IMPROVED SSA THROUGH ORBIT DETERMINATION OF TWO-LINE ELEMENT SETS

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ABSTRACT

Orbit determination processing of two-line element (TLE) sets to extract additional orbital accuracy has been studied for several years. Various approaches have claimed success, and full catalog processing is conducted at ESA. We extend the existing analyses and conduct detailed evaluations of alternatives for the OD processing. This includes examination of the number of TLEs used, method of splicing ephemerides, force models, fit spans, satellite category, and if the satellite is classified as maneuverable.

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, it is generally well known that the TLEs are of limited accuracy, and often contain mis-tagged and missed maneuver information.

The Simplified General Perturbations (SGP) model series began development in the 1960s, and became operational in the early 1970s. The development culminated in Simplified General Perturbations-4 (SGP4), and although the name is similar, the mathematical technique is very different from the original SGP technique. Several papers trace the history of SGP4 including [13] in 2006 with a comprehensive update to the SGP4 computer code, with test cases, and analysis.

Over time, there have been numerous studies of TLE limitations, methods for accuracy improvement, for generating a covariance matrix, and various other operational applications. Ref. [12] summarized much of the literature that has accumulated over the years with respect to TLEs, their use and accuracy. Attention was paid to the OD processing of TLE information, and initial runs were made to assess the viability of this approach. This paper extends that analysis and performs additional tests against a variety of orbital classes.

The exact process for updating the TLEs is not well known and we gather information from several sources 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. 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 additional (minutes) delay.

Public release of the TLE catalog has occurred 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. All data for this paper comes from the publically available http://www.celestrak.com/ website.

1.1 Problem Statement

The fundamental limitations of TLEs are the facts that they are of limited accuracy, and that they do not come with a covariance, making it very difficult to use in practical operations such as conjunction analyses. There are only two general solutions: processing the TLEs to try and extract additional information, and fusing TLEs with independent data. Both approaches can use Orbit Determination (OD), but the first solution has more numerous approaches. The latter approach is the best opportunity to determine accuracy and covariance information, but it's also the most difficult as additional observational data must be available.

We extend existing analyses and conduct detailed evaluations of alternatives for the OD processing. This

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includes examination of the number of TLEs used, method of splicing ephemerides, force models, fit spans, satellite category, and if the satellite is classified as maneuverable.

1.2 Previous Studies

Numerous authors have looked at the problem of increasing the accuracy and generating a covariance for TLEs by additional OD processing using one of the two approaches mentioned previously (e.g. [1], [7], [8], [2], [11], and [4]). The notional concept is illustrated in Figure 1. OD processing results in TLE's that will degrade in accuracy as they are predicted forward.

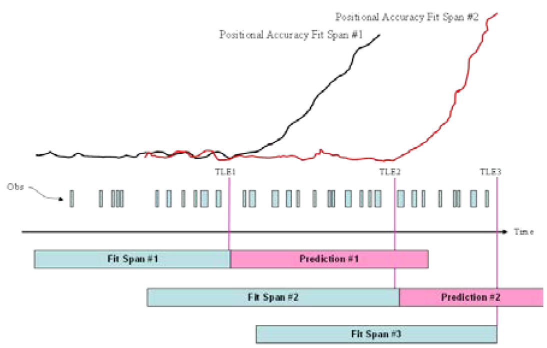


Figure 1. Notional TLE Generation and Accuracy. TLEs are generated from observations combined in a fit span. Several notional fit spans and resulting TLEs are shown. The TLEs may not be at the end of the fit span due to the practice of backing the epoch to the time of the last ascending node. When the TLE is propagated and compared to later TLE generated values, an estimate of the uncertainty is obtained, and shown here as increasing over time. It would seem logical that the prediction is better during the period of observations, which would be before the TLE epoch.

In Figure 1 when we mention comparing to a future truth, we take the OD Positional Accuracy Fit #1 ephemeris containing the fit span OD plus the prediction (all using numerical OD and propagation), and compare it to a spliced ephemeris where the SGP4 ephemeris of TLE1 is propagated backwards from the TLE1 epoch time, and adding it to the SGP4 ephemeris of TLE2 propagated backwards from the TLE2 epoch time to TLE1 epoch time, and adding on to the SGP4 ephemeris of TLE3 propagated backwards from the TLE3 epoch time to TLE2 epoch time. Although we cite backwards propagation here, it could also be from the TLE epoch "forward" to the next epoch, or mid-point.

Ref. [1] was perhaps the first to examine the OD process with some detail. His work is essentially implemented in the operational processing at the JSPOC today. He found that indeed the TLEs could be improved during the time of the OD processing, and the results were often better even 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.

Refs. [11] and [10] 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. Later studies shifted towards processing the TLEs as observations.

However, few if any have examined the entire catalog in a systematic way. Perhaps the most extensive investigation of this approach is by Refs. [4] and [5]). They use 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 all derived from single TLE, 1-day arcs.

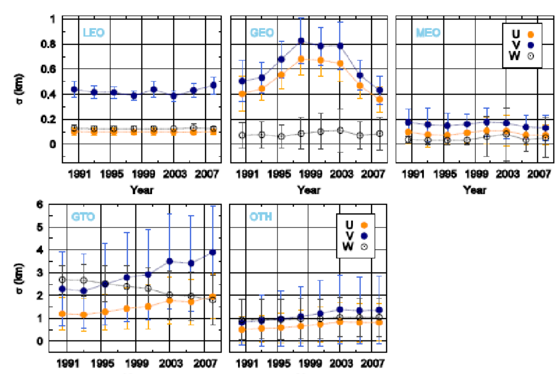


Figure 2. Summary Error chart from [4]. Their summary chart included results for LEO, MEO, GTO, HEO, and GEO orbital classes. The results were found by performing OD on simulated measurements (state vectors) derived from the TLE's. The standard deviation of the error is shown versus the time in years.

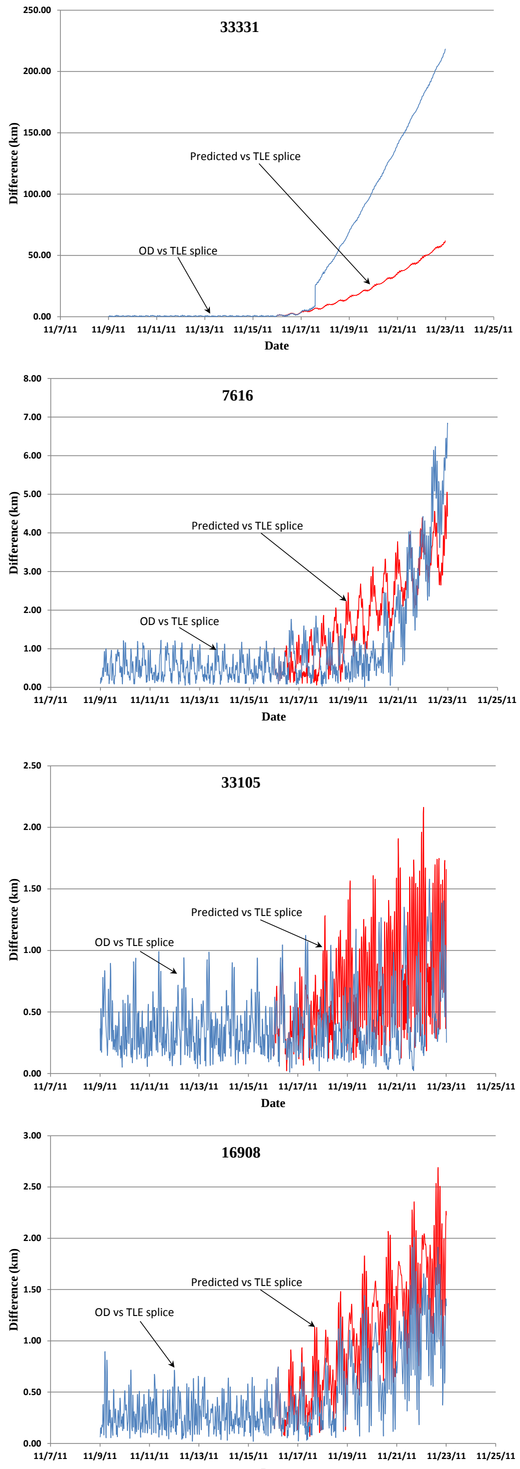


Figure 3. Difference Plots for Spliced TLE Ephemeris and OD and Prediction (5 km initial uncertainty). The tests for comparing a spliced TLE to an OD of a portion of the spliced ephemeris, and the comparison with a propagation of a single TLE are shown. Scales between the graphs are not the same. Satellites 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 seemed to affect the fit (resulting in smaller uncertainty during the OD processing). If the OD processing yielded better results in all cases, the blue line should be lower than the red line for all the predicted cases.

Ref. [12] conducted some preliminary tests to determine the effect of numerically processing the TLE spliced orbits. The spliced orbits "should" most closely approximate the truth, so both the numerically generated OD ephemeris and a simple TLE predicted ephemeris near the end OD time were compared to the longer TLE spliced ephemeris. Figure 3 shows their results. Notice that while there is sometimes an improvement, not all cases were better. The initial uncertainty was set to 1 km.

We mentioned the backwards SGP4 propagation here, but it could be forward from each TLE epoch, or midpoint as well. The idea is that we are comparing to future TLE's that may or may not all have the same amount of error in them.

Because a Kalman filter OD process was used for some initial tests, the only parameter that seemed to make a difference in the processing (other than the results shown later in this paper for Batch Least Squares techniques), was the initial assumed uncertainty. Using a 5 km as the initial uncertainty, we found the comparisons in Figure 3.

These results seemed to indicate that calibration satellites (Jason 2 and Ajasai) might perform better with the OD processing. This was an initial impetus to exploring various OD processing alternatives in the remainder of the paper.

2 PROCESS OUTLINE

2.1 Develop orbital classes from which to pick candidate satellites

Selecting orbital classes let us examine if there is an effect of certain orbital classes on the accuracies of the TLEs, and therefore, of the ability to improve the OD through processing the TLE information. The ESA Database and Information System Characterizing Objects in Space (DISCOS) system categorizes satellites and we choose the following categories. Data is as of 2013-02-27 and the total catalog is about 17000 objects. Our selections represent about 74% of the catalog, but could have been conducted for the whole catalog with slight adjustments to the setup and additional time.

Orbital Categories					
Category	**Name**	**Eccentiricity / Inclination**	**Mean Altitude km (perigee/apogee)**	**Number in Catalog**	**% of catalog**
LEO	Low Near Earth Circular	0.00 < e < 0.05	0 < alt < 575	400	2.35
LEO	Medium Near Earth Circular	0.00 < e < 0.05	575 < alt < 1000	6564	38.61
LEO	High Near Earth Circulr	0.00 < e < 0.05	1000 < alt < 2500	2147	12.63
LEO	Near Earth Eccentric	0.05 < e < 1.00	0 < alt < 2500	623	3.66
NSO	Navigation Satellites	50 < i < 70	18100-24300 / 18100-24300	253	1.49
GTO	GEO Transfer	0 < i < 55	100-2000 / 34786-36786	232	1.36
MEO	Mid Earth	0 < i < 180	2000-34786 / 2000-34786	200	1.18
HEO	Highly Elliptical	0 < i < 180	100-34586 / 38586-90000000	895	5.26
GEO	Geosynchronous	0 < i < 70	32986-38586 / 32986-38586	1176	6.92
HAO	High Altitude Above GEO	0.0 < i < 180	38586-90000000 / 38586-90000000	54	0.32

2.2 Consider the following sub-categories – active (maneuvering), calibration, debris

JSPOC tracks calibration satellites differently from other objects because additional observations are needed to produce the higher accuracy orbits. Likewise, actively maneuvering satellites receive significantly more tracking than debris objects because if the time between observations encompasses one or more maneuvers, the satellite may become lost and present challenges to recover and re-establish the orbit. (NB: Some efforts exist to determining maneuvers [9]. Detecting maneuvers lets us classify active/non-active objects (within certain limits, of course) for LEO. For GEO we used the list of controlled objects as per the ESA Classification of Geosynchronous Objects covering 2012 (Issue 15, T.Flohrer, 2013). Ref. [6] presented results from a Matlab evaluation of looking at TLEs to try and understand maneuvers. His results were reasonable, although they highlighted the wide variability of the TLEs.) For the remaining categories, there is an associated decrease in accuracy as the number of observations decreases.

2.3 Study the effect of –

2.3.1 How to form the Reference Orbit

Forming the reference ephemeris (forward splicing, mid-point, backwards) can assume many forms. A small study was conducted to determine the differences in the approaches, and which method could produce better results. We concluded that the backwards ephemeris produced slightly better results.

2.3.2 OD Force Models

We selected various force models to use with each orbital class. Atmospheric drag presented some options. DISCOS assumes a standard mass and area. The BStar term could approximate a BC, but there is a large variability because the BStar term soaks up the error from reduced force models, limited tracking, etc. We opted to use area and mass from DISCOS and the available atmospheric drag models (MSIS-90, and NRLMSIS-00). Although we performed analyses in the past, the goal of doing this operation at the current time would necessitate using predicted satellite indices, either from NOAA/NGDC, or ESA. This prohibits using the Jacchia-Bowman atmospheric models because there is about a 1 month lag in the delivery of the appropriate indices. The force models did not seem to make any difference in the initial runs. We used a 30 × 30 JGM3 gravity model in all cases except GEO and HAO where we used an 8 × 8 field. NRLMSIS-00 was used for all orbits affected by atmospheric drag, and third body and solar radiation pressure were used for higher altitude orbits.

2.3.3 OD Processing fit span

The observations here are the TLEs, and the associated ephemerides derived from them. Existing studies have generally used 1 day ephemerides for all orbital classes. However, common practice uses several fit spans for different orbital classes. This implies processing a day or so for LEO orbits, and a week or more for GEOs. We used one day for LEOs, and one week for all others.

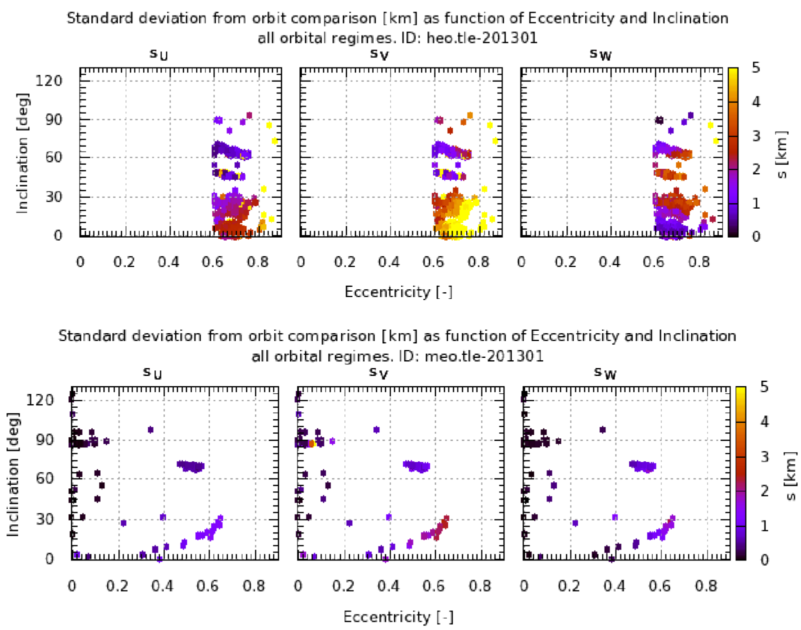


Figure 4. Orbit Comparison Standard Deviations Several categories. Several subcategories within the LEO regime are shown

2.3.4 Number of TLEs used in the fit span

Some authors [1] have suggested that the number of TLEs used in forming the reference ephemerides do not contribute to the overall accuracy. However, as the fit span is increased, consider a case where there is 1 TLE in a 1 week fit span, vs. a case where there are 7 TLEs. We know that the TLEs possess potentially wide variability. In the case with 1 TLE, if that TLE is inaccurate, it will have a much greater effect on the overall result than that same inaccurate TLE in the presence of 6 other TLEs. The number of TLEs are related to the operational processing generation. The generation takes places when new observations come into the JSPOC. When the newly created TLE is larger than some pre-defined tolerance, a new TLE is issued. Two times per day, the TLEs are grouped and distributed to space-track. The TLE generation fit span varies for the classes and types of satellites. Generally, LEO are in the 3-5 day or longer range while GEO's are 2-3 weeks or more.

2.3.5 Object size

The size of the object often is directly related to the length of the fit span with longer values being used for larger objects. The object size also may contribute to the success of the TLE OD processing. Very small objects may be tracked less often, and may have more noise than other objects. The difficulty in testing this technique is obtaining accurate object size information.

3 RESULTS

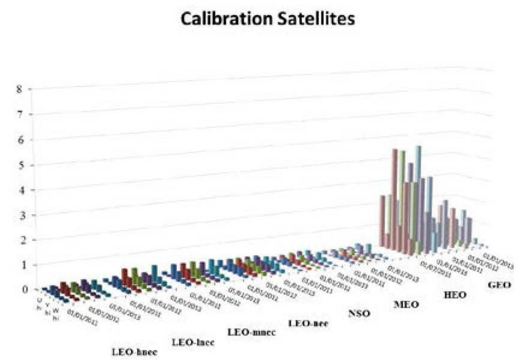
We conducted tests similar to those conducted previously by [4]. Several steps were needed to arrive at final answers. The various approaches were coded and tested on ESA's computer system for the selected subset of the satellite catalog. Results were assembled into UVW (radial, along-track and normal) components. The differences were found as the uncertainty of the OD process with respect to the TLE ephemeris used as observations. As such, this will not necessarily be the "accuracy" or covariance of the satellite, but it does give an indication of uncertainty. Notice also that this is not the uncertainty during prediction, but rather during the OD process, and as such, will be substantially less than the prediction uncertainty.

Sample plots are shown for all satellites for the various orbital categories. Figure 4 shows representative UVW components for various orbital classes. In all cases, the V component was the largest.

We added several new cases to previous analyses to understand if the tracking and perceived accuracy of the input TLEs affected the results. In these new tests, we examined the following:

- Epochs: twice per year over the last several years (2011, 2012, in Jan and Jul, and 2013 Jan). These results are shown in each category.
- Orbital Categories: LEO (subcategories of lec, mec, hec, nee), MEO, NSO, GTO, HEO, GEO, HAO.

- Object classes: Payload (PL) maneuverable, PL-calibration, PL-notMan, Rocket Body (RB), mission-related objects (MRO), and fragments (general debris).



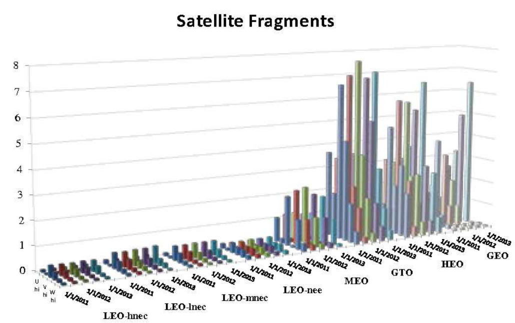


Figure 5. Results for different Satellite Object Classes and Sizes. Several satellite classes were examined to understand any effect they would have on T LE OD processing. High and Low UVW component values are shown for each orbital class. Error values are in km and the scales are the same for each plot.

- Size bins (area): We used sizes from the DISCOS database. This includes objects except fragments, for which we could use the published RCS values, although they have significant error in many of the values and was therefore not considered valid. For the other objects, we used areas of minimum (< 1 m^2), medium (1 m^2 < area < 10 m^2), and large (10 m^2 < area).

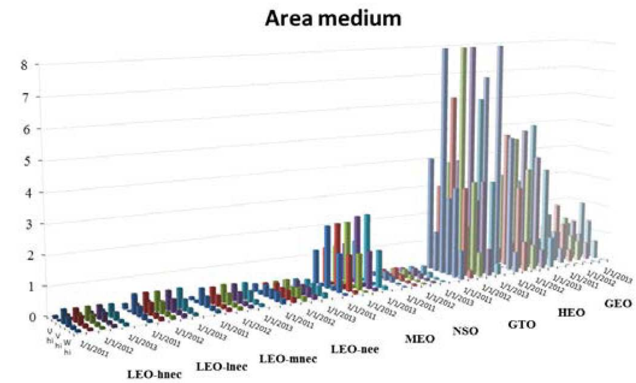


Figure 6. Results for different Satellite Object Sizes. Large, medium, and small areas (respectively from top left) were explored to understand any effect they would have on TLE OD processing. Error values are in km and the scales are the same for each plot.

- TLE propagation: 1 day forward, 1day backwards, 1 day centered (for GEO and MEO, 7 days. After an initial comparison of forward, centered and backwards ephemeris generation, we only performed a backwards propagation. (without splicing at this time). Given the large uncertainty of TLEs, we felt it important to perform this study before conducting more extensive whole catalog tests.
- Splicing TLEs: To generate a spliced ephemeris, recall Figure 1. We have notionally shown many observations being taken over time, with 3 distinct TLEs being created. Two OD and prediction intervals are shown. As the prediction goes into the future, the error goes up as we would expect. When the second OD is finished, the fit span includes some of the data from the previous OD, and the results are a little different. We assumed no maneuvers, although they would simply increase the uncertainty depending on the magnitude of the maneuver.
- Force Models: We performed a LEO test case with the two atmosphere models (NRLMSIS-00 and MSIS-90). There was less than a 1% difference in the results leading us to conclude that varying the atmospheric model would not yield significant differences in the results.

4 CONCLUSIONS

We confirmed earlier results [1].

- The number of TLEs did not seem to make a difference in the OD accuracy.

- Force models for various orbital classes added only a small effect.

We also determined some new results.

- The largest uncertainty in virtually all cases was in the along-track direction. The notable exception was for GEO orbits where the radial component was very large.
- HEO and GTO orbits consistently experienced the largest uncertainty. Next in decreasing uncertainty were GEO and MEO, and then the NSO and all the LEO orbits.
- LEO orbits seemed to have about a 1 km epoch uncertainty for all configurations.
- HEO and GTO orbits showed about a 6-8 km epoch uncertainty, GEO orbits were about 2-4 km, MEO were about 1-2 km and NSO were about 1 km.
- Forming the reference orbit backwards does appear to improve results. 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.
- Force models, specifically the atmospheric model, do not seem to make much difference. At the level of accuracy of the TLE, it is probably not observable.
- Fit spans likely did make a difference, since we were only using 1 TLE for the whole time. Time did not permit tests of splicing TLEs when forming the reference OD ephemeris. The 7 day fit span was probably also responsible for the larger uncertainty in non-LEO categories compared to results in [4].
- Object type (category, maneuverable, calibration, etc.) seemed to be a factor in some cases and should probably be kept as a part of the standard treatment in processing the catalog data.
- Object size seemed to be a factor, but it's also possible that this observation is also affected by the orbital regimes within the various object size categories.

5 REFERENCES

1. Cappellucci, D. A. (2005). Special Perturbations to General Perturbations Extrapolation Differential Correction in Satellite Catalog Maintenance. *Paper AAS 05-402 presented at the AAS/AIAA Spaceflight Mechanics Conference, January 23-27, 2005. Copper Mountain, CO*.

2. Delavault, S. (2008). Improvement of the TLE Accuracy Model Based on a Gaussian Mixture Depending on the Propagation Duration. *Paper AIAA-2008-6772 presented at the AIAA/AAS Astrodynamics Specialist Conference. August 18-21, 2008. Honolulu, HI*.

3. Delavault, S., P. Legendre, R. Garmier, and B. Revelin. (2007). Improvement of the Two-Line Element Accuracy Assessment Based on a Mixture of Gaussian Laws. *Paper AAS 07-390 presented at the AAS/AIAA Astrodynamics Specialist Conference, Mackinac MI*.

4. Flohrer, T., et al. (2009). Improving ESA'S Collision Risk Estimates by an Assessment of the TLE Orbit Errors of the US SSN Catalogue. *Paper S4.4 presented at the 5th European Space Debris Conference. Darmstadt, Germany. 30 M arch – 2 April 2009*.

5. Flohrer, T., H. Krag, and H. Klinkrad. (2008). Assessment and Categorization of TLE Orbit Errors for the US SSN Catalogue. *Paper presented at the AMOS Technical Conference. Maui, HI*.

6. Kelecy, T., et al. (2007). Satellite Maneuver Detection Using Two-line Element (TLE) Data. *Paper presented at the AMOS Technical Conference, Maui HI.*

7. Legendre, P., B. Deguine, R. Garmier, and B. Revelin. (2006). Two-Line Element Accuracy Assessment Based on a Mixture of Gaussian Laws. *Paper AIAA 2006-6518 presented at the Astrodynamics Specialist Conference. August, 2006. Keystone, CO.*

8. Legendre, P., R. Garmier, G. Prat, B. Revelin, and S. Delavault. (2008). Improvement of the Two-Line Element Accuracy Assessment Based on a Mixture of Gaussian Laws *Adv. Astronaut. Sci.*, **129**(3), 2189-2207.

9. Lemmens, S. (2012). Non-natural event detection method for satellites in Low Earth Orbit. *Paper F4.6-13-12 presented at the 39th COSPAR Scientific Assembly, 14-22 July 2012, Mysore, India.*

10. Levit, C., and W. Marshall. (2011). Improved orbit predictions using two-line elements. *Adv. Sp. Res.*. **47**, 1107-.

11. Muldoon, A. R., et al. (2009). Improved orbital debris trajectory estimation based on sequential TLE Processing. *Paper IAC-09.A6.2.9 presented at the 60th International Astronautical Congress. Daejeon, South Korea*.

12. Vallado, D. A., and P. Cefola. (2012). Two-Line Element Sets – Practice and Use. *Paper IAC-12.C1.6.12 presented at the 63rd International Astronautical Congress. October 1-5, 2012. Naples, Italy.*

13. Vallado, D. A., et al. (2006). Revisiting Spacetrack Report #3. *Paper AIAA 2006-6753 presented at the AIAA/AAS Astrodynamics Specialist Conference, August 21-24, 2006. Keystone, CO.*