

An Accuracy Analysis of the SGP4/SDP4 Model

Abstract

Based on the latest release of the SGP4/SDP4 (Simplified General Perturbation Version 4/ Simplified Deep-space Perturbation Version 4) model, in this paper we have designed an orbit determination program. Through calculations for the 1120 objects with various types and orbital elements selected from the space objects database, we have obtained the accuracies of the orbit determination prediction dealt with various types of space objects by the SGP4/SDP4 model. The results show that the accuracies of the near-earth objects are in the order of magnitude of 100 meters; the averages of the orbit determination accuracies of the semi-synchronous and geosynchronous orbits are, respectively, 0.7 and 1.9 km. The orbit determination accuracies of the elliptical orbit objects are related to their eccentricities. Except for few elliptical orbit objects with $e > 0.8$, the orbit determination errors of the vast majority of the elliptical orbit objects are all less than 10 km. By using the SGP4/SDP4 model to make 3 days predictions for near-earth objects, 30 days for semi-synchronous orbit objects, 15 days for geosynchronous orbit objects and 1 day for elliptical orbit objects, the errors of prediction generally don't exceed 40 km.

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Simplified Approach to Detect Satellite Maneuvers Using TLE Data and Simplified Perturbation Model Utilizing Orbital Element Variation

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Abstract

In this study, an algorithm to identify the maneuvers of a satellite is developed by comparing the Keplerian elements acquired from the two-line elements (TLEs) and Keplerian elements propagated from simplified perturbation models. TLEs contain a specific set of orbital elements, whereas the simplified perturbation models are used to propagate the state vectors at a given time. By comparing the corresponding Keplerian elements derived from both methods, a satellite's maneuver is identified. This article provides an outline of the working methodology and efficacy of the method. The function of this approach is evaluated in two case studies, i.e., TOPEX/Poseidon and Envisat, whose maneuver histories are available.

The same method is implemented to identify the station-keeping maneuvers for TDRS-3, whose maneuver history is not available. Results derived from the analysis indicate that maneuvers with a magnitude of even as low as cm/s are detected when the detection parameters are calibrated properly.

Keywords:

two-line elements; simplified perturbation models; Keplerian elements; trial & error and maneuver detection

1. Introduction

Almost 5250 launches have been made since the first artificial satellite, Sputnik, was launched on 4 October 1957 by the Soviet Union, leading to almost 42,000 objects in orbit [1]. Out of these, as of 22 July 2020, 20,987 objects are constantly being tracked by the Space Surveillance Network of the United States and among them around 1300 have the capability of performing orbital maneuvers [2]. Detecting these maneuvers is crucial to maintain a catalog of these objects. In addition to helping maintain a catalog, these orbital maneuvers are a key element in space situational awareness, specifically in small-scale maneuvers that cannot be detected by traditional methods [3]. Maneuver detection also has to be performed to monitor active satellites and space debris, look for space events, and ensure that low Earth orbit satellites adhere to the deorbiting standards. By analyzing the maneuvers of a satellite, the purpose of orbital control can be determined. An important requirement in space situational awareness involves ascertaining the current locations of all the known space satellites [4,5,6,7]. The space surveillance network, along with a space-based surveillance satellite, has a total of 29 space surveillance sensors, which are placed at strategic locations worldwide, to maintain a space object catalog that contains the current Keplerian elements of these objects in space [8,9]. Many modern applications in industry and the military rely on this space catalog to perform various tasks, such as re-entry predictions, collision avoidance, drag make-up, space weather, orbit estimation, and deorbiting [10,11]. **Substantial research has been conducted on maneuver detection. Patera developed a data processing algorithm to detect space collisions and satellite maneuvers [12].** In this method state vector parameters for tracked objects are placed in a catalog with the corresponding time. These time-dependent data can be processed to reveal sudden unexpected changes in parameter values referred to as space events. Huang et al. analyzed the semimajor axis to predict the mode of maneuver on the basis of the anomalies found in it [13]. Oltrogge and Alfano developed a method using a low-pass orbit element filter, and the method proved to be an efficient

technique to identify a potential cross-tagged or similarly degraded orbit solution accuracy event [14]. Jaunzemis et al. developed an algorithm by calculating the span between two state distributions evolving from nonidentical uncorrelated tracks to detect spacecraft anomalies [15]. A study was conducted by Chul Ko and Sheeres to detect the maneuvers on the basis of the event representation approach by using 14 thrust Fourier coefficients to identify the change point of unknown accelerations [16]. Satellite maneuver prediction using two-line element sets has been studied for several years, and various approaches have claimed success so far. One such study was conducted by Lemmens et al., who proposed two novel methods to predict maneuvers using the two-line element (TLE) sets of a satellite [17]. The first method checks for certain anomalies of satellites between arbitrary element sets. The subsequent algorithm works by checking for unexpected changes by analyzing the robustness, harmonics, and statistics using the time series. Both algorithms work only on low Earth orbit (LEO) satellites and have achieved perfect results [18]. Kelecy et al. introduced a trial-and-error method by finding the huge difference in the subsequent observation of a satellite's semimajor axis and by setting a threshold filter for a first-order polynomial with a window length between the successive data points through analysis of a satellite's TLE data. Surprisingly, the results have a 95% detection rate for all the maneuvers down to change in velocity at magnitudes less than cm/s [19]. Li et al. suggested a technique to detect a satellite's maneuvers by comparing the establishment state of a certain orbital parameter with the probability error prediction, which is fitted using sample data generated by a polynomial fit from the TLE sets of a satellite [20]. Bai et al. proposed an algorithm to detect orbital maneuvers by using unsupervised classification methods, such as K-means, hierarchical, and fuzzy C-means clustering, through data mining of the TLEs of the satellite [21]. Levit and Marshall proposed a series of least-squares differential correction fitting and propagation methods to detect a satellite's maneuver on the basis of the TLEs of the satellite. Their research also consisted of a viable collision avoidance system from space debris [22]. Clark and Lee implemented parallel processing by fusing TLE and state propagation methods to detect maneuvers, thereby increasing the computation speed and accuracy of the existing technique by factors of eight and four, respectively [23]. Fieger improved the accuracy of the long-term prediction of orbital elements by using the least-squares method, which deduces a fit for long sets of TLE data by a semianalytic propagator [24].

At any given point in time, TLE is a representation of the orbital parameters of an object orbiting Earth [17]. Given that TLEs

are updated on a regular basis, they comprise vital information, such as the perturbation effects (environmental and non-environmental) of the orbit. TLEs have been used in several applications, which derive all the information from the TLE catalog [25,26,27]. One specific use of TLEs is to advance the atmospheric density corrections pioneered by Yurasov et al. [28]. However, the interest of this study was to detect the maneuver history of Earth's orbiting satellites using TLE datasets. As the name suggests, TLE data consist of two lines comprising a series of orbital elements of a given object orbiting Earth at a specific instant in time, sometimes with a preceding title line. Simplified perturbation models are used to predict the orbital position and velocity vectors of a particular satellite or space debris at any given point in time [29,30,31]. In total, five sets of prediction models are used: simplified general perturbations (SGP), SGP4, simplified deep space perturbations (SDP4), SGP8, and SDP8 [32,33]. However, SGP4 and SDP4 are the most used models, depending on the altitude of the considered satellite [34]. These five models predict the state vector of a satellite in consideration of the effects of the perturbations that are caused by the shape, atmospheric drag, and radiation pressure of Earth, as well as the gravitation caused by different celestial objects, including the Sun and the Moon [35,36,37]. TLEs are generated only for Earth-orbiting objects, and the format of the TLE sets is distinct to each simplified perturbation model. Therefore, not just any model can be used for any TLE dataset; one must implement the specific format of TLEs for specific simplified perturbation models.

However, all these methods can be used to detect a satellite's maneuvers only if substantial operational data are available. Detecting the maneuvers for all active objects that do not have any operational information or very little maneuver information can be difficult. Nevertheless, the same maneuvers can be easily detected by using historical TLE data. Maneuvers must be detected in real-time to provide enough time to analyze spacecraft anomalies and clear a suspected threat to a nearby spacecraft or debris. The maneuvers of a satellite can be detected by following certain patterns or trends from recorded data such as maneuver histories, semi-major axis, eccentricities, etc. of active satellites [38]. Such information is vital because it can be used to predict or foresee and analyze a possible maneuver in the future; it can also be provided to a tracking algorithm that allows real-time maneuver detection and analysis. Recording and storing such information can reduce the risk of losing several active satellites, which could go off track due to maneuvers occurring in between tracks. Therefore, detecting and

recording the information of all maneuvers by using the TLE data of satellites with no operational data are important. Although various algorithms and methods can detect the maneuvers of a satellite, the best achieved detection reliability is 95%, which includes a 6% false detection. Just using TLEs to detect maneuvers can lead to false results as the accuracy of TLEs can be limited, but advancements have been proposed. However, combining SGP4 to find the propagated Keplerian elements and compare them with the observed Keplerian elements from the TLEs can improve the existing accuracy rate from 95% to 100%. Hence, this study proposes a new method to detect a satellite's maneuver information by comparing the data obtained using TLEs and SGP4.

2. Methodology

The basic SGP4 model used in this study was obtained from MathWorks [39]. This specific SGP4 prediction model is a modified version of the works of Lane and Cranford, who used the latest Brouwer's equations for the gravitational and density function for the atmospheric model calculations [40]. A small variation in any equation or constant makes a huge difference in estimating the semimajor axis or the inclination. Many studies have been conducted on testing the accuracy of the TLE data sets [33,41,42]. One such study that fits a variety of objects in various orbits was analyzed by Dong and Chang-yin using the latest SGP4 model [43] (en üstte). They conducted extensive research on 1120 objects and came to a conclusion that the SGP4 model has an error in the magnitude of 100 meters in the altitude while the average inaccuracies in the semi-synchronous and geosynchronous orbits are 0.7 and 1.9 km, respectively, and the errors in the elliptical orbit do not exceed 10 km. Hence, the accuracy of this modified matlab model must also be tested. A sample test case that was given in the original Spacetrack Report No. 3 was compared with the proposed modified MATLAB algorithm developed in this study [44]. The accuracy comparison between the two cases is given in Table 1 (in the units of min and km). T since is the propagated time from the reference TLE set fed in; X , Y , and Z are the position vectors; $XDOT$, $YDOT$, and $ZDOT$ are the velocity vectors.

Table 1. The accuracy comparison between the two cases. Difference in the values of the sample case provided in Spacetrack Report No. 3 and the results of the Matlab model. The output is given at 360-min intervals in km and minutes.

This table reveals differences in the predicted values in the order of 10^{-7} and 10^{-8} in the position vectors (in kilometers)

and the velocity vectors (in kilometers per minute), respectively. These small errors could be due to the change in various constants in the past, improvement of the prediction model, or changes in data quality. Nevertheless, the magnitude of these errors does not affect the prediction performance of the algorithm developed in this study. This result suggests that the magnitude differences of 10^{-7} and 10^{-8} in the position and the velocity vectors, respectively, may not create a considerable difference in the predicted semimajor axis or the inclination.

The MATLAB version of the SGP4 model was downloaded from MathWorks, and it was modified to suit the scope of this study [39]. Each TLE must be propagated separately for each data point or day in the SGP4 model. Hence, MATLAB must be restarted each time a TLE is fed in to the SGP4 model. To reduce the processing time, the model was modified in such a way that an array of days/propagation periods can be fed into the model once to estimate the orbital parameters of the required satellite for a prolonged period. In the two case studies of TOPEX and Envisat, a period of 3 years was propagated at once. The SGP4 model was also modified in such a way that orbital parameters, such as inclination, semimajor axis, right ascension of the ascending node (RAAN), argument of perigee, orbital energy, and eccentricity, are obtained instead of the position and state vectors. A function is created to convert the Cartesian position and velocity parameters of any satellite in orbit into classical orbital elements. This changed model of SGP4 was merged with another algorithm, which directly obtains the value of the orbital parameters, such as inclination, semimajor axis, RAAN, argument of perigee, orbital energy, and eccentricity, directly from the TLE sets that were fed into the modified SGP4 model for the same period. Therefore, in the end, the whole algorithm package will compare the values of the orbital parameters estimated using this changed algorithm with the corresponding values of the orbital parameters observed from the TLEs and provide the maneuvers as a function of time, which forms a peak that represents the sudden change found in the difference between the observed and propagated orbital parameters. This change is identified with the two parameters; the threshold and the window length. Window length is the time span between each of the maneuvers, whereas detection limits are set on the basis of the peaks that represent the sudden change found in the difference between the observed and propagated orbital parameters.

Most active satellites frequently perform only in-plane and out-of-plane maneuvers to change their semimajor axis and inclination, respectively. In-plane maneuvers are responsible for the changes that are brought about in the orbit's shape and size by altering the

semimajor axis; eventually, the orbital energy is also changed in this process. This type of maneuver evinces a sudden change in the mean motion, thereby changing orbital energy. By contrast, out-of-plane maneuvers are responsible for the changes that are brought about by the orientation of the plane by evincing an abrupt change in the inclination. In this study, an algorithm was set to detect sudden changes in the orbital parameters by calculating the difference between the adjacent segments of the orbital parameters propagated by SGP4 and the observed orbital parameters obtained from the TLEs. First, the required TLE data were downloaded from either the Celestrak or the Space Track websites as text files [45,46]. Then, the text files were fed into the algorithm to recover the history of the satellite's orbital parameters. Five observed orbital parameters, comprising semimajor axis, inclination, RAAN, eccentricity, and orbital energy, were extracted. In parallel, the TLE data were also fed into the SGP4 propagator to propagate the estimated orbital parameters, with the first TLE as the starting reference point; then, the parameters were propagated using SGP4 to the time the next TLE was available. The process was repeated until the last available TLE. Similarly, the five corresponding orbital parameters, comprising semimajor axis, inclination, RAAN, eccentricity, and orbital energy, were propagated. Once the two processes were completed, the observed and propagated orbital parameters were compared, and the differences between their respective values were found. **Figure 1** illustrates the approach used to detect a satellite's maneuvers.

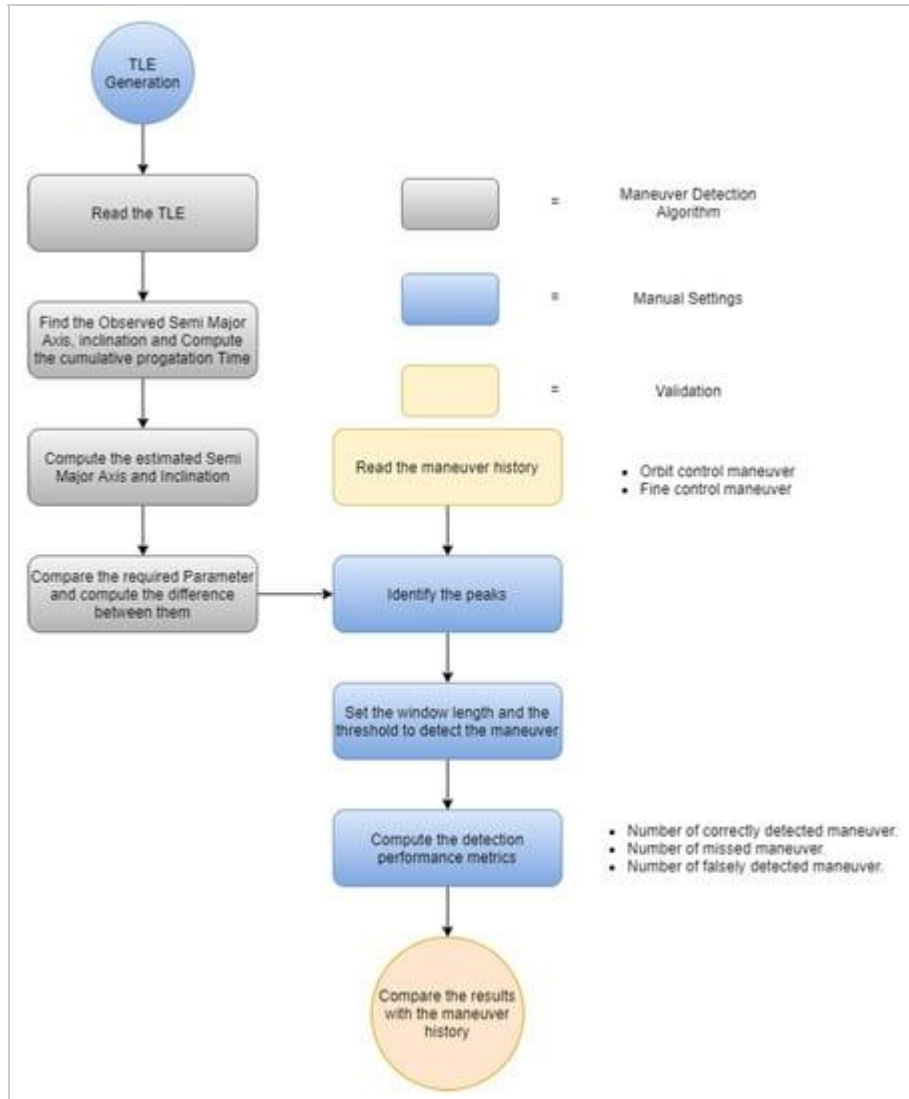


Figure 1. Maneuver detection and analysis algorithm.

Once the differences between the corresponding propagated and observed orbital parameters were found, potential maneuvers were marked when the difference between the adjacent values exceeded a user-specified detection limit. For example, as shown in Figure 2, two potential maneuvers of TOPEX are flagged as red dots when the difference between the adjacent values exceeds a user-specified detection limit, which is represented as a horizontal green line (see Supplement Section 2 for pseudo-code used in this algorithm). The plot is a time function, which forms a peak that represents the sudden change found in the difference between the observed and propagated orbital parameters. The results of the analyses indicate that these peaks correlate with the known maneuvers of the satellite. This study follows the "trial-and-error" method in fine-tuning two parameters (i.e., window length and detection threshold) for each satellite. In this method, before finalizing the perfect values for the two parameters, the values of each parameter were manipulated to find the perfect possibilities of the two parameters that could

result in perfect detection of all the maneuvers. Many factors could affect the results of this algorithm; these factors include the size of the maneuvers, the duration between each TLE data point, the time span of the data, and the gap between adjacent maneuvers. Other factors include the quality of TLE data (e.g., amount of noise in the data and skews derived from the observational and environmental effects). In consideration of the set of TLE data, the performance of the algorithm was evaluated on the basis of two parameters: window length and maneuver detection limit. Window length is the time span between each of the maneuvers, whereas detection limits are set on the basis of the peaks that represent the sudden change found in the difference between the observed and propagated orbital parameters. These parameters offer a way to judge the potentiality and sensitivity of the algorithm to detect a maneuver. This technique and the analysis may not include all discrepancies in all the environmental aspects such as gravitation, the atmosphere, vacuum, micrometeoroids, and debris, but it might be adequate to illustrate the work of the algorithm and the performance evaluation settings.

5. Conclusions

Three years of TOPEX data (i.e., between 1993 and 1995) and Envisat data (i.e., between 2003 and 2005) were studied in this work, proving that the maneuvers of a satellite can be detected by analyzing the variance between the propagated semimajor axis or inclination obtained using SGP4 and the observed semimajor axis or inclination derived using TLE datasets. During this three-year period TOPEX had a total of six in-plane maneuvers while Envisat had a total of nine out-of-plane maneuvers and all the maneuvers were detected successfully. Maneuvers that are even in the range of cm/s could be detected using this technique if the parameters in the algorithm are calibrated properly. In the case studies of TOPEX and Envisat, two types of maneuvers (including fine control maneuvers, which are characterized by in-plane energy maneuvers and orbit control maneuvers, which are characterized by out-of-plane inclination maneuvers) were detected with a detection rate of 100%, even though the last part of the TOPEX data had substantial noise. Along with TOPEX and Envisat, the TLE data of TDRS-3, whose maneuver history is not available, were evaluated using the same method. A total of 19 maneuvers were performed during this period and out of the 19 maneuvers, 18 maneuvers were detected successfully. This was because of an error in the TLE data at that point. The efficiency rate of maneuver detection for TOPEX and Envisat was 100%, while for TDRS-3, which did not have any maneuver data, it was 94.73%. The data quality, density, and maneuver geometry for each satellite vary. **Therefore, no one set of defined parameters could work on all satellites to detect their maneuvers under all conditions.** The window length and detection threshold fed into the algorithm differ for every satellite. However, by analyzing a satellite's semimajor axis or inclination, both the parameters can be optimized in a manner that can predict the maneuvers.