Orbital Anomaly Detection and Application of Space Object

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ABSTRACT

Maneuver, collision, explosion, and sudden change of space weather can lead to an orbital anomaly of a space object. Owners and operators of spacecraft need to be aware when such an anomaly occurs so that mitigation action can be taken. An orbital anomaly detection technique of a low Earth orbit (LEO) object based on historical Two-Line Elements (TLE) data is studied, and a detection technique based on SGP4 model’s secular dispersion is presented. Semi-major axis and inclination are taken as characteristic orbit parameters, parameters’ secular predictions of the last TLE to the current TLE’s epoch are seen as expected values, and the secular parameters of current TLE are practical values. The dispersion between the practical and expected parameter is a criterion of orbit anomaly detection. Outliers in the dispersion data are detected by Mahalanobis distance-based method. The detecting method is implemented and tested on Terra satellite’s historical TLE data, and orbital anomalies are readily detected.

Keywords: Orbital Anomaly; Event Detection; Two Line Elements (TLE)

1、Introduction

It is increasingly important to be aware of space events such as space vehicle maneuvers, explosions, collisions, fragmentations, sudden changes in ballistic coefficients, solar corona mass ejections that impact the Earth, and so on. For example, a severe solar event can affect all low Earth orbit (LEO) satellites. Satellite operators need to be aware when such an event occurs so that mitigation action can be taken. An explosion could generate space debris that could cause collision risk to operational satellites.

The importance of spacecraft maneuvers in the Low Earth orbit (LEO) altitude region led to recent research on LEO maneuver detection. Patera[1] proposed a method to detect space events based on the Moving Window Curve Fit (MWCF) technique. Swartz[2] presented a method based on the Space Incident Flagging Technique (SIFT). Kelecy[3][4] advanced a satellite maneuver detection method using Two-line Element (TLE) data, and then analyzes the limitations of deriving satellite maneuver information from historical TLE data. Unfortunately, a systematic means of detecting
various kinds of space events based on orbital anomalies is currently not widely available. Most of the above researchers analyzed the spacecraft maneuver detection problem with just pure mathematical techniques, but not from the perspectives of the orbital characteristics and motion laws.

This paper presents a detection method based on the SGP4 secular model and Mahalanobis distance. The accuracy and effect of this method are validated through the comparison with the MWCF method.

2. Moving Window Curve Fit Method

The moving window curve fit method is an effective space events detection method proposed by Patera. The MWCF method consists of the following steps:

a. To fit the historical characteristic orbital parameters using a polynomial by the Least Square method, the size of the moving window should be chosen carefully.

\[
p(t) = c_3 t^3 + c_2 t^2 + c_1 t + c_0
\]  

(1)

The dispersion data could be gained by differencing between the practical parameter and the parameter derived from curve fitting.

b. Once the dispersion data is obtained, the mean, variance and standard deviations are computed.

c. If dispersion data exceeds a predefined threshold, an event is declared for that data point. The standard deviation threshold is defined in units of its standard deviation. Figure 1 illustrates the moving window curve fit method.

![Figure 1. The moving window curve fit method](image)

Another method to detect changes in a parameter is to evaluate the derivative of the polynomial curve fit at some time within the window. If a parameter, such as energy, has a step increase at the midpoint of the window, the derivative of the curve fit method indicates a sharp increase at that point. The derivative of the polynomial in Eq.(2) is given by

\[
\frac{dp(t)}{dt} = 3c_3 t^2 + 2c_2 t + c_1
\]  

(2)

3. Detection Method Based on the SGP4 Secular Model

The state vector of the satellite can be predicted by Two Line Element sets with the SGP4 model. The change of orbital elements is smooth and continuous in normal situations. Maneuvers, collisions, explosions, and sudden changes of space weather can lead to an orbital elements anomaly of the satellite. According to the differences
between the normal and abnormal situation, this method provides a useful measure to detect space events of the satellite.

The detailed steps of the LEO satellite space event detection method are as follows:

a. Select the characteristic orbit parameters which can represent the satellite orbit anomaly. For LEO satellites, the semi-major axis and inclination are taken as characteristic orbit parameters, which can reflect the orbital anomaly of in plane and out of plane.

b. Generate the dispersion data based on the SGP4 secular model. Dispersion data are the foundation of an accurate anomaly detection. The precision of dispersion data will directly affect the correctness of the detection result. The basic method is as follows. The predicted parameters of the last TLE to current TLE’s epoch with the SGP4 secular model are taken as expected values, and the secular parameters of the current TLE are taken as practical values. Then we can get the absolute dispersion at the current epoch.

\[
p_{i} - p_{i-1} = \frac{dp}{dt} (t_i - t_{i-1})
\]

A sequence of relative dispersion, which includes the epoch and parameter change rate, is obtained by the method.

\[
\left\{ t_k, \left( \frac{\Delta a}{\Delta t} \right)_k, \left( \frac{\Delta i}{\Delta t} \right)_k \right\}, \quad k = 1, 2, \ldots, n
\]

c. Anomaly detection based on Mahalanobis distance.

When different dimensions, which represent different kinds, or magnitudes, vary widely between different dimensions, the contribution of the dimension, where the magnitude is small, may be covered in a multidimensional anomaly detection. Mahalanobis distance is imported for avoiding this problem. Mahalanobis distance describes the closeness between two quantities by disposing these data with a weighting process. We assume that the mean of the population is \( \mu \), and the
covariance matrix of the population is $\Sigma > 0$. $r_i$ is a sample vector in the population.

Then the Mahalanobis distance from $r_i$ to the population is computed by the following formula

$$d_M (r_i, \mu) = \sqrt{(r_i - \mu)^T \Sigma^{-1} (r_i - \mu)} \quad (5)$$

The mean of the population $\mu$ and the covariance matrix of population $\Sigma$ are unknown in anomaly analysis of relative dispersion. The $\mu$ and the $\Sigma$ can be replaced by their unbiased estimation sample mean $\bar{r}$ and sample covariance matrix $C$, then we can get the Mahalanobis distance.

$$\bar{r} = \frac{1}{n} \sum_{i=1}^n r_i \quad (6)$$

$$C = \frac{1}{n-1} \sum_{i=1}^n (r_i - \bar{r})(r_i - \bar{r})^T \quad (7)$$

$$d_M^{(i)} = d_M (r_i, \bar{r}) = \sqrt{(r_i - \bar{r})^T C^{-1} (r_i - \bar{r})} \quad (8)$$

The Mahalanobis distance substantially describes the departure level from the sample to the distribution center, which considers the probability distribution of the population. The bigger Mahalanobis distance indicates the less generable probability of this sample.

The determination of the detection threshold ($d_M$) is complicated. We can choose a threshold according to the different precisions of detection. The magnitude of $d_M$ is generally 3 or 5, and the relative dispersion data can be detected through this threshold. It is considered as an orbital anomaly, if the Mahalanobis distance is bigger than $d_M$.

4. Comparison Between the MWCF Method and the SGP4 Secular Forecast Method

In order to compare the results between these two methods, the Terra satellite is set as an example. This satellite has executed six orbit maneuvers, including three altitude keeping maneuvers and three inclination maneuvers in 2010.
Figure 3. Terra’s results of detection calculated by MWCF method

Figure 4. Two-dimensional distributing of Terra’s dispersion calculated by MWCF method
Figure 5. Terra’s detection results calculated by SGP4 Secular Forecast method and the black lines represent the known maneuvers.

Figure 6. Two-dimensional distributing of Terra’s dispersion calculated by SGP4 Secular Forecast method

Comparing the above results, the accuracy of these two methods are almost the same. Their advantages and disadvantage can be summarized as follows.

The moving window technique filters noise and permits processing of time varying data. The method does not involve state vector propagation and is very computationally efficient. However, larger window sizes require higher order polynomial curve fits to capture the expected variation of the parameter. It is difficult to identify the window sizes, and the curve should not be extrapolated beyond the window.

The SGP4 Secular Forecast method is based on the orbital characteristics of the satellite, rather than a single mathematical method, and it can give the physical explanation about the anomaly. This method provides a new thought to solve the problem by analyzing the orbital laws of physics. However, this method is based on
an accurate physical model and high precision in the calculation.

5、Anomaly Situation

For a LEO satellite, the semi-major axis should decrease without control as a result of atmospheric drag. A strange phenomenon that the semi-major axis of ROCSAT-2 is increasing appeared during research, and most altitude keeping maneuvers are used to reduce the satellite’s orbit altitude. The reason is unknown until now!

![Figure 7. Anomaly change of ROCSAT-2’s semi-major axis](image)

6、Further Research

The probability of a missed alarm and the probability of a false alarm can be used to evaluate the detection method of space events, but their basic concepts and relationship need further analysis.

Although the probability of a missed alarm and the probability of a false alarm are contrary in math, a novel method, which can balance these two factors, should be studied by analyzing the orbital laws of physics

Reference