Two-line element sets – Practice and use

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TWO-LINE ELEMENT SETS – PRACTICE AND USE

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Two-line element sets have been in regular use for decades. As space centers have largely transitioned to numerical operations, the role of TLE's as an initial estimate tool seems only slightly diminished. Use in conjunction and other operations often requires a covariance, which is unavailable. The accuracy can be limited, but advancements have been proposed. We summarize existing research and discuss the capabilities, possibilities, and limitations of the TLE's for use in several applications.

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1. INTRODUCTION

The Two-Line Elements (TLEs) that result from Simplified General Perturbation 4 (SGP4) orbit determination allow rapid, modestly accurate propagation of space object motion. As the only openly available, comprehensive catalog of space objects, the U.S. TLE database supports many technical analyses. However SGP4 is based on the Brouwer theory (Brouwer 1959) with a power law density model (Lane 1965) and reflects the knowledge of the space environment in the 1960's. Additionally, the tracking data used in SGP4 orbit determination has improved in absolute accuracy, and in how the data errors are understood. Over time, there have been numerous studies of TLE limitations, methods for accuracy improvement, for generating a covariance matrix, and various other operational applications. Given the continued importance of the TLE for space activities, we summarize these topics and provide recommendations for the use of newer theories.

We begin by examining the technical processes used in SGP4 orbit determination and in the formation and distribution of the TLEs. Originally designed to accommodate computer software and hardware limitations, the TLE format is compact and admits a simple propagation technique (SGP4). Exclusion of the one kilometer tesseral m-daily terms, coupled with the irregular distribution of the tracking stations results in long observation fit intervals for many cases. Likewise, orbital maneuvers and dynamic atmosphere and solar radiation pressure effects are important error sources that are omitted in SGP4.

Advancements have been proposed to significantly improve the quality of the existing TLE. Additional terms can be inserted into the SGP4 algorithm with remarkable improvements in accuracy (Cefola and Fonte 1996). Researchers have also shown how using either TLE or numerically generated ephemerides as observations in the TLE formation can improve the quality. We find that for TLE ephemerides, the results are dependent on the satellite orbit and type.

Conjunction operations, and others, often require a covariance which is unavailable with TLEs. CNES and The Aerospace Corporation have periodically visited the issue of generating a covariance that can be used with TLE operations, and we summarize those efforts.

Several applications derive useful information from the TLE catalog. In particular, advances in atmospheric density corrections were pioneered by Yurasov et al (2005), and others. Their techniques are still valid today and have been extended by several organizations. Maneuver detection has received some interest, and we discuss the possibilities and limitations using TLE data.

All data comes from the publically available http://www.celestrak.com/ website.

2. HISTORY, BACKGROUND, and LIMITATIONS

The Simplified General Perturbations (SGP) model series began development in the 1960s (Lane 1965), and became operational in the early 1970s (Lane and Cranford, 1969). The development culminated in SGP4, and although the name is similar, the mathematical technique is very different from the original SGP technique – mainly in the treatment of atmospheric drag.

The first release of the refined SGP4 propagator source code was Spacetrack Report Number 3 (Hoots and Roehrich, 1980). That release resulted from a user compatibility survey of space surveillance operational sites and official users. The magnitude of the resulting variations spurred an effort to promote better compatibility for users. The intent was to get the operational community, as well as ordinary users, synchronized with respect to the implementation. The best vehicle for this was a technical report, including the computer source code. It was designed for the widest possible dissemination. Although most of the equations were given, the use of the source code became common practice for using Two-Line Element (TLE) sets.

In 1998, Hoots published a history of the equations, background, and technical information on SGP4. In 2004, Hoots et al. published a complete documentation of all the equations (including the deep-space portion). In 2006, Vallado et al published a comprehensive paper to update the SGP4 computer code, provide test cases, and analysis. This document reset the baseline from which studies take place, and the code is now in use at many space centers around the world. Finally, in 2008, Vallado and Crawford published a paper detailing SGP4 orbit determination code. While the code was a simplistic look at OD, it was intended to complete the process of producing a TLE from observational data.

The exact process for updating the TLEs is not well known and we piece pieces of information together for this discussion. Essentially, the observations are collected several times a day at the Joint Space Operations Center (JSPOC) operated by the

US Air Force Space Command (AFSPC). Once the observations pass through an initial association and verification pass, they are passed to the Orbit determination operation. OD is conducted on the observations, once using SGP4, and once using numerical techniques.

Two versions exist – the online version which is continuously updated so the results are available in near real time, and periodically for the release through space-track to the public.

An important consideration is that the epoch time for the TLEs is not necessarily the epoch resulting from the last observation processed in the OD. This is because the TLE is moved to the last ascending node before release for distribution.

Public release of the TLE catalog has been accomplished for many years, first through NASA, and more recently through the www.space-track.org web site. In addition, Celestrak (http://www.celestrak.com/) has maintained a website for obtaining the TLE catalog for several decades. The catalogs provided by these sources contain only objects deemed unclassified by AFSPC. Other catalogs exist, but are not as comprehensive for all orbital regimes and types.

The format for the TLE is shown in Fig. 1 with sample data. Notice that the TLE supports two theories – SGP and SGP4 through the use of mean motion rates and Bstar (respectively).

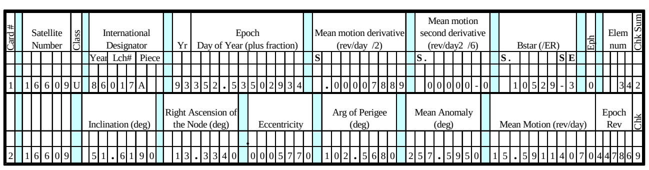


Figure 1 Two-line Element Set Format. An example TLE is shown, with descriptions and units of each field. Note that the eccentricity, mean motion second derivative, and Bstar have implied decimal points before the first numerical value. The mean motion derivative is already divided by 2, and the second derivative is already divided by 6. Shaded cells do not contain data. The signs may be blank, "+" or "–". A classification field is sometimes included after the satellite number.

The JSPOC has used several propagation theories over the years. In the beginning, SGP was the primary propagation tool, accounting for atmospheric drag by the mean motion rate and acceleration. As SGP4 developed and became more widely used, some sensor sites still maintained software requiring SGP. The presence of mean motion rate terms in the TLE is a testament to the continued instances of SGP. For all SGP4 applications, these terms are ignored.

The TLEs are created in a nearly continuous operational processing cycle by the JSPOC. As new observations arrive, they are processed into new TLEs. Periodically, about every 8 hours, a new snapshot of the system is extracted and the element sets begin the process to arrive at www.space-track.org for dissemination to the public. This operation inserts a time delay for use of the TLEs even if a user is able to immediately download and use each new TLE. The Celestrak site mirrors these timing updates with a short (minutes) delay.

In general, we will discuss the accuracy, covariance formulations, conversions, and applications of TLE's in subsequent sections.

3. ACCURACY

The accuracy of SGP4 and the precursor TLEs has been the subject of extensive analyses over the last few decades.

Hartman (1993) suggested that "confidence" in SGP4 propagation could only be guaranteed for a few days. This conclusion came from an examination of several satellites in different orbital classes. TLEs were used to determine when the propagation error was more than 25 km (compared to future TLE values).

Boyce (2004) examined a specific case of non-maneuvering Iridium satellites, for which he had precise owner ephemerides, purportedly 2-4 m. He examined the determination of the mean semimajor axis from the reference ephemerides and the TLEs. The TLE accuracy was about 50-100m. The in-track error was a few km.

Kelso (2007) performed a similar study with GPS satellites. He used the precise GPS ephemerides as a baseline, and specifically addressed consistency and abutment checks of the ephemeris information. He found that potentially significant biases exist in the TLE data, and that backwards and forwards propagation accuracies often differ for the various satellites.

Obviously, the mathematical implementation limits the overall accuracy. The formation of the TLEs (Orbit Determination) also limits the accuracy. SGP4 is designed to model the largest perturbations affecting satellites – J_2 to J_5 zonal harmonics, simplified drag and third body and solar radiation pressure. The many assumptions can severely limit the accuracy of the resulting propagation. Because many of the short periodic effects are unaccounted for, the maximum possible accuracy is limited.

The un-modeled forces result in seemingly inconsistent values in the TLEs. For example, negative BStar values don't mean that energy is being lost from the system, but rather that the un-modeled forces have aliased that parameter during the OD solution.

Time was not available to determine the effect of BLS and KF processes applied to a baseline set of observations. This would give a quantifiable indication of the magnitude of the mathematical assumptions and approximations.

The previous discussions allude to some limitations of TLEs. There are many factors that go into accuracy, including the mathematical formulation, the observation quantity and quality, etc. Figure 2 shows the relationship between force models, OD accuracy, and prediction accuracy. Note the importance of force models during the OD phase. For filter applications, force models are often reduced during the observation interval, however, data gaps necessitate additional force models during this time. In the prediction phase, we know that rigorous force models are required to properly move the state and covariance in a realistic fashion. For BLS systems, the general approach is to keep the force models the same between the OD and prediction phases.

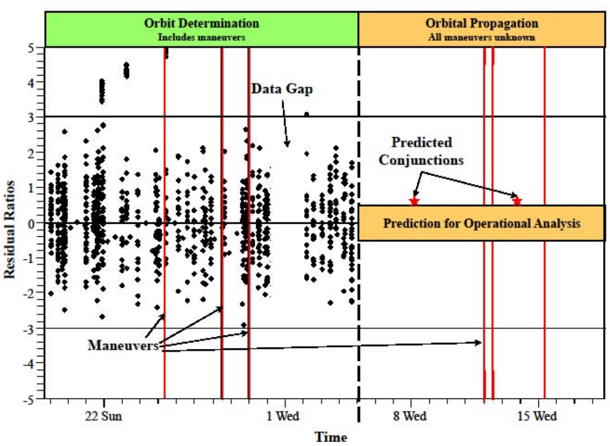


Figure 2 Notional Observations and Prediction. An example residual ratio plot (residuals divided by the standard deviation) is shown where a period of observations is processed (orbit determination). Notice the 2 day data gap during which OD force models become important. In the prediction phase, force models are important, as well as knowledge of future maneuvers. The unknown future maneuvers do not affect the first predicted conjunction, but the next maneuver will likely make the second prediction meaningless.

The presence of unknown maneuvers complicates the propagation accuracy considerably for "any" application having no knowledge of those maneuvers. Figure 2 shows a notional residual ratio plot where there are measurements for a period of weeks prior to the current time. While there are maneuvers in this time period, there are also sufficient observations to process through. A data gap is shown to illustrate real-world considerations - if it's too long, other difficulties can arise. Once the OD is complete, the prediction period may encompass additional maneuvers, however, these are completely unknown to any passive SSA system. Of course, after the first maneuver, the prediction is diminished in importance and any operational planning past this point is meaningless.

The preceding discussion has a direct influence on the creation of the TLE data. AFSPC (JSPOC) processes observations for satellites in an automated fashion. Batches of data arrive and are processed to form TLEs (and a parallel operation to produce numerical Special Perturbation (SP) vectors). There is no knowledge of maneuvers before or after the current time of OD generation. During the processing, the presence of maneuvers inflates the uncertainty of any estimate, but because the TLEs are delivered without a covariance, there is little way of knowing if there is increased uncertainty in a particular TLE from the previous estimates. Likewise, there is no way to know if future maneuvers are planned by an owner operator, but not included in the TLE (or SP) prediction.

Intelsat performed studies that found that the TLEs (and also the numerically derived SP vectors provided in Conjunction Summary Messages (CSM)) have large errors, especially for maneuvering satellites (Editorial 2012, and Warren 2012). This is not surprising given that the JSPOC has no knowledge of satellite owner maneuvers, and estimation processes will produce increased uncertainty in the residuals due to the presence of unknown maneuvers. The maneuver magnitude may be large enough to prevent successful completion of the OD process, and the satellite may become lost. Figure 2 illustrates this with notional residual ratios. The data gap is shown to highlight the irregularity of observations, and the maneuvers in the past would all contribute to increase the uncertainty. The future maneuvers are completely unknown and can adversely affect all operations as there are no observations even to process. If these maneuvers occurred 30 minutes after the OD, virtually the entire OD would be rendered useless - and that applies to SP (numerical) vectors as well.

The Space Data Association (SDA) routinely uses precise owner operator ephemerides with the public TLE catalog to make conjunction predictions.

These ephemerides provide an opportunity to examine the TLE accuracy against a known reference orbit, including maneuvers. The resulting comparisons show that the accuracy of the TLE can vary considerably (Vallado, 2012). Satellites that maneuver often typically show the greatest variation, but the magnitude of the maneuver is also a large differentiator. The following figures show some real-world data comparisons of TLE and owner data. Each plot shows the timing placement of each TLE and each Maneuver. The owner ephemeris is differenced to the spliced TLE ephemeris. The differences are plotted in radial, in-track and cross-track directions. The range is simply the magnitude of the difference. The in-track dominates the errors in all cases.

Because the TLE tracking has no knowledge of maneuvers and the Space Surveillance Network (SSN) tracking data is not usually dense, recovery of the unknown maneuvers can be challenging. In some cases for small maneuvers, the OD fit span can be large enough to process over the maneuvers. In other cases, the OD is unsuccessful. Radial, in-track and Cross-track values are shown, along with the range, or the magnitude of the vector from the satellite to the going sensor.

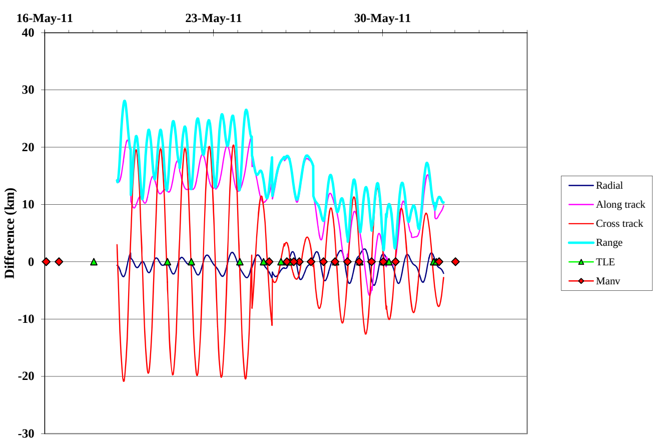


Figure 3 **Reasonable TLE Accuracy.** The nominal accuracy for this satellite is about average. The numerous maneuvers were all very small.

Maneuvers can insert considerable uncertainty as shown in the following figure. Note that the scales are different in each figure.

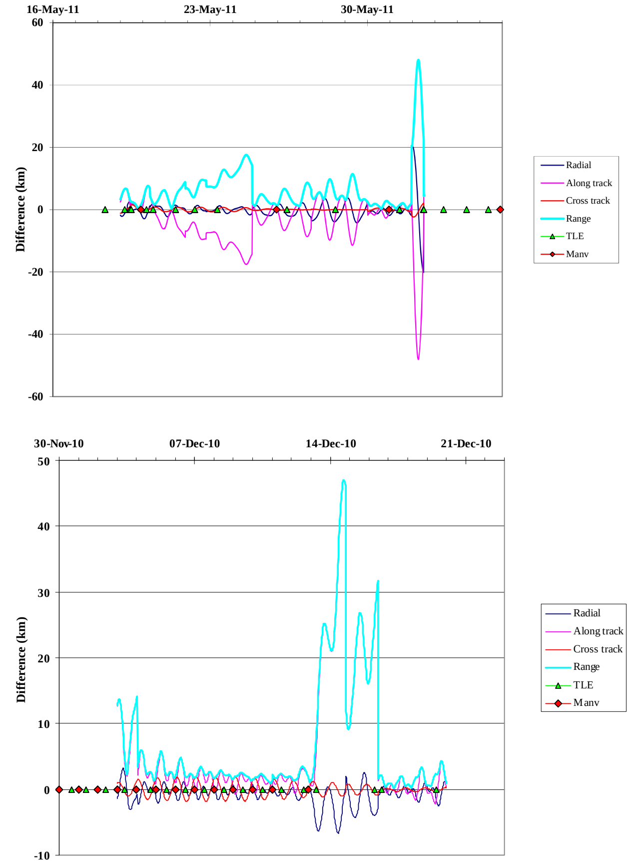


Figure 4 **TLE Accuracy in the Presence of Maneuvers.** Maneuvers can cause difficulties with the TLE accuracy. The top plot has a few maneuvers, but when one is missed, the accuracy gets much worse. In the bottom plot, a few maneuvers are missed, and then recovered.

In some cases, the maneuvers are large enough that the satellite becomes lost. It's important to realize that if the satellite is lost in the formation of a TLE, any numerical processing (SP) of the same satellite and the correlated observations would also be lost, and incorrectly assigned.

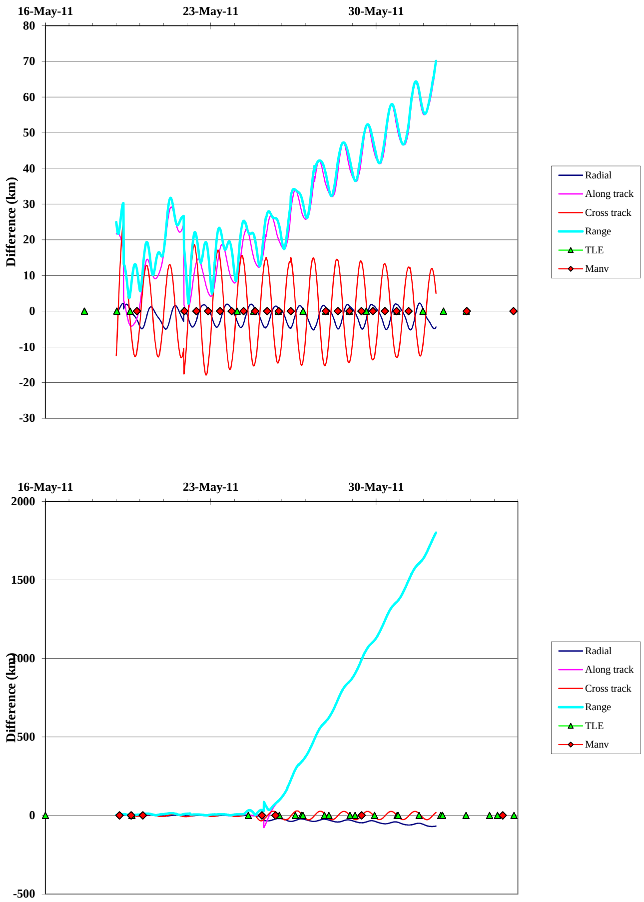


Figure 5 TLE Accuracy in the Presence of Maneuvers. The top plot shows the cumulative effect of many small maneuvers being missed. The bottom plot shows a satellite that is lost after a maneuver.

4. CONVERSION to TLEs from EPHEMERIDES

Studies are sometimes conducted where a numerical ephemeris is converted into a TLE. While the loss of precision could be questioned, the use is sometimes warranted where accuracy is not as great a concern, or some other limitation is in the system. Vallado (2007:705-706) describes 2 common approaches for accomplishing this task – the single point conversion, and the precise conversion of elements. The latter approach uses an orbit determination technique, processing some span of an ephemeris while the former accomplishes a conversion at a single point in time. Each technique yields varying accuracies, and introduces different levels of error into the resulting TLE’s. We saw this in the previous section…

We examined the process of converting a numerically generated ephemeris into a TLE for LEO and GEO satellites, taking numerically propagated ephemerides (from sample orbits, not actual data) and using the trajectory sampling (TSamp) and single point (SPoint) conversions in STK to form a TLE from each, and then comparing to the original numerical baseline (RIC components). The TSamp approach was generally better, but not always as much as might be expected. Note that the GEO results are much closer than the LEO, and in some cases the SPoint conversion was actually better for a short period of time in prediction.

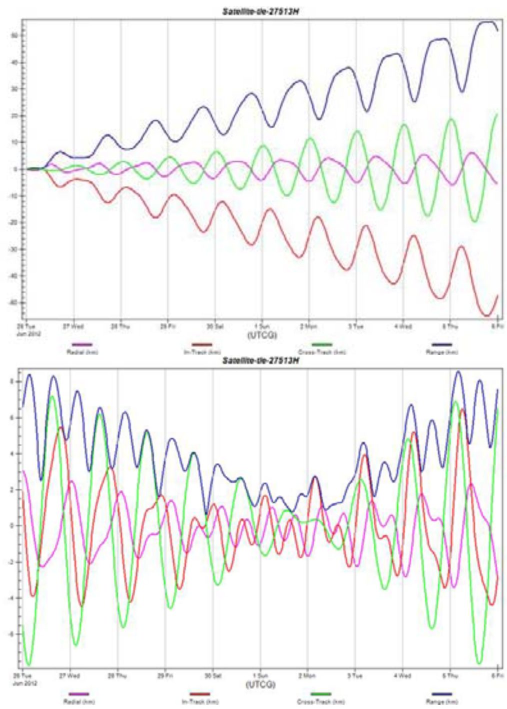


Figure 6 TLE accuracy from Ephemeris to TLE Conversion. Results for a GEO (Intelsat 906) are shown when TLEs were created through SPoint and TSamp techniques (respectively left and right). The SPoint technique produces a TLE at the epoch time, here about Jun 26, 2012. The TSamp technique processes about a week of data, with a TLE resulting about Jul 1, 2012. Note that the scales are not the same. Note that the scales are not the same.

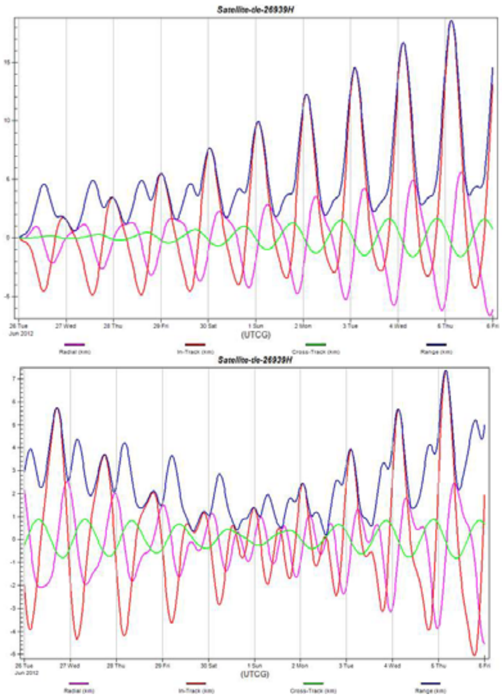


Figure 7 TLE accuracy from Ephemeris to TLE Conversion. Results for a GEO (SL2 R/B) are shown when TLEs were created through SPoint and TSamp techniques (respectively left and right). Note that the scales are not the same.

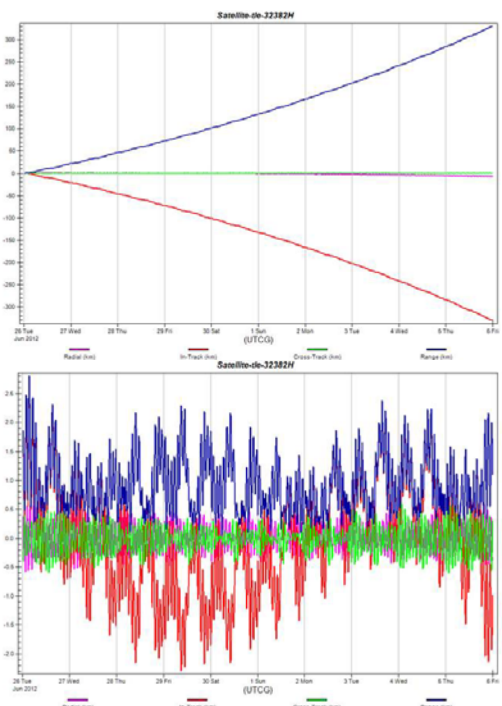


Figure 8 TLE accuracy from Ephemeris to TLE Conversion. Results for a LEO (Radarsat 2) are shown when TLEs were created through SPoint and TSamp techniques (respectively left and right). Note that the scales are not the same.

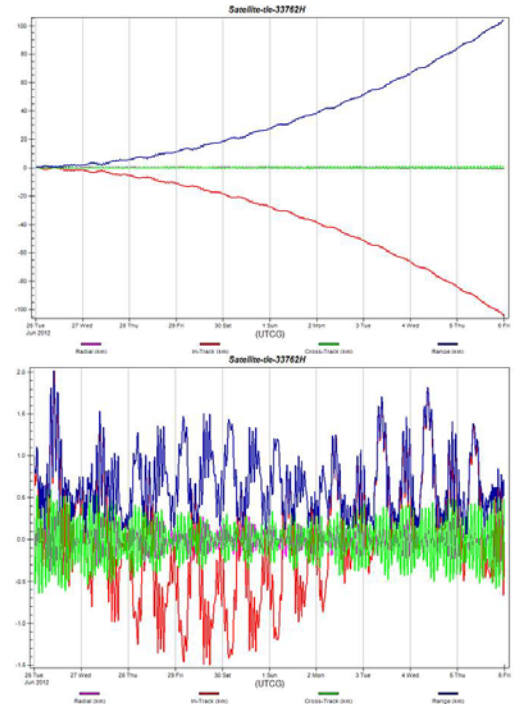


Figure 9 TLE accuracy from Ephemeris to TLE Conversion. Results for a LEO (Cosmos 2251 Debris) are shown when TLEs were created through SPoint and TSamp techniques (respectively left and right). Note that the scales are not the same.

5. COVARIANCE

With the current interest in evaluating orbital conjunctions, the availability of an accurate covariance is receiving extensive analysis and investigation. The TLEs do not come with a covariance, and although their widespread use and availability makes them obvious choices for initial screening, use for operations is diminished due to the lack of covariance (and also the lack of accuracy of the state vector!).

Herriges (1988) studied the operational implementation and mathematical theory of SGP4 and its architecture in the Space Defense Operation Center (SPADOC). The report infers that the original design of the TLE processing included a covariance in equinoctial elements, but at the time, there was no operational requirement for distributing this information. Current Conjunction Summary Messages using numerically generated state vectors include a covariance in a Cartesian representation. Conversion techniques exist to transform covariances between equinoctial and Cartesian representations (Vallado 2003).

Importantly though, Herriges discusses that the internal processing solves for mean motion rate, and then converts to BStar, and he gives equations for the calculation of the mean motion rate

$$\frac{\dot{n}}{2} = \frac{3}{2} n C_2 B^* \tag{1}$$

And the variance of the mean motion rate.

$$Var_{\frac{\dot{n}}{2}} = \left(\frac{3}{2} n C_2 \right)^2 Var_{B^*} \tag{2}$$

If this practice is still in operation today, it makes sense that the covariance is not distributed because the internal solution is incompatible with the external TLE parameters. That is, the mean motion rate covariance is not used in the SGP4 algorithm.

The best option is to perform the orbit determination on the observations using SGP4 and simply extract the covariance from the normal equations, with whatever solve-for parameter is designed in the system. Vallado and Crawford (2008) provided computer code to do this although the observation processing had an error. The processing of ephemerides did work.

Because observations are generally unavailable, other approaches have been used. The first tries to assemble the covariance at a point in time from previous TLE values. The assembled covariance is then propagated using traditional techniques to a future time. A second uses several approaches to determine the time varying covariance values. The usual method is to propagate TLEs to a common time, or a series of times, and differencing the results. The covariance is then formed by the distribution of points at the time (s).

For all approaches using TLE information, it's important to remember that the data has already been processed, and some of the information content of the observations has been lost in the OD processing. At best, you can try to determine the statistical distribution of the TLEs when processing TLE spliced ephemerides as the observations. Although not the actual uncertainty from the observations, it gives an acceptable look at the error. If high quality reference orbits exist, better determination made be made, but it still depends on the frequency of the TLE values, and the accuracy of those evaluations.

Also, processing the TLEs as observations assumes they're unbiased (something that Kelso (2007) disagreed with), but it also assumes a reasonably consistent tracking schedule. This may not be true, especially given the intricacies of the JSPOC tasker algorithm (Wilson 2004). Based on operational requirements at the time, SSN sensors may be tasked to observe another higher priority target during the period of interest. Thus your satellite may have significantly less tacking (and therefore TLEs) than usual. If a maneuver occurs in this time, it only worsens the effect!

ESA (Flohrer et al. 2008 and 2009), CNES (Delavault 2007, and Delavault et al 2008) and the Aerospace Corporation (Peterson et al 2001), and several others have all used TLE values as observations. The OD of the resulting ephemerides have shown some positional improvement, but not in all satellites all the time. The benefit from all these approaches is that an improved state estimate and covariance are obtained in the same operation.

When performing an OD on TLE ephemerides, or using TLE single epoch points as observations, consideration should be made concerning the use similar force models as in TLE generation (SGP4 force models of J_2, simplistic drag, third body and solar radiation pressure). It may be better to use complete force models such as EGM-08 70 x 70 gravity, NRLMSISE00 atmospheric drag, etc.

6. TLE IMPROVEMENTS

Many improvements to the TLEs have been proposed over the years. Topics include improving the mathematical theory, obtaining better accuracy of the TLEs, and developing a covariance that approximates the true accuracy of the state representation.

Several studies including the recent National Research Council (NRC 2012) have confirmed that the observational density and quality used to derive the TLE catalog are insufficient if the goal is to achieve the highest precision. The resulting accuracy is designed for routine operations, and therefore adequate for that purpose. However, modern operations are requiring significantly more precise positional information.

The mathematical theory could be extended to include additional effects, and this could improve the accuracy. Cefola and Fonte (1996) showed that adding tesseral m-daily terms to the Position Partials and Time (PPT3) propagation algorithm, could significantly enhance the accuracy of the technique. They noted that additional improvements could be made by including secular and long periodic terms due to the zonal harmonics that are presently unmodeled (J_6 and above), as well as the tesseral linear combination short periodic terms.

The preceding methods are sometimes difficult to implement. As a result, the most common approach to improve the TLE accuracy is by performing an OD of the vectors at each time of a TLE, TLE parameters, or ephemerides derived from the TLEs. Numerous studies have been performed with variations of this approach. Factors include the length of ephemerides, the number of TLEs, etc. We'll introduce some of the larger studies and approaches.

7. OD PROCESSING of TLE EPHEMERIDES

An obvious technique to improve the accuracy of the TLE is simply to process more observations. This effect can be achieved using numerically derived ephemerides as observations (Cappellucci 2005). He found that indeed the TLEs could be improved during the time of the OD processing, and the results were often better outside the interval of OD processing. Many of the results showed performance comparable with numerical techniques. The number of points around the orbit seemed to give approximately equal results except for elliptical orbits where about 60 points per orbit seemed to perform quite well. The orbital class made a difference, with the higher altitude satellites performing worse than the LEOs. Finally, he found that the fit span (batch least squares OD processing) needed to be longer than 12 hours. The similarity of results for longer fit spans is likely because the time need only be long enough for the parameters to be solved by the OD process.

Muldoon et al. (2009) and Levit and Marshall (2011) explored using TLEs themselves. The original technique used a polynomial/trigonometric evaluation of the TLE elements and achieved reasonable results, but mainly on calibration satellites. The later studies shifted towards processing the TLEs as observations.

Perhaps the most extensive investigation of this approach is by Flohrer et al (2008, 2009). They discuss a program to perform OD on simulated observations derived from TLE states, and the formation of a covariance for a majority of the space catalog. The processing was limited to 1-day arcs of data simulation and included a detailed look at orbital classes, and different snapshots of the catalog population. Initial comparisons were made to the Envisat satellite for reference and baseline purposes. They found that the accuracies of the TLEs were relatively constant over the last 18-20 years by their approach. Elliptical orbits performed much worse. From their summary, they found the following. Remember that the results were derived from 1-day arcs.

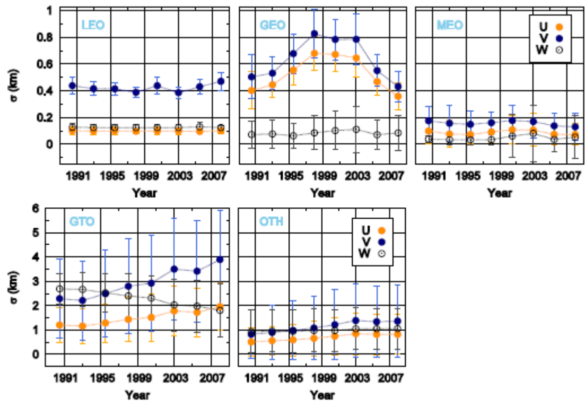


Figure 10 Summary Error chart from Flohrer et al (2009). Their summary chart included results for LEO, MEO, GTO, HEO, and GEO orbital classes. The results were found by performing OD on simulated measurements (state vectors) derived from the TLE's. The standard deviation of the error is shown versus the time in years.

Several practical issues arise when processing the TLEs as observations. When using TLEs as observations, the question arises for how to generate the ephemerides that are ultimately used in the formation of the new TLE. Because the TLE epoch is moved to the last ascending node, the epoch of each TLE will only be close to the actual last observation in the original TLE formation. As a TLE is predicted, the error grows rapidly due to un-modeled forces, approximations, and unknown maneuvers. Thus, simply propagating from one epoch to the next may not be the best approach. A related problem arises when splicing the TLEs at the midpoint between epoch values. The TLE "should" be most accurate before the epoch time as it is in the fit span, and thus has observations potentially surrounding the epoch time. The best approach would be to propagate *backwards* from the epoch to the previous TLE epoch. For a day or two, he results of Kelso (2007) seem to show this phenomena. Figure 7 shows a notional situation.

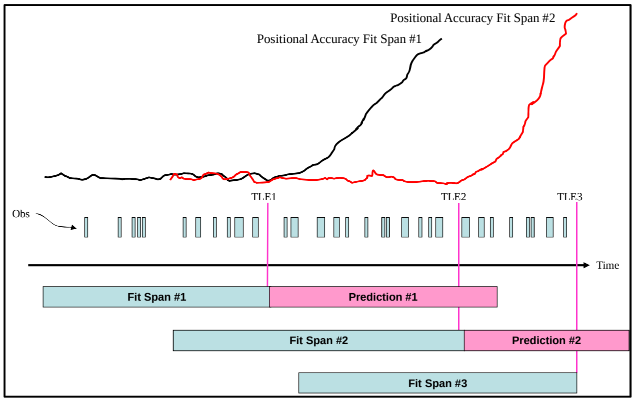


Figure 11 Notional TLE Accuracy. Several notional fit spans and resulting TLEs are shown. The TLEs may not be at the end of the fit span due to the practice of backing the epoch to the time of the last ascending node. Notional positional accuracy is shown. During the fit span, the accuracy should be the best. During prediction, the accuracy increases, sometimes quickly.

We sought to understand how these results would be affected by additional data (longer arcs). We conducted independent tests of this approach and summarize some results here. There are several things to note:

- How the OD is done is important. One setup generally doesn't fit all satellites. Bias, dynamic variables, etc are all usually tweaked in the overall OD process.
- How many TLEs are available would seem important. In essence, the information is gathered into one time (the TLE epoch) is like having 5 TLE's. This is somewhat analogous to having just 5 observations. However, being able to propagate the TLE mitigates this concern to some extent, but the mathematical model certainly limits long propagations from adding new and impendent information to the process.
- How much time the OD process uses (and therefore how many observation data points) is important. More data is generally better, and time is required to achieve convergence in all estimation techniques.
- The type of estimation technique is used (BLS vs KF) has an effect on how quick a solution is settled on, and how quick the parameters may be adequately estimated.
- When assembling the ephemeris information, the length, spacing, and location of any midpoints used for splicing is important. A maneuver may influence a previous TLE midpoint well before the actual maneuver occurred. Although the SGP4 TLE processing may not "notice" a maneuver for several days, the splicing technique can move this artifact back in time to a time before it actually occurred.

The following satellites were considered. Notice the range in values for the number of available TLEs for each satellite during the study period.

Table 1 Satellites Studied. Satellite parameters shown for each test case, along with the number of TLEs for each.

SSC #	Name	# of TLEs	a (km)	e	i	alt ap (km)	alt per (km)
33331	GEOEYE 1	21	7056.94	0.00090	98.11	685.17	672.42
7616	DELTA 1 R/B	9	7256.29	0.01867	97.71	1013.63	742.68
33105	JASON 2	9	7715.86	0.00079	66.04	1343.82	1331.64
16908	EGS (AJISAI)	10	7865.85	0.00113	50.01	1496.59	1478.84
20026	COSMOS 2024 (ETALON 2)	9	25499.82	0.00155	64.41	19161.31	19082.06
28163	MOLNIYA 1-93	10	26558.05	0.69177	64.77	38551.98	1807.84
37753	NAVSTAR 66 (USA 232)	9	26560.14	0.00061	55.01	20198.08	20165.93
18103	COSMOS 1851	9	26571.66	0.56497	69.17	35205.68	5181.36
27513	INTELSAT 906	4	42164.39	0.00028	0.01	35798.23	35774.27
4250	SKYNET 1	5	42164.84	0.00246	10.08	35890.50	35682.91

12545 is also interesting as it appears there is a maneuver in the OD portion (or a mistag!), but it recovers.

Several tests were conducted during the OD processing of observations to understand the validity of the setup. (See Vallado 2011) for additional information on these tests. The residual ratios are the residual divided by the standard deviation. This normalizes the results so you can examine all observation types on one plot. The results should be zero-mean, and within ±3. The position uncertainty is the covariance during the observation processing. The value is preferred to be low, and have a small standard deviation. Finally, the Filter Smoother Consistency test (FSC) determines the relation of the filter and smoother outputs. It is very sensitive to the sensor, satellite, and observation setup. The average should be about 0.0 and the standard deviation should be small, generally less than ±3.

Using a single standard OD setting, we found the following results. Red shaded cells indicate poor results. These results are easily changed with different noise settings, but the intent was to use a single setting for the initial tests.

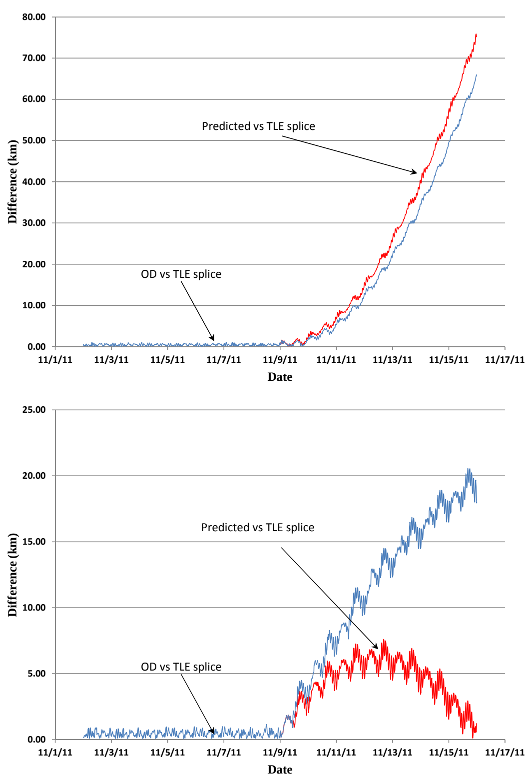
Table 2 Satellites OD Evaluations. OD results are shown for each satellite. The residual ratios are the residual divided by the standard deviations. The position uncertainty is the covariance and the Filter smoother Consistency tests

SSC #	Name	Res Ratio largest	Res Ratio avg	Res Ratio sd	Pos Unc mag (m)	Pos Unc sd mag (m)	FSC Avg	FSC SD
33331	GEOEYE 1	1.110	-0.010	0.314	268.29	10.34	0.230	2.658
7616	DELTA 1 R/B	1.240	-0.010	0.323	270.59	10.70	0.200	3.348
33105	JASON 2	0.920	0.000	0.216	273.89	10.70	0.060	1.861
16908	EGS (AJISAI)	0.680	-0.010	0.175	274.79	10.69	0.010	1.566
20026	(ETALON 2)	0.170	0.000	0.056	326.90	14.08	0.100	0.526
28163	MOLNIYA 1-93	11.280	-0.360	3.061	370.50	40.87	1.630	6.316
37753	NAVSTAR 66 (USA 232)	0.560	0.000	0.120	324.91	15.19	0.110	1.544
18103	COSMOS 1851	4.130	-0.030	0.798	327.61	33.77	2.200	4.909
27513	INTELSAT 906	9.350	-0.120	1.146	316.64	26.50	4.000	6.047
4250	SKYNET 1	1.400	-0.010	0.520	308.37	19.26	4.200	4.831

are also shown. Both the residual ratios and FSC should be within ±3.

Each of the result plots has two lines. The comparisons for all cases are the full ensemble of TLE's during the period Nov 2, 2011 to Dec 16, 2011. The first test line compares the TLE propagated from near Nov 9, 2011 throughout the interval. This should show the approximate error in a single TLE vs the reference orbit created by splicing the TLEs together. The second line is the OD result from processing about a week's worth of observational data (the SGP4 spliced ephemeris), and then a numerical propagation into the future for comparison to the spliced TLE ephemeris.

The first 4 satellites were all LEO satellites, some active, others not. Consider Fig. 12. The results were about as expected, except for 7616 (debris) and the better performance of the single TLE in prediction. This would seem to confirm the SDA study in that sometimes the TLE outperforms the numerical solution.



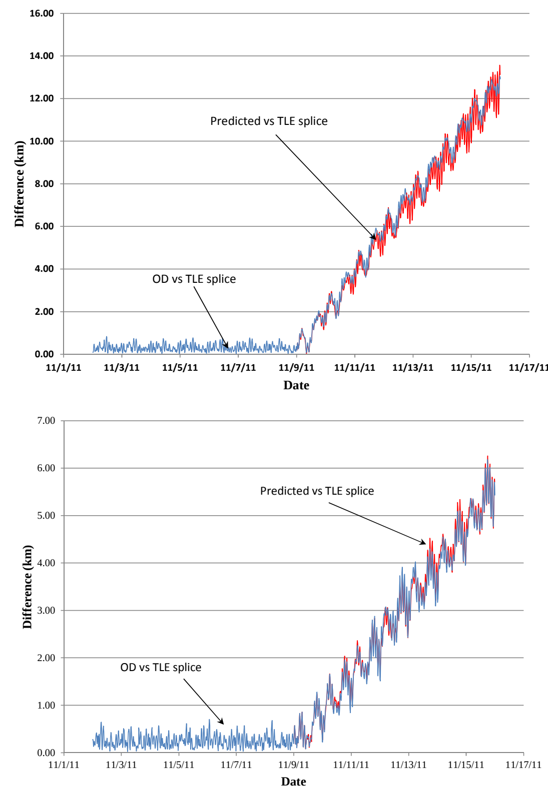


Figure 12 Difference Plots for Spliced TLE Ephemeris and OD and Prediction. The two tests for comparing a spliced TLE to an OD of a portion of the spliced ephemeris, and the comparison with a propagation of a single TLE are shown. Scales between the graphs are not the same. Satellites are from the top, 33331 Geoeye1, 7616 Delta 1 R/B, 33105 Jason 2, and 16908 Ajasai. The OD ephemeris is not always the best, often close or a little better and the number of TLEs definitely affects the fit (resulting in smaller uncertainty during the OD processing).

The next four satellites were in GPS, HEO, or GTO type orbits.

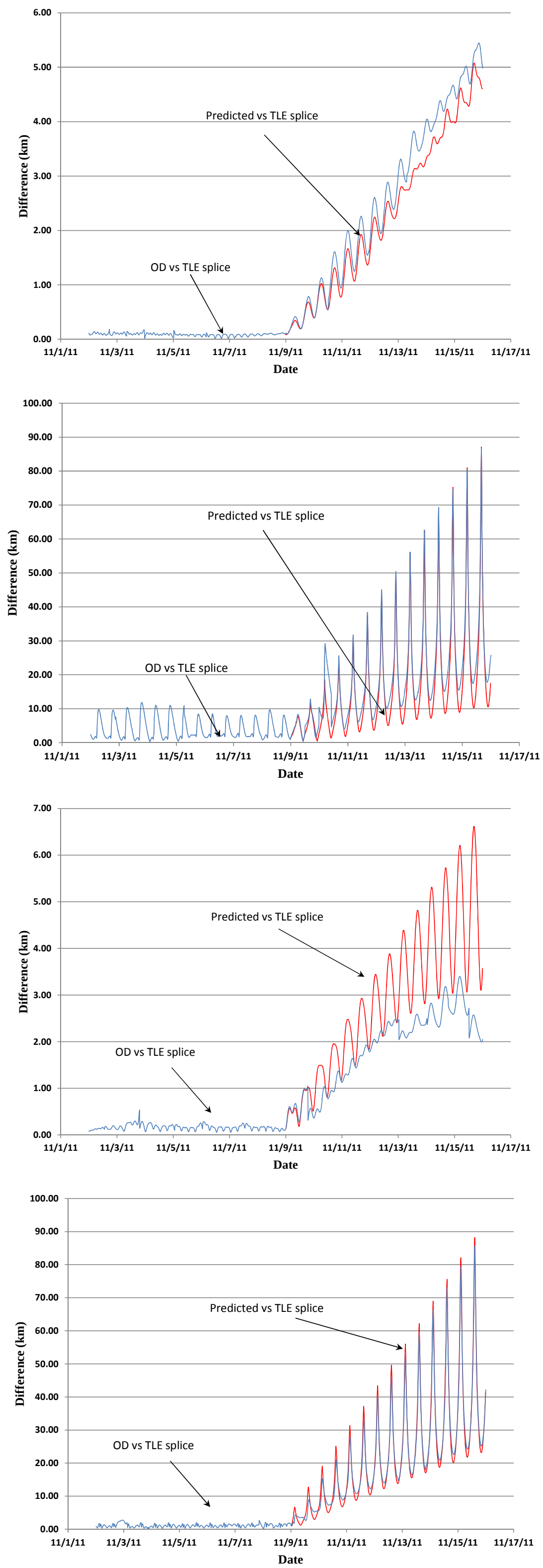


Figure 13 Difference Plots for Spliced TLE Ephemeris and OD and Prediction. The two tests for comparing a spliced TLE to an OD of a portion of the spliced ephemeris, and the comparison with a propagation of a single TLE are shown. Scales between the graphs are not the same. Satellites are from the top, 20026 Etalon 2, 28163 Molnyia, 37753 GPS, and 18103 Comsos 1851. The OD ephemeris is not always the best, often close or a little better.

Examining 2 Geo satellites, 27513 Intelsat 906 and 4250 Skynet1 provided some additional details. Obviously the maneuvers cause difficulty as is well known.

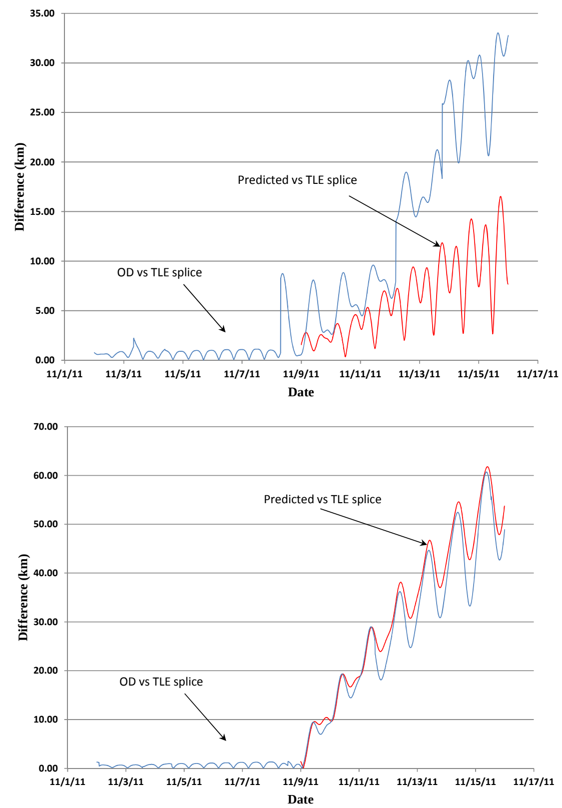


Figure 14 Difference Plots for Spliced TLE Ephemeris and OD and Prediction. The two tests for comparing a spliced TLE to an OD of a portion of the spliced ephemeris, and the comparison with a propagation of a single TLE are shown. Scales between the graphs are not the same. Satellites are top, 27513 Intelsat 906, and bottom 4250 Skynet 1. The OD ephemeris is not always the best, often close or a little better.

After setting this up, we determined that the particular satellite and orbital class were necessary discriminators for success. In particular, calibration satellites for which external independent reference ephemerides are available for checking, generally have significantly more observational tracking, and therefore more TLEs, and greater accuracy. Thus, the process worked well on those satellites as there were sufficient observations and TLE frequency to contain additional information content, not captured in the individual TLEs. However, when examining random pieces of debris, the tracking was significantly lower. The number of TLEs was lower, and the process did not work as well, sometimes producing lower quality estimates than the original.

8. APPLICATIONS

There are numerous applications still using TLEs. Conjunction analysis often uses TLEs as a quick initial screening technique. However, as we saw with some cases, the TLE may be better or worse than a sub-sequent numerical test. Thus, large pads may be included in the calculations, which somewhat negates the reason to use TLEs in the first place. TLEs have also been successfully used in atmospheric research, forming the basis of some dynamic calibration of the atmosphere approaches.

As shown in Fig 2, future maneuvers will always plague any passive SSA system, both numerically and analytically. TLEs have been used to identify some maneuvers. Kelecy (2007) showed several cases where this was true. He found a time lag that appears to be intrinsic to the raw TLE data. This is reasonable given that the TLE formation uses a Batch Least Squares approach. Analysis showed that the average offset is around 2-3 days, and has a standard deviation of around 2.4 days. This provides a bound on the timeliness for which maneuvers can be detected using these techniques Unfortunately, there is no way to exactly accommodate the lag since adequate post-maneuver data is needed to conclusively determine whether or not a maneuver has occurred using the TLE data."

9. CONCLUSIONS

This paper has summarized major thrusts of the analyses that have taken place concerning SGP4 and the formation of TLEs. The continued widespread use of TLEs shows the reliance on that data, the compact form of the data, and the perceived flexibility in meeting various accuracy needs.

Major research thrusts have centered on improving the accuracy, and determining a realistic covariance. OD is a viable method to accomplish both tasks. Of course, the best solution is to perform the OD on additional observations, but observational data is scarce.

When conducting TLE OD analyses, we note several conclusions.

- Length of processing and number of TLEs does not seem to have a direct effect on the accuracy of a newly created TLE.
- The covariance from a converted TLE ephemeris will not accurately represent the covariance of the observations. At best, it represents only the uncertainty of the processed TLEs.
- The method of forming the TLE ephemeris is important for OD tests because the greatest accuracy for a TLE is generally best before the TLE epoch.
- Trajectory sampling is better for conversion of numerically generated ephemerides than single point conversions.

Accuracy can also be improved through mathematical techniques - adding tesseral m-dailies and additional forces.

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