A Method for Improving Two-line Element Outlier Detection Based on a Consistency Check

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Abstract

As the most complete source of orbital element information available to the public, the NORAD two-line element sets (TLEs) are used in a wide variety of orbit propagation tasks. Unfortunately, there is no error information provided for the TLEs. Due to orbit manoeuvres, errors introduced during the TLE generation and unmodelled perturbations, there are inevitable outliers in the TLEs, which have a large deteriorative impact on orbit determination and propagation. Most of current methods identify outliers using a three-sigma rule or a Mahalanobis distance-based detection method. However, in these methods the perturbation characteristics of space objects in different altitudes are not taken into account. This study presents a method for detecting outliers in the TLEs of space objects based on a consistency check on pair-wise differential residuals of a series of TLEs. A filter based on the principle of locally weighted regression is applied on the pair-wise differential residuals to investigate their underlying structure. The detection threshold is then determined by the variance in a moving window running over the filtered residuals.

Satellites from different altitudes with known manoeuvre histories were selected as examples to demonstrate the effectiveness of the proposed method. Our results show that reliable detection of the manoeuvre events can be achieved. The differences in the characteristics of TLE outliers between satellites and debris objects are also analysed to facilitate the application of the satellite-based method to debris to identify erroneous TLEs. It is expected that the improvement made by the new method will contribute to more robust orbit propagation and conjunction analysis that are based on TLEs.

1. Introduction

The most complete and publicly available source of orbital element information is the Two-line Element (TLE) catalogue generated by the US Air Force using radar and optical tracking data from its Space Surveillance Network (available at www.space-track.org). Unfortunately, there is no error information provided for the TLEs and therefore no measure for the data quality. Due to orbital manoeuvres, errors introduced during the TLE generation and unmodelled perturbations, outliers in the TLEs inevitably exist, which will largely deteriorate orbit determination and propagation results.

The outliers of the TLE data were proven to lead to erroneous results in TLE applications such as the deriving of thermospheric density from the TLEs [1], determination of spacecraft position and velocity information [5], and assessment of the accuracy of the TLE data [4]. Most of the current methods identify outliers using the three-sigma rule or a Mahalanobis distance-based detection method [3&4]. However, the characteristics in the perturbation of space objects at different altitudes are not taken into account in these methods. This result in misdetection and this is also the reason for the use of those methods that are for space event detection.

In the last decade a number of methods for space events detection from TLE time series have been proposed by several research groups. Generally, these techniques can be divided into two groups. The first group applies statistical methods by comparing the current TLE series against its historical data [8&9]. The second group uses state vector propagation to determine whether an ephemeris is the natural evolution of a previous one [10].

This paper presents a method based on a TLE consistency check (TCC) on pair-wise differential residuals of a series of TLEs for detecting outliers in the TLEs of space objects. A filter based on the principle of locally weighted regression is applied on the pair-wise differential residuals to investigate their underlying structure. The detection threshold is then determined by the variance in a moving window running over the filtered residuals. The detection threshold is specified in units of standard deviation. The moving window method serves to remove small variations due to noise. In this manner, those large deviations indicative of outliers in the data series can be identified. This method is tested on several satellites with known manoeuvre events since the pair-wising differential residuals of TLE from manoeuvre events are similar with that of true outliers of space objects.

2. Outlier Detection Methods

The core idea behind the TCC algorithm is that when an object is free from any non-natural disturbance, propagating a TLE of an object to the following TLE of the series should be consistent, i.e., the spatial difference between the propagated state and the following published state should have a good agreement. The spatial difference/residual can be in any coordinate systems. In this study the Earth Centred Fixed (ECF) coordinate system is adopted. In basic pair-wise differencing, the residual is the difference between the propagated state vector S_j and its counterpart published state vector S_k, where S_j is propagated from the time interval $\Delta t = t_k .- t_j$. The residual ΔS can be expressed as

$$\Delta S = S_j - S_k \tag{2-1}$$

ΔS is defined as the spatial difference hereafter and it is 3-dimentional. Fig. 1 gives an example for the pair-wise differential residuals of the International Space Station (ISS) in 2012.

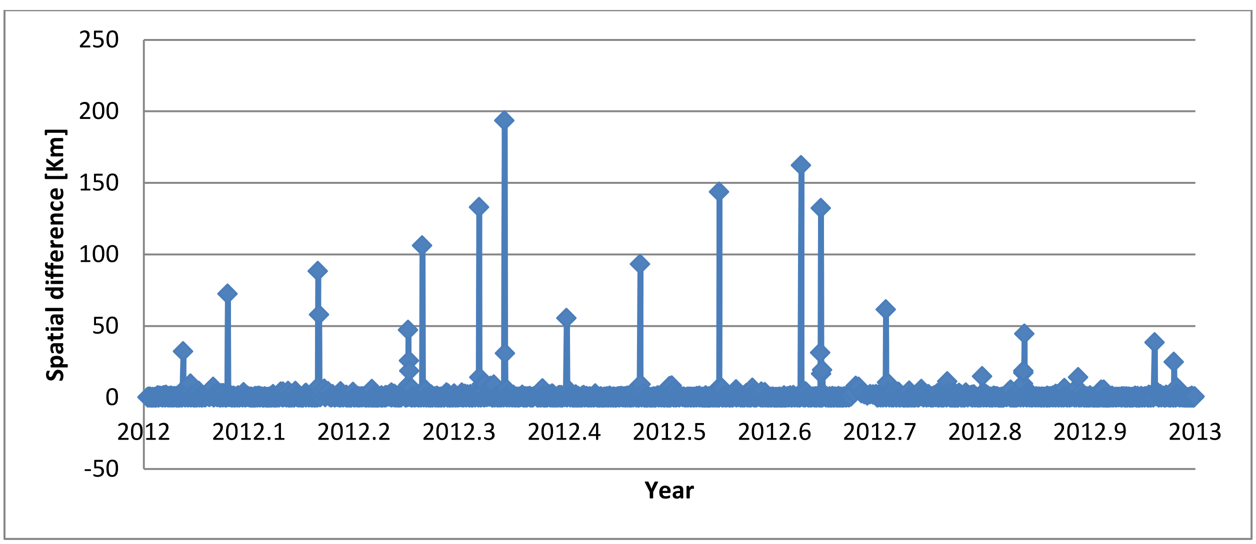

Fig. 1 Example of the TCC spatial deference of the International Space Station in 2012.

Since the residual series can be very noisy and thus to be difficult to interpret directly. The raw ΔS time series is usually filtered for uncovering its underlying structure.

Let the filtered time series be ΔS'. A filter based on the principle of locally weighted regression, called LOWESS, is applied to generate the ΔS' time series. The LOWESS filtering routine runs a moving window over the ΔS time series and generating a data point for ΔS' by a weighted least-square fitting of a second degree polynomial to the data in the window and retaining the value of the fit at the center of the window. The length of the moving window can be up to a few times the period TLEs need to converge to a new stable orbit after a space event is finished. This, in turn, drives the need for a higher-order polynomial for fitting the nonlinear behavior introduced by manoeuvres. However, a higher-order polynomial leads to over fitting of the noisy data, which may introduce artificial harmonic periods in the fitted data. In general, a second degree polynomial is sufficient.

The traditional weight function used for LOWESS is the tri-cube weight function. The weight $\omega(x)$ given to any data point in the moving window is computed as:

$$\omega(x) = \begin{cases} (1-|x|^3)^3 & for[|x|<1] \\ 0 & for[|x|\geq 1] \end{cases} \tag{2-2}$$

Once the data are filtered, the technique of detecting outliers based on thresholds is applied. The thresholds are calculated by the standard deviations of the sample in the moving window. A moving window runs over the ΔS' time series and stores the values of the sample mean and variance with the timestamp of the centre of the window. The window size can be large, so that the outliers will not significantly affect the statistics.

3. Result and Analysis

A. Manoeuvre Detection Examples

We selected the ISS as an example. The ISS maintains an orbit with an altitude of between 330 and 435 km (205 and 270 mi) by means of reboost manoeuvres using the engines of the Zvezda module or visiting spacecraft. It completes 15.54 orbits per day.

Fig. 2 illustrates manoeuvre detection for the ISS in 2012 in comparison with the known manoeuvres. The known manoeuvre data was downloaded from the International Laser Ranging Service. The red dots are the pair-wise differential residuals of the ISS TLE, the blue dots are the manoeuvre time, and the green dots are the detected manoeuvre time point.

The threshold was set to three-sigma and most of the manoeuvres were successfully detected, although one missed and 5 falsely detected. If the threshold were lowered, more events would be identified. However, lower threshold would result in either too many false detections or less significant events.

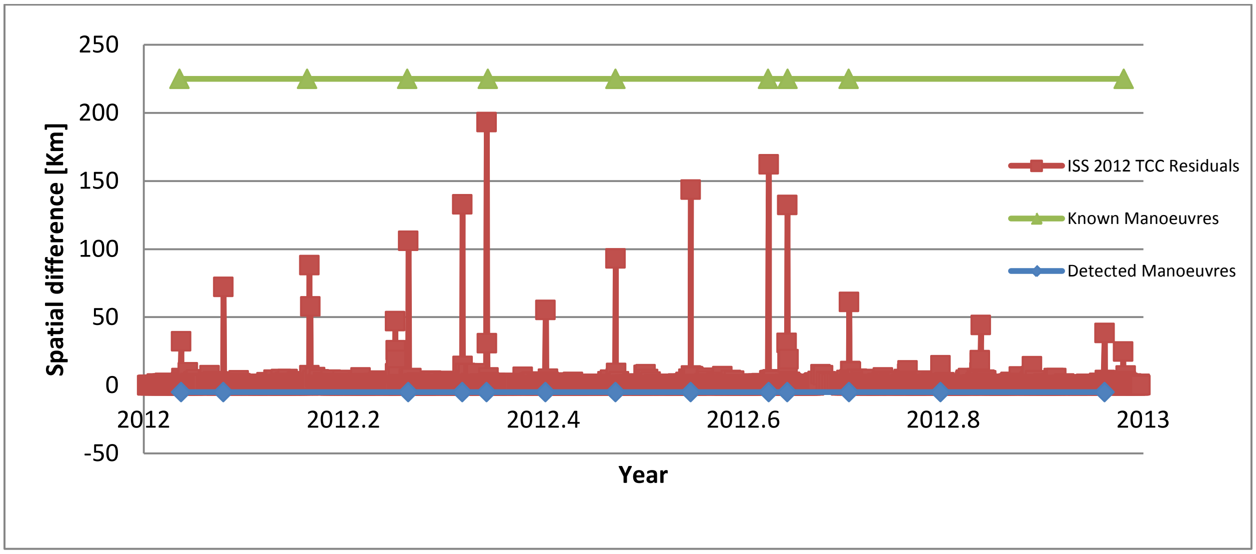

Fig. 2 Comparison of detected manoeuvres and known manoeuvres of ISS in 2012

Envisat ("Environmental Satellite") is an inoperative Earth-observing satellite still in orbit. It was launched into a Sun synchronous polar orbit at an altitude of 790 km (490 mi) (± 10 km (6.2 mi)). It orbits the Earth in about 101 minutes with a repeat cycle of 35 days.

Fig. 3 illustrates manoeuvre detection results for the Envisat satellite in 2002. The threshold was set to 2.5-sigma and only half the manoeuvres were successfully detected. This may result from the fact that some of the manoeuvres were attitude manoeuvres, and our method is more suitable to detect those manoeuvres that causes change in position.

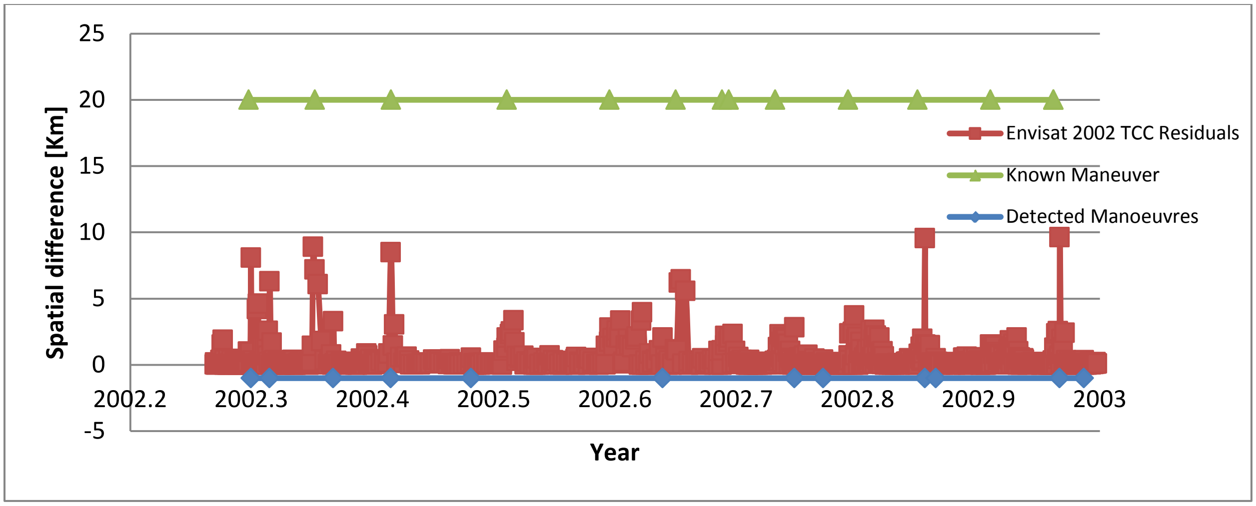

Fig. 3 Comparison of detected manoeuvres and known manoeuvres of Envisat in 2002

B. Outlier Detection on Debris

To test the effectiveness of the proposed method for outlier detection, we selected debris DEB33666 as an example, and the threshold was set to two-sigma.

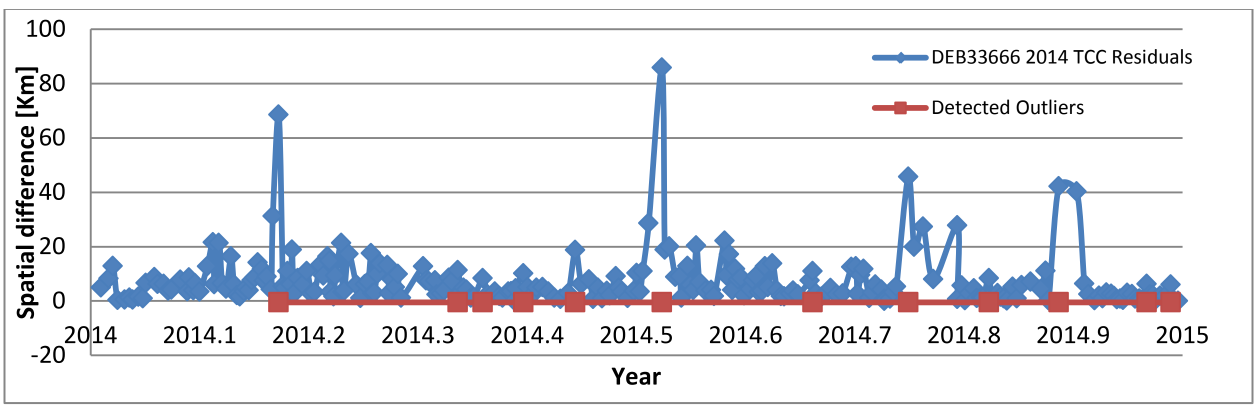

Fig. 4 Filtered differential residuals and detected outliers of DEB33666 in 2014

This example illustrates that the method proposed in this study works well in detecting outliers in the TLE series of debris. Since the debris cannot be manoeuvred, so the results can hardly be validated using the method for manoeuvrable satellites.

Comparing the TCC residuals of DEB33666 and the Envisat, we found that the consistency between adjacent TLEs of the debris is not as stable as the satellite. We also found that the update frequency of debris can be lower than satellites, thus the residuals can be larger when there are long time gaps between consecutive TLEs. To deal with this, the algorithm will restart when a time gap is greater than the average TLE update time plus three times the standard deviation.

4. Summary and Conclusions

This paper presents a method for detecting outliers in the TLEs of space objects based on a TLE consistency check (TCC) on pair-wise differential residuals of a series of TLEs. The TCC method detects space events and outliers by comparing a published state of an object with a propagated state and analysing the spatial difference between them. The threshold is determined by the standard deviation of the differential residuals of spatial position in a moving window of the same object. The advantage of using the moving window technique to determine the threshold is that sudden changes in the differential residuals can be identified and then considered in the detection. The test results indicate that this method is effective. Future work will focus on applying this method to some TLE applications and assessing improvement made by the use of this method.

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