT) files of summary results. This aids quick discernment as to how the initial processing went. Many satellites process correctly through this initial setup operation. Others require additional work to adjust (usually) the sensor parameters and statistics.

To process individual satellites that may show some error form the initial setup run, the following figure is used to assess the results and determine a course of action. Fig 8 is not exhaustive, but representative of items seen or noticed in the various OD evaluations performed.

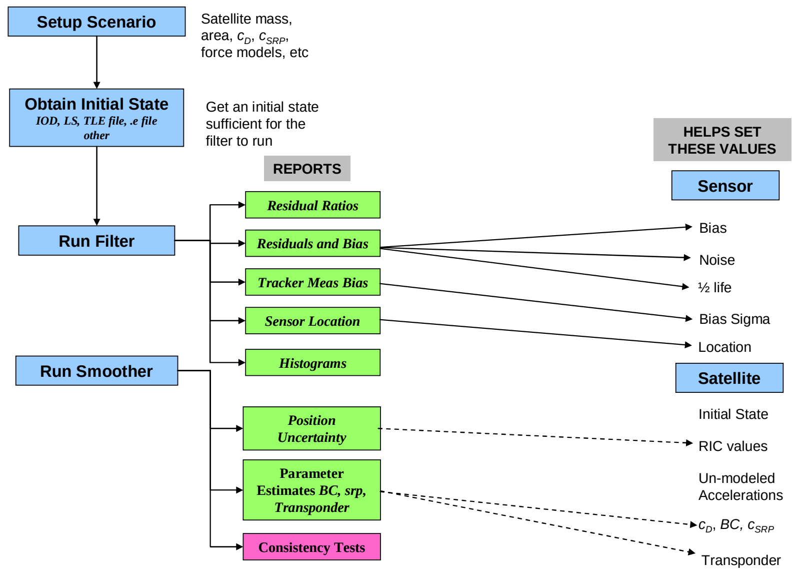

Figure 9. Decision Tree for OD Processing. This simplistic tree shows various options and reports that are useful in adjusting the OD evaluations. The consistency tests are useful for determining how good the OD setup is.

Iterating the OD Results

A very difficult part of the verification process is actually iterating and getting the OD properly setup and running so that subsequent evaluations can be assessed. Fig 1. shows the overall process. I'll elaborate on the steps here.

Use the satellite defaults (mass, area, maneuvers, etc) – the owner values are very precise. Set the force models with as much rigor as possible and get the satellite parameters inserted as close as possible. Be sure to also set the RIC covariance values. The RIC values establish the confidence in the initial state. These values also influence how much data is initially edited. The velocity has a large effect on the results (*R*-component mainly). If your initial guess is from the following sources, some sample RIC values are as follows. I show separate values for LEO and GEO just for the TLE case, but in fact, each case is orbit dependant.

```
TLE  LEO                 5000 / 10000 / 5000 and 0.06 / 0.04 / 0.02 m and m/s
TLE  GEO                 5000 / 100000 / 50000 and 0.06 / 0.04 / 0.02 m and m/s
Owner ephemeris          50 / 300 / 100 and 0.05 / 0.03 / 0.01 m and m/s
GPS Navsol data          (noisy) 500 / 700 / 300 and 0.3 / 0.2 / 0.2 m and m/s
GPS Navsol data          (good)  50 / 100 / 30 and 0.03 / 0.02 / 0.01 m and m/s
Herrick-Gibbs IOD        5000 / 10000 / 3000 and 0.06 / 0.04 / 0.02 m and m/s
Angles-only IOD, try     5000 / 70000 / 30000 and 0.6 / 0.4 / 0.2 m and m/s
LS stages                5000 / 10000 / 3000 and 0.06 / 0.04 / 0.02 m and m/s
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Obtaining the initial state is very important and is more difficult if there is no initial state, TLE, or other data to begin with. For the case of GEO operators though, the initial state is provided from the owner operators in various forms. This is generally sufficient to immediately begin filter operations. If the state is not accurate enough, a short batch Least Squares usually provides the added accuracy.

The filter will determine if the state is good enough for convergence. Overall, the Residual Ratio report should fall within the ±3 limit. You want the residuals to "approximately" fill the ±3 limit. You may need a better initial guess if they're way off, or if the data begins to diverge at some point (there may be an unknown maneuver as well – check to see if any data is available, otherwise you may need to re-start the filter after the maneuver, or try and recover the maneuver, a separate procedure). If the residuals are grouped in a location that is all above or below the zero line, there may be a positive/negative bias in the sensor measurement statistic values.

Check the initial filter residual ratios graph. If it's way out (i.e. throwing all the data out) try to obtain a better initial guess (IOD, LS, or Initial State tool). In some cases, it may be the sole factor in getting reasonable results. For some cases, even a .navsol or .e file initial vector will not be accurate enough (if it is very noisy) and a LS stage will be required. Be cautious of initial states that are near maneuvers as the original ephemeris construction may have additional error in the solution. The initial state will also affect the initial FS consistency, but not the later values.

Examining the orbital elements may give some insight into what is in error. The following figures depict various conditions.

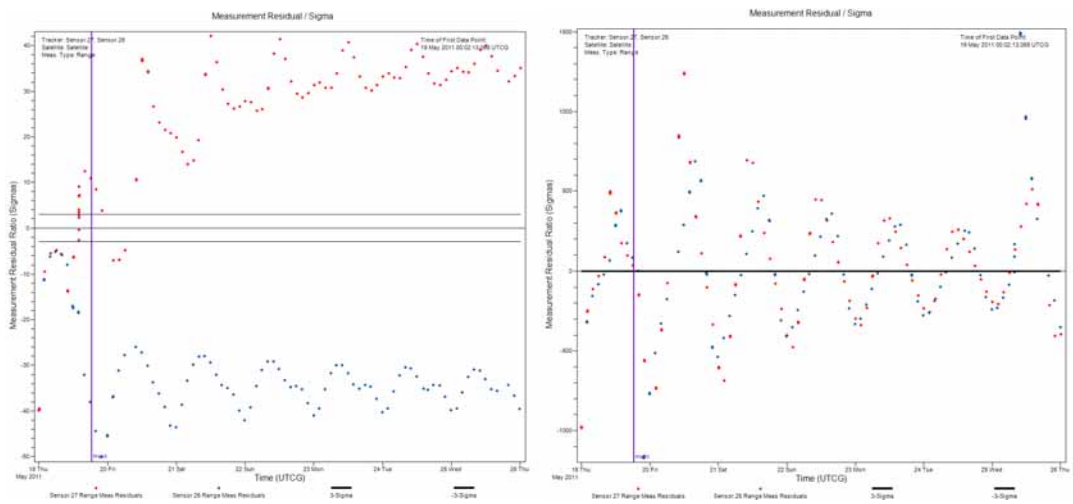

Figure 10. Residual Ratio Results from changing Initial State Estimate. Two examples are shown changing the initial state. The left hand image results when the semimajor axis is off by 4 km (GEO orbit). The right hand image results from an eccentricity that is too high by a factor of 10.

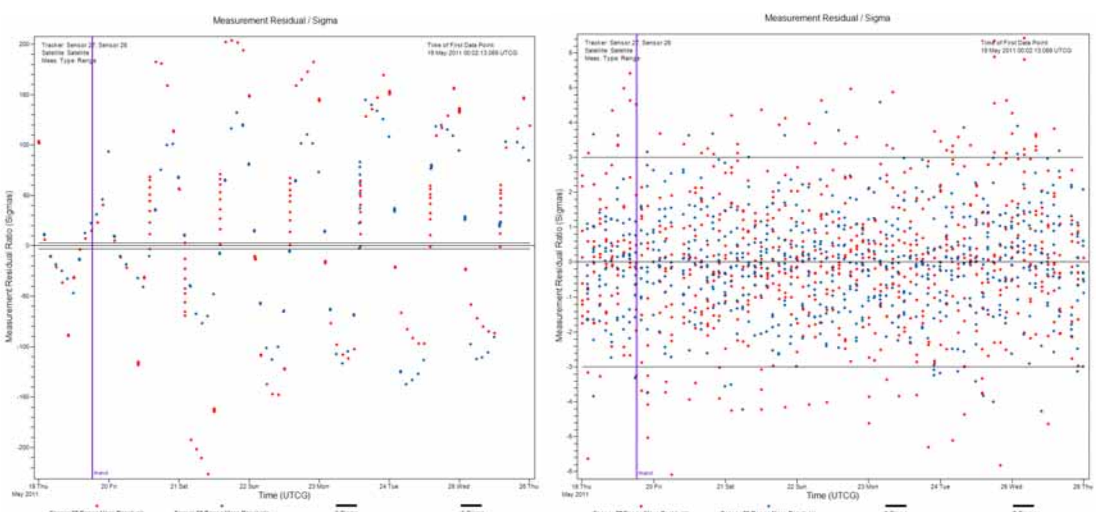

Figure 11. Residual Ratio Results from changing Initial State Estimate. Two examples are shown changing the initial state. The left hand image results when the inclination is too high by a factor of 10 (GEO orbit). The right hand image results from a correct initial estimate.

Simultaneous with obtaining the correct initial state is setting the proper RIC covariance values. The RIC values tell the filter approximately how good the initial state is. Increasing the RIC values will inflate the initial covariance, and thus it will accept more data at the start. The velocity *R* component has a very large effect early on in the filter-smoother position consistency test. If the filter is processing data, then the position uncertainty should be decreasing to a steady state value (assuming the observations are generally coming in at a constant rate). If you see the filter uncertainty increasing over time and then achieving a steady state, it indicates that your initial position covariance was too small and the observation accuracy does not support it. You can generally pick these approximate RIC values from a previous run of the smoother position and velocity uncertainties, assuming they are processing reasonably well. Fine tuning of the RIC values are not needed as the filter will adjust the RIC values as soon as measurements are processed. The idea is to set the RIC values large enough so that the first good measurements are processed and the refinement process can begin.

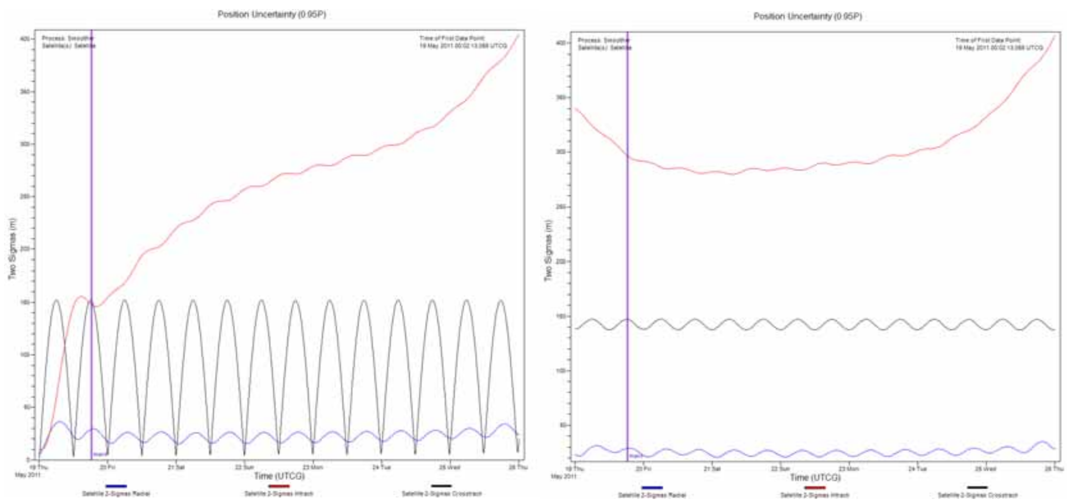

Figure 12. Setting the Correct RIC values. An example is shown changing the RIC = 3 / 5 / 1 / .05 / .03 / .01 m and m/s, to RIC = 30 / 350 / 150 / .05 / .001 / .01 m and m/s. Note that the velocity components have a very strong effect in this process. The position uncertainty is more realistic when using proper RIC values and doesn't show increasing uncertainty.

Next, you need to correct the sensor statistics (bias, WNS, bias half-life and bias sigma) using the Residual and Bias Graph. You examine each measurement type (range, azimuth, elevation for example) from each sensor site individually. Be careful not to change things too quickly, or to use insufficient observational data. You can set the bias (probably just after one run) from the residual and bias report. Note that exact values are generally not needed and you can "eyeball" the values. Routines to automatically find the precise values are useful but the values generally need to be increased "some" to avoid being too tight – it's better to be a bit conservative. For larger satellite systems, this can be quite time consuming, and this is one reason for automating various graphs and outputting the results to a PPT file for quick analysis and review.

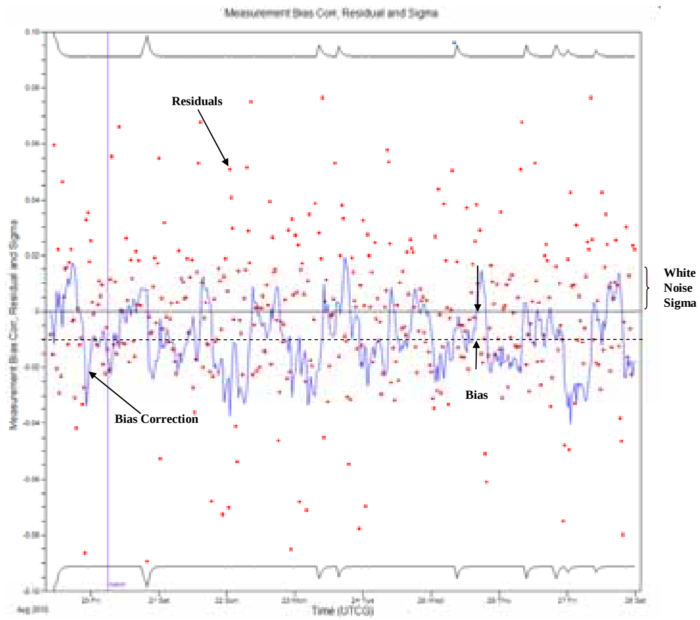

Figure 13. Using the Residual and Bias Graph. This plot shows an example of how to set the various parameters. The observation type is azimuth. The bias is the average of the individual bias corrections (assuming the initial bias is zero) – in this case, the bias is about -0.01043°. The white noise sigma is the 1σ variation of the residuals – here about 0.01°. The half life is probably sufficient at about one day as the bias doesn't seem to be moving faster than that.

We find the bias sigma using the Measurement Tracker Bias graph.

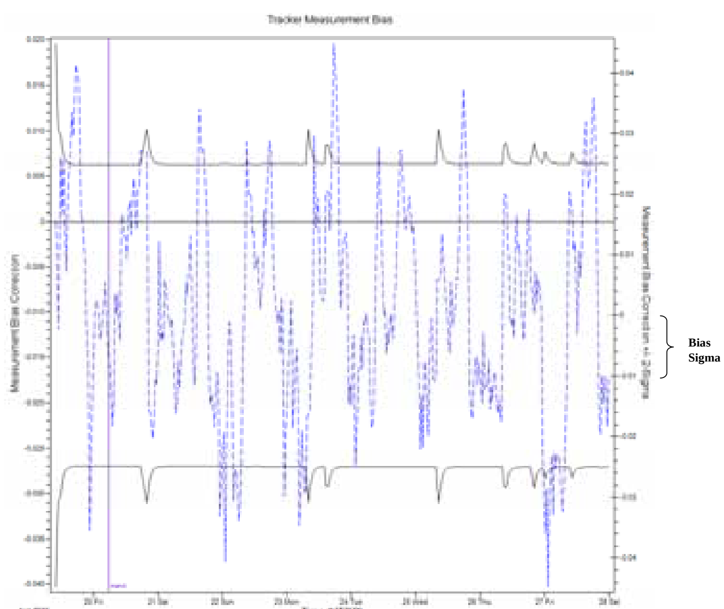

Figure 14. Using the Tracker Measurement Bias Graph. The bias sigma should be about ½ the 2-sigma steady state depiction in the graph. Don't start too small with the bias sigma because it influences the bias estimates. The bias sigma in this case is about 0.01°.

The result of these iterations is that the residual ratios should look evenly distributed, mostly within the ±3 limit. Iteration on the satellite and sensor parameters will usually achieve this relatively quickly. For the satellite parameters (c_D, c_{SRP}, BC, etc), you can usually start out setting the ½ life to 2 days and the sigma to be 0.5. Then run the filter (and assuming success) run the smoother. Then look at the smoother SRP graph and make corrections based on gross signatures (if it's trending monotonically then adjust based on the value at the end of the run). You might have to repeat this a few times. Once the estimated corrections no longer trending in one direction, you can decrease the bias sigma and see what happens. The bias sigma should usually get down to 0.1 or less, meaning that it isn't changing very much during the run.

Transponders are the most common ranging system for the owner operators. Initial values are generally the manufacturers initial value with little to no adjustment. Modeling a transponder delay can aid in the OD processing, and it is coupled with the sensor range bias estimate, but it gives additional flexibility in the OD solutions. To determine the constant bias, select a long half-life (say 3 months or more) and see if the smoother transponder estimate moves to a "constant" value. Once the transponder bias is set, it can be left alone for the remainder of the iterations. Some operators do not model a separate transponder on the satellite and instead rely on setting a ground bias.

Evaluating the OD Results

Once the OD is completed, the difficult process of interpreting the results begins. Assuming both solutions are correct, the challenge is to seek to understand the differences. This is especially true for GEO satellites where the difference between an along-track error is virtually indistinguishable from a range or transponder bias. For example, for a [common] GEO transponder ranging from a single sensor, the longitudinal separation to the satellite can induce nearly complete un-observability of satellite and sensor parameters. Even for the case of partial degradation, it is often nearly impossible to identify an error in the radial direction. Thus, different biases can be set, and you are essentially moving the satellite along-track, but getting the same OD results (residuals, uncertainty, etc).

The key to determining a bias or other nearly unobservable parameter is to have independent observations to either fuse with, or solve separately, and then compare. We perform many comparisons to ensure we use all available data resources (TLE, owner, ODTK, etc).

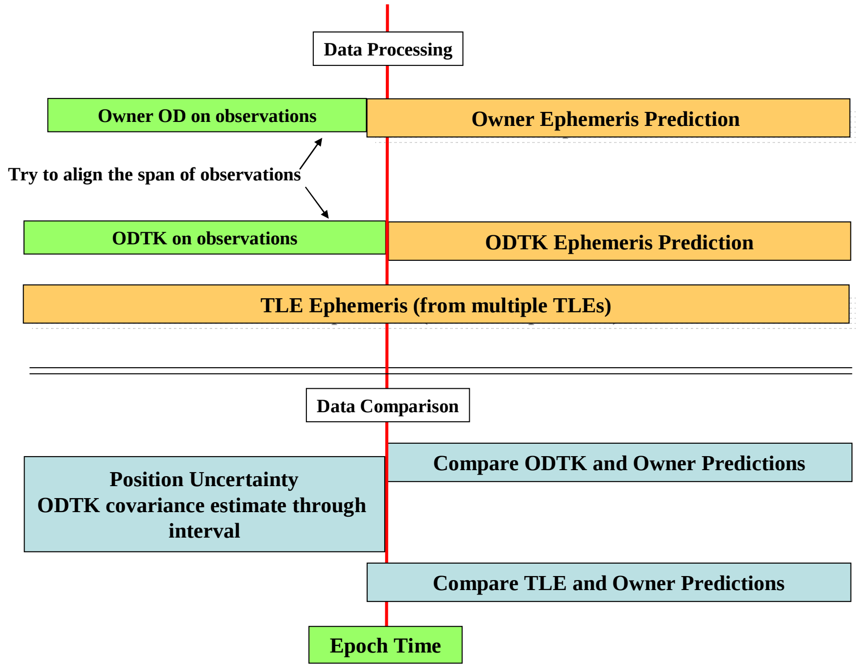

Figure 15. Various OD Evaluations. Once the observations are processed, numerous comparisons can be made to assure proper interpretation of results and processing.

While the TLE's are generally of poor quality, they can sometimes be useful to aid in the determination of gross positional errors. Consider the following results for a known operator ephemeris, and the spliced TLE's (an ephemeris formed by taking each TLE and propagating ½ way to the next TLE epoch) for the same satellite. The times from the known maneuvers are shown, and the resulting departure from the truth. The result of the Space Surveillance Network passive angles-only OD on maneuvering satellites is quite evident from the large differences (tens of kilometers).

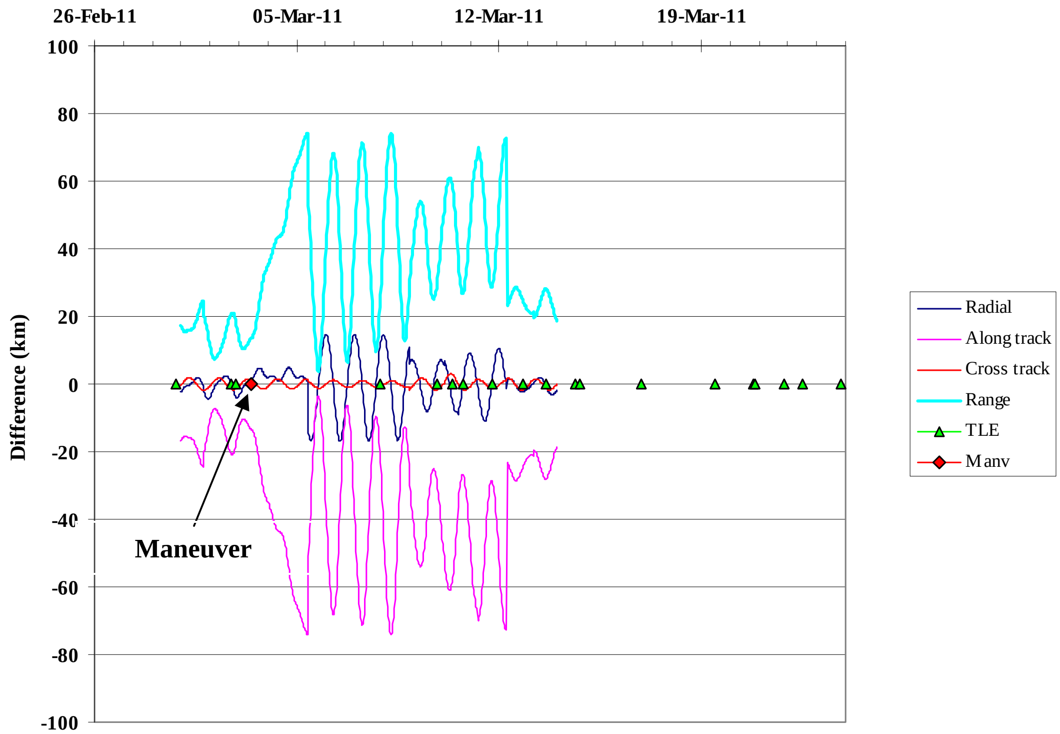

Figure 16. Ephemeris comparison to two-line element sets. This plot shows a comparison of an owner ephemeris to a spliced TLE. The times of individual TLEs are shown along with the maneuvers. Because AFSPC doesn't know when the maneuvers occur, there is generally significant error after a maneuver.

Figure 16 shows the comparisons to TLE data. Notice that before the maneuver, the average uncertainty was about 10-20 km. However, immediately after the maneuver, the TLE's stop (indicating difficulty in finding the satellite, or perhaps even losing it for a while, and errors reaching almost 80 km. Even after TLEs were being produced again, the uncertainty remained significantly higher than before the maneuver.

The periodic processing of observational data further benefits the operators as they can pose questions on anomalies or new operations they encounter. Having two organizations looking at a problem is a luxury not usually available.

ODTK gives us uncertainty estimates while processing the observations. We can compare the ephemerides of ODTK during the observation processing to owner ephemerides. However the owner ephemerides are usually for predicted times to satisfy requirements in the CA processing. Thus, the comparison isn't exactly equivalent. A better comparison is to perform the OD and generate a predicted solution and compare it with the owner predicted ephemeris. This assumes we can approximately align which observations were used for each OD process. Figure 17 shows an example of such a comparison.

Future work seeks to extend this concept and perform detailed overlap studies in which we take the existing span of data and sequentially step through solutions, and make comparisons to a reference orbit generated using the entire span of data. By comparing both the positional and covariance differences, understanding of the covariance realism are sought.

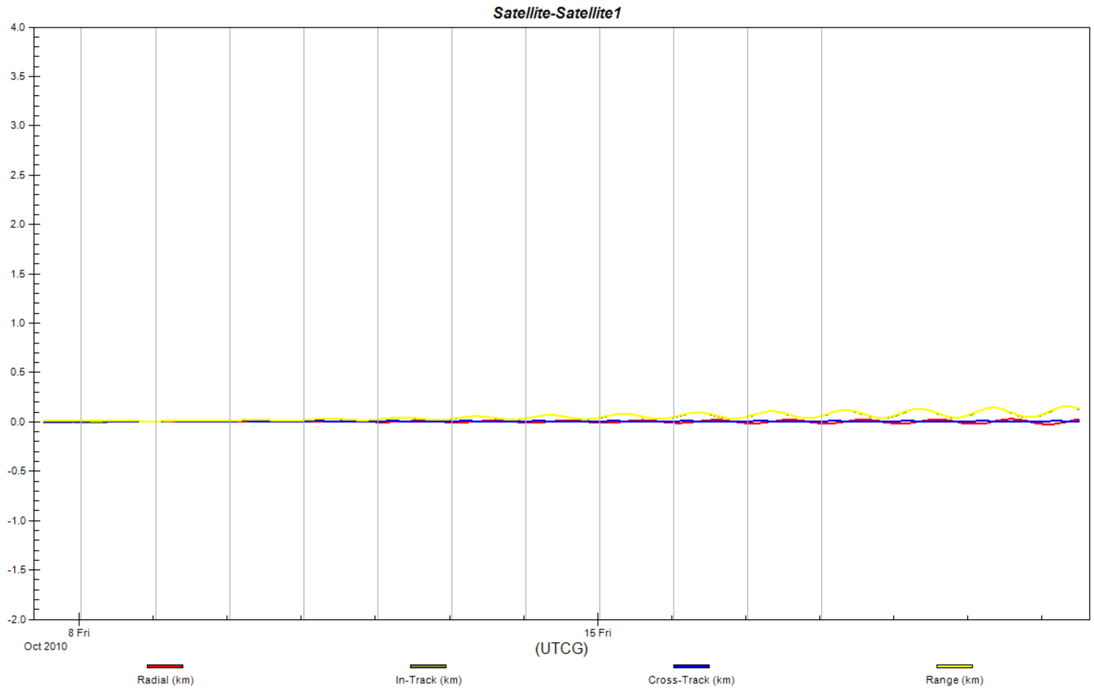

Figure 17. Ephemeris comparison to ODTK observation processing. Comparing an owner ephemeris to the ODTK result from the same data should be relatively close – in this case, about 10-20 m at the start and about 50 m at the end of the prediction interval. Ensuring the same observations are used is often the most challenging aspect of this process.

ATTENTION TO DETAIL – EOP AND COORDINATE SYSTEMS

Time, coordinate systems, and data formats play an important role in the overall process. A small change in any of these or any misunderstanding of a format can have an impact in a resulting conjunction calculation. They underlay the entire flight dynamics operations process, as shown in Fig 18. The purpose of this section is to determine how these changes affect a conjunction – tracing the effect through the various processes and how much variation in the orbital position can be expected.

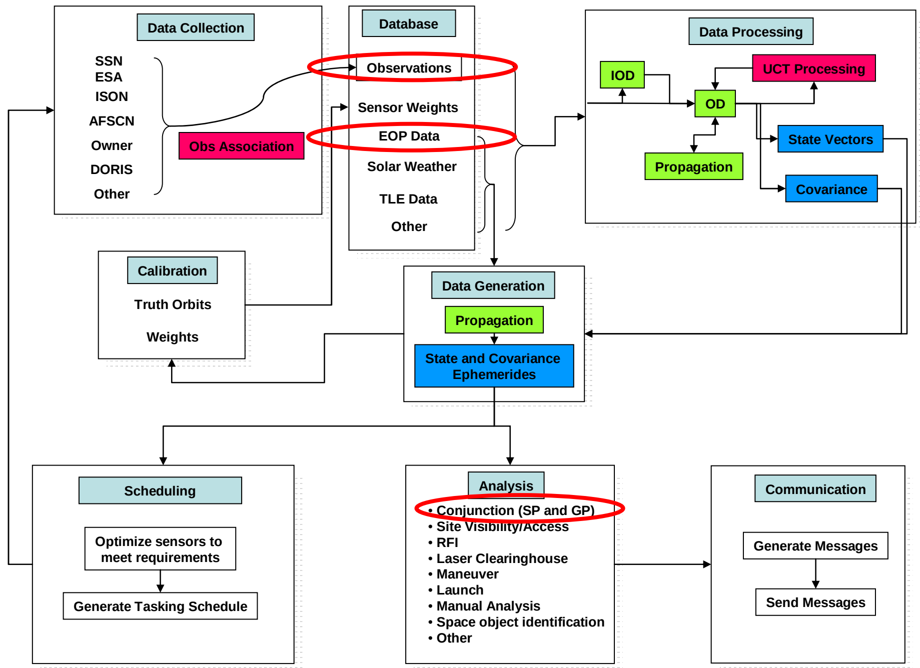

Figure 18. Space Situational Awareness – the Big Picture. Time and coordinate systems can be seemingly obscure in the overall process, but they can have a large impact in the final solutions for operations such as conjunctions or RFI.

The nomenclature for coordinate systems can be confusing. For example, a mean of date (MOD) system may actually be a FK5/IAU-76 (aka J2000) system. Understanding how a B1950 MOD system relates to the FK5 or IAU2010 implementation of MOD is important.

EOP files are routinely used, and sources like Celestrak maintain current values. However, not all systems use current EOP files, and the predicted values change continuously, although they are reasonably consistent. Bradley et al (2011) discusses the need to interpolate EOP values in the same way atmospheric drag indices are interpolated (Vallado and Finkleman, 2008).

To assess the impact of time and coordinate systems, consider an 800 km (LEO) and a 35780 km (GEO) altitude circular satellite. Several sensitivity tests were run to determine the effect of various methods employed, or envisioned in operational systems. In each case, the vectors were transformed from Earth fixed (ITRF) to Earth Inertial (GCRF) coordinates, permitting a positional difference determination at the end state.

The first set of options center mainly around the EOP values and how they are used. Much discussion has occurred with leap seconds (Finkleman, Seago and Seidelmann, 2010) it is possible that some systems may not use leap seconds, or may not update them. This would lead to errors of 1 or 2 seconds in TAI. Because this is used only as an argument in the transformation, the difference is quite small.

Next, if the TT is off by a minute, perhaps because of assumptions or EOP values simply not being used, it is again used as an argument in the transformation.

We know that the EOP files change periodically and are updated daily to include recent observational data. If old EOP files are used, the ΔUT1 value could differ by 0.01 sec. here we see additional effects because the UT1 time is affected, along with GMST. If ΔUT1 is not used, the differences become larger in each transformation. If the UTC is off by a second, a clock could be off, or a script error could be present. Since UTC affects all the parameters and arguments, the differences are very large.

Finally, it's conceivable that the time tags could be off by a second. This is very different from the previous leap second and EOP errors because the argument is no longer an input into the transformation, but rather a simple offset. The results here are significantly larger.

Table 1: EOP Sensitivity Tests: Several tests were run to examine potential errors and the effect on satellite positions from various EOP discrepancies.

Test	Possible Cause	LEO	GEO	Notes
ΔAT error of 1 sec	Old EOP file	0.0001 m	0.001 m	Only TAI affected
TT is off by a min	Not using TT	0.004 m	0.02 m	TT is an argument
ΔUT1 value differs by 0.01 sec	Truncation, old EOP	6.0 m	31.0 m	
Ignoring ΔUT1, assume -0.25 sec ΔUT1	Not using EOP	130.0 m	800.0 m	
UTC error of 1 sec	Clock off	581.0 m	3075.0 m	
Time tag is incorrect by 1 sec	Script error	7000.0 m	3000.0 m	Transmitting ephemerides

Coordinate systems present additional challenges as they incorporate the potential uncertainties in time, plus add variations to standard coordinate systems. These changes are sometimes a result of computational throughput, sometimes a result of particular simplifications made for assumed accuracy constraints, and others. I'll use the same two orbital types in these examples.

First consider the Quasi Mean-of-Date (QMOD) system variously described by Nogales et al. (2011). This system ignores polar motion (a common assumption, especially for GEO satellites), ignores the dynamical equation of the equinoxes (a small value), truncates the nutation terms (formerly quite popular for computational throughput), and sometimes assumes UT1 ~ UTC. Consider an input vector in the quasi MOD system.

QMOD r = -38835.6795140 -16447.1221180 -14.2130660 m, v = 1.198025040 -2.830905510 -0.002048130 km/s

The first step is to transfer the QMOD vector using the QMOD "approach" (no polar motion, UT1~UTC, 9 nutation terms, etc) and find an Earth fixed vector.

ECEF r = -12283.2252126 40346.5013839 -15.3541020 m, v = 0.001169433 0.001201961 -0.002001603 km/s

Next, use the full nutation, EOP, polar motion, etc transformations, from the ECEF vector. This would show the difference in the assumptions in the QMOD approach. Taking the ECEF vector and transforming to Mean of Date (MOD),

MOD r = -38835.9893295 -16446.3904817 -14.2902248 m, v = 1.197971687 -2.830928018 -0.002048123 km/s

d (rMod – QMOD) = -0.3098155 0.7316363 -0.0771588 km, magnitude = 0.7982674 km

The difference is about 798 meters. This difference represents the accumulated effect of the assumptions in the QMOD approach.

We can also investigate the general differences between the various coordinate systems. Using the same vectors as before, the difference between each coordinate system is shown below.

Table 2: Coordinate System Sensitivity Tests: Several tests were run to examine potential errors and the effect on satellite positions resulting from coordinate system terminology and differences.

Test	Change	LEO	GEO	
ICRF to IAU/FK5	System Frames	1.0 m	5.0 m	
IAU-76/FK5 to MOD	Precession	10,000.0 m	40,000.0 m	
MOD to TOD	Nutation	800.0 m	2,000.0 m	
TOD to PEF	Sidereal Time	Huge	Huge	
PEF to ITRF	Polar Motion	16.0 m	70.0 m	
QMOD	Approximation		800.0 m	

In addition to EOP and coordinate system details, the manner in which ephemerides are sent affects the accuracy of an operation. Oltrogge et al. (2011) has shown the sensitivity of accuracy and how it relates to the ephemeris interpolation method and order. Using an ephemeris that's too widely spaced, or not using a large enough interpolation order can result in errors similar to the EOP and coordinate system errors.

CONCLUSIONS

This paper has sketched the procedures and results for independent OD evaluations to support the SDA. It's all about the data. Better data in gives better results. Collaboration and trust are key. Imposing guidelines and procedures in a vacuum doesn't work. The attention to detail requires constant checks, but automation helps eliminate common mis-typings and data transcriptions.

The issue of comparison inevitably evokes right and wrong. In our case, the process is much more effective when we work together to understand differences. The best solution would be to have independent data to fuse and process separately to arrive at an optimal solution. This appears to be quite feasible once some limitations are removed.

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Dan Oltrogge provided valuable insight and reviews during the writing of this paper. Tom Johnson also provided detailed comments for the OD sections.

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