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IMPROVED ORBITAL DEBRIS TRAJECTORY ESTIMATION BASED ON SEQUENTIAL TLE PROCESSING

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ABSTRACT

The growing quantity of space debris in LEO is becoming a significant concern for satellite operators. Accurate prediction of the future path of debris is critical in deciding if and when to maneuver satellites to avoid collisions. As the majority of debris objects are available as Two-Line Elements (TLEs), the only appropriate algorithm for predicting debris motion is SGP4/SDP4 (referred to collectively as SGP4). In this paper we present a new approach to orbital modeling: using data-driven modeling to predict future orbital parameters. This system leverages SGP4 and is thus compatible with TLE data. However instead of an analytical model our method uses data-driven modeling techniques to predict future orbital state. Using the historical data available for an object, we train a predictor system for each of the TLE parameters. We then construct a new TLE near the desired prediction time using estimates from those trained predictors. With a naïve predictor system, we have achieved results comparable to or better than SGP4 when predicting out two weeks from the end of available data. We believe that a more advanced predictor system could produce results significantly better than SGP4.

1. INTRODUCTION

The problem of Space Situational Awareness is becoming an increasingly significant concern for satellite operators due to the growing amount of debris. While once a concern only for governmental entities or organizations with large constellations of satellites, the volume of debris on orbit has risen to a level where entities with only a single satellite need to be concerned. For all of these entities, accurate prediction of the future path of debris is critical in deciding if and when to maneuver satellites to avoid collisions. To this end, our research is focused on improving the prediction of debris motion up to two weeks into the future.

Traditional approaches for predicting the future motion of orbiting objects use either analytical models (mathematical models of the orbital perturbations caused by various effects) or numerical methods (time-step integration using complex models of physical forces). While extremely accurate models exist, sufficient data for the majority of debris objects is unavailable. The only data on debris objects readily available to satellite operators are the Two Line Elements (TLEs) published by the US Strategic Command (USSTRATCOM) and available from http://www.space-track.org/ or courtesy T.S. Kelso at http://celestrak.com/.

The SGP4 propagator is the only appropriate algorithm when working with TLE data, as USSTRATCOM appears to generate their TLEs using it, though there does not seem to be a consensus standard for orbital determination and the code used to generate TLEs has changed over the years[1]. First released in 1980 and only receiving minor updates since, it accounts for general perturbations for objects from Low-Earth Orbit (LEO) to Geosynchronous Earth Orbit (GEO) and beyond. TLEs have had periodic variations removed in a particular way which the SGP4 propagators reconstruct in exactly the same way[2], resulting in SGP4 being the only appropriate method for calculating actual object trajectory.

In this paper we present a new approach to orbital propagation: a data-driven model. We consider each orbital parameter individually, training a model fitting system using historical data, fitting a model to the last available data, and evaluating that model at the future point to estimate the future value. Our present model fitting system uses blending[3] of several window-optimized polynomial models of different orders for estimating epoch time, and a polynomial plus optimal periodic components for all other parameters. Using this approach we have achieved accuracy comparable to or better than SGP4.

Our development and analysis was guided by several constraints. First, to avoid the possibility of station keeping or other maneuvering complicating the modeling process, we consider only debris objects. Second, in order to guarantee that we have adequate data for which to build a model, we consider only objects that have historical TLEs for at least three years and an average of at least 0.5 TLEs published per day. Third, we consider a fixed prediction duration of two weeks into the future. We believe this prediction duration to be a reasonable tradeoff between utility to debris avoidance efforts and limits on prediction accuracy. Finally we make no consideration of computational complexity, as we believe that potential users will either be limited to considering a small number of objects with potential conjunctions or large efforts with massive clusters at their disposal.

Our results are obtained by training the modeling system using a year of data, fitting a model to the end of that data, and requesting a modeled TLE that coincides with an actual TLE approximately 14 days after the end of that year. We then use SGP4 to evaluate the TLEs at the actual TLE's epoch time and compare the resulting positions in the VNC error metrics.

In section 2 we review other work in orbital propagation and error estimation for TLEs. Section 3 presents a detailed review of our techniques, followed by analysis of our results in section 4. Section 5 offers a summary of our results. Several ideas for improvements to this system that we have not yet had time to implement are discussed in the final section.

The code used to obtain the results in this paper is available from the author's website at http://soe.ucsc.edu/~newmoon/STM and works with both MATLAB and GNU Octave.

2. RELATED WORK

Our analysis is based on comparison to future TLEs, so we must have some idea of how accurate TLEs are to begin with. Several studies have compared TLE propagation results to truth data.

A 2007 study by T.S. Kelso[4] compared the position of GPS satellites to their position calculated using published TLEs and SDP4. It showed that while the accuracy is not minimized at the epoch, the propagation error 14 days post-epoch is a factor of 5 to 10 worse than the accuracy at the epoch.

While GPS satellites are at the upper bound of our region of interest, a similar 2004 study compared truth data for objects in the Iridium constellation to TLEs at their epoch[5]. They found that in-track and radial errors are on the order of 2km and 100m, respectively. These results are more relevant to our analysis as the Iridium satellites are in LEO and thus representative of the bulk of the objects under consideration.

Some work has been done attempting to improve the quality of results from SGP4. Chan & Navaro[6] considered adding back some short period perturbations based on truth data. Their results show a reduction in radial error of almost an order of magnitude. However, this work is not particularly relevant as it applies to objects in geosynchronous orbits.

SOCRATES currently exists to predict future conjunctions between on orbit payloads and unclassified objects in the space catalog[7]. They currently assume a conjunction box size of 1km for times up to one week out. Given current errors in TLEs, this error box is far too small to be useful in predicting conjunctions.

3. OUR APPROACH

Traditional approaches to orbital prediction fall into two categories: analytical models and numerical models. Analytical models use a complex, physically informed mathematical representation of the behavior of orbiting objects. They directly calculate the future state of a system based on some parameterized description of its motion. Numerical models take a very different approach, using numerical integration to simulate the actual physical effects acting on an orbiting object. Our research introduces a third approach to orbital modeling: data-driven modeling.

TLEs, by their nature, can only be converted to position data using the SGP4 algorithms. As TLEs are the only data readily available for the vast majority of orbiting objects, our model must operate in conjunction with these algorithms if it is to be useful for debris objects. To this end, we chose to model the evolution of the TLE parameters over time.

TLEs include 11 parameters, though only 8 directly affect the output of the SGP4 a4 propagator is the only appropriate algorithm when working with TLE data, as USSTRATCOM appears to generate their TLEs using it, though there does not seem to be a consensus standard for orbital determination and the code used to generate TLEs has changed over the years[1]. First released in 1980 and only receiving minor updates since, it accounts for general perturbations for objects from Low-Earth Orbit (LEO) to Geosynchronous Earth Orbit (GEO) and beyond. TLEs have had periodic variations removed in a particular way which the SGP4 propagators reconstruct in exactly the same way[2], resulting in SGP4 being the only appropriate method for calculating actual object trajectory. In addition to several other parameters not used by SGP4, every TLE includes a revolution number. This is an integer number of orbits, increasing by one every time the object crosses its right ascending node.

TLEs are issued as an object crosses its right ascending node (as it passes over the equator from south to north). This provides two things: consistency of values between TLEs, and a requirement on when we can generate future TLEs. Because of this constraint, we cannot use time as an independent variable. Instead the only logical independent variable is revolution number. Our approach is to individually model each of the TLE parameters, epoch time included, as a function of revolution number.

Ambiguity and Normalization

Before modeling the values, we perform a few steps to normalize and remove ambiguity from the TLE parameters. Several of the TLE parameters are angles in degrees, expressed mod 360. To aid in modeling, we unwrap these values such that the change between any two sequential values is no greater than 180 degrees. This results in a value that changes continuously, and thus can more easily be modeled.

Two of the TLE parameters can be ambiguous for some orbits. For an object with small inclination it can be difficult to determine when it crosses the equator (as it's always very near it), resulting in the right ascension being ambiguous. This ambiguity is insignificant for objects in LEO, as few if any have an inclination below five degrees.

The more significant ambiguity, however, is the argument of perigee for objects in a nearly circular orbit. This value is increasingly ambiguous as the eccentricity goes to zero. While argument of perigee has increasingly limited effect on the orbit shape as the eccentricity approaches zero, it still greatly affects the interpretation of the mean anomaly value. To remove this ambiguity, for objects with an eccentricity of below 0.02 we add the argument of perigee to the mean anomaly before modeling and subtract in the predicted values.

Initial Prediction Methods

Our initial method for predicting all values was to model the signal as a combination of polynomial and periodic components. Starting with a polynomial, we use a simple form of stepwise regression, finding the optimal periodic component to fit the residual at each step. In early tests we tried polynomials as high as 5th order and up to 4 periodic components. We eventually found a 2nd order polynomial and 2 periodics to provide optimal prediction results.

Applying this method to all parameters produced disappointing results. Comparing modeled TLEs to actual future TLEs we found median cartesian errors in excess of 40km. However, by replacing individual parameters with their "perfect" value from the future TLE, we were able to determine that only one parameter was responsible for over 95% of the in-track error: epoch time (see Table 1). Because of this we focused additional effort on the prediction of epoch time.

Model Type	V	N	C
Full	40.3	0.49	0.39
Perfect Time	1.5	0.32	0.39
Perfect Other	38.4	0.10	0.00

Table 1. This table shows Median VNC error in kilometers of predicted TLE vs. actual future TLE. Perfect Time and Perfect Other results are acquired by replacing either epoch time, or all parameters besides epoch time, in the predicted TLE with the actual future value. This analysis was performed on three randomly selected target TLEs on each of about 400 objects, using one year of training data ending 14 days prior to the target TLE.

Global Optimization of Model Parameters and Blending

Investigation of how the present modeler was fitting time revealed two key characteristics. Predictably, it has a strong almost-linear component. A quadratic can fit more precisely but still leaves significant low-order but non-periodic residuals. Because of this the periodic refinement approach often identified only one periodic component in its variation, if any at all. We also found, looking at residuals after removing a quadratic, significant low frequency entropy that makes the period refinement process difficult and, to a large degree, futile. Because of these two elements, we started investigating shorter-period fitting approaches. Rather than using the entire year of training data, we fit polynomials to only the last few weeks, or even days of TLEs leading up to the end of available data. This resulted in improved predictions but required hand-tuning of the fitting windows for each object. To eliminate this step we started investigating using optimization approaches to determine the optimal fitting window and polynomial order for an object.

In a simple model fitting approach, all of the model parameters are simultaneously optimized to minimize some error metric against training data. In this approach we identify some parameters of the model (the fitting window size) to be globally optimized. The remaining parameters (polynomial coefficients) are optimized for each specific application of the model. We use traditional non-linear optimization techniques to find optimal global parameters to minimize errors when making predictions.

While this reduced errors significantly, we found that different order polynomials still fit different objects better. Rather than treat this as a global parameter, we employ a modeling technique known as "blending". Popularized by The Netflix Prize data mining competition, blending allows an ensemble of various modeling techniques to be applied simultaneously to the same problem[3].

Blending is another form of global parameter optimization – of the coefficients of a linear combination of the individual modeling techniques. It allows us to combine a large set of modeling approaches in an optimal and often synergistic way. For our final results, we blended four predictors to create the model: 1st through 4th-order polynomial fitters with optimal input windows between 1 and 90 days.

4. RESULTS

For our current study we chose 411 randomly selected debris objects from the TLE catalog, most with an orbital period of less than 10 hours which were in orbit on both 2006-01-01 and

2009-01-01. We chose mostly LEO objects as that is where the greatest density of objects, and thus concern for conjunctions, lies. We retrieved TLEs for these objects for all of 2006, 2007 and 2008. We then pruned objects with an average of fewer than 0.5 TLEs per day, leaving 397.

For each of these objects we randomly selected two dates during 2007 and 2008 to use as simulated prediction dates. For each date we created a model using TLEs within the year prior to that date and selected the TLE closest to 14 days after that date as the reference TLE. The model was then used to create a new TLE at the revolution number of the reference TLE. The resulting predicted TLE and reference TLE were then evaluated at the epoch time of the reference TLE and the VNC error between the two points was calculated. For comparison the last TLE in the training data was propagated forward to the epoch time of the reference TLE using SGP4.

Figure 1 shows the cumulative distribution function of absolute errors between the reference TLE and the predicted (thick) or propagated (thin) TLE. While this shows the improvement is not dramatic, the median error is comparable for the V direction and improved for N and C. Overall, the error in the C direction is most improved with an average reduction in error of about 50% across all percentiles.

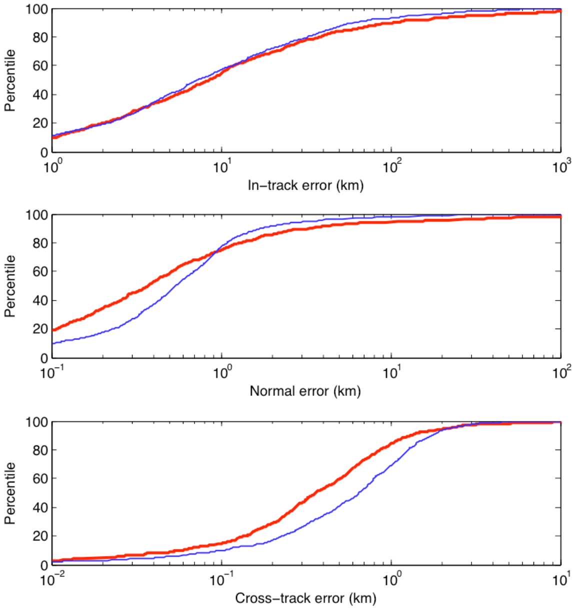

Figure 1. Cumulative distribution function of error comparing our predicted positions (thick red line) and SGP4-propogated positions (thin blue line) to actual future TLEs. From top to bottom, these are errors in the V, N and C direction.

In attempting to identify the source of our errors, we discovered that TLEs are not generated with the object exactly at right ascension or even in a consistent position. For the 411 objects under consideration, 10% have standard deviation in their argument of latitude at epoch of more than 0.1° and 5% have a deviation of more than 0.5°. In addition, we found a strong correlation between deviation of argument of latitude at epoch and both prediction and propagation accuracy, presented in Figure 2. We believe our large errors on objects with large deviation in TLE issue position is due to noise in mean motion and epoch time, preventing the model from fitting finer nuances.

5. CONCLUSION

We have presented what we believe to be one of the first applications of data-driven modeling to orbital prediction using only TLEs as input. With a few naive modeling approaches combined with blending, we have achieved results comparable to SGP4 when looking 14 days out. Our improvements to cross-track position prediction, while not significant in the context of conjunction analysis, show that approaches of this type can easily improve over

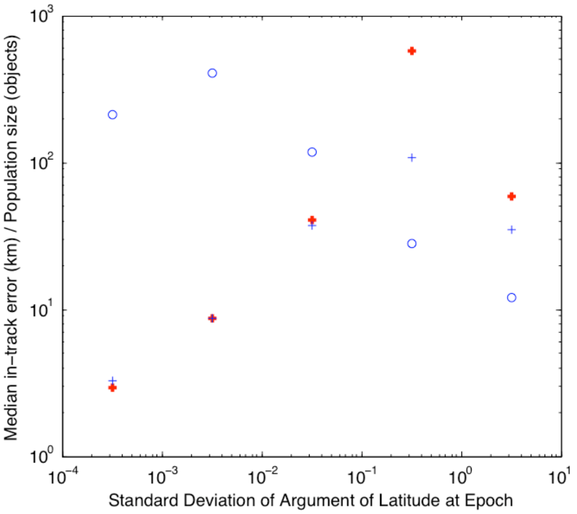

Figure 2. In-track error in prediction (thick red marks) and propagation (thin blue marks) versus actual future TLEs. Grouped by standard deviation in argument of latitude over the entire three years of object data available. Circles indicate population size contributing to each sample

the established analytical models without requiring data beyond that available in TLEs. Finally, as our approach works directly in the TLE parameter format, it can be trivially integrated into existing systems as a simple preprocessing step.

6. FUTURE WORK

As a result of how well a simple approach could do modeling TLEs, we plan to investigate adding more robust modelers to the ensemble being blended. One possibility is to employ SGP4 itself as a predictor, using it to predict when the object will cross its right accession. Given the nature of blending, this would result in a model no worse than SGP4 on all but statistical flukes but with the potential to be significantly better.

Our discoveries regarding the consistency of object position at TLE issue suggest other improvements as well. Assuming these noisy TLEs remain accurate near their epoch, equivalent noise must be present in the epoch times. By eliminating this noise, we would likely be able to capture more detail in our model of epoch time, improving prediction accuracy.

Finally, as we have been focusing on debris objects to avoid complications from maneuvering, we have no way to compare our prediction results to truth data. Though it would require careful avoidance of maneuvering events, we would like to apply this technique to objects with truth data. We suspect that for shorter duration predictions, our modeling approach would diminish the effect of noise present in TLEs, resulting in improved prediction accuracy.

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