STARLINK SATELLITE CLASSIFICATION AND ORBIT MANEUVER DETECTION

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ABSTRACT

In recent years, with the deployment of mega-constellations in low Earth orbit (LEO), the collision risk of LEO satellites has rapidly increased. Constellation satellites have strong maneuver ability. Usually, satellites in the working phase will perform irregular maneuvers to compensate for the influence of atmospheric drag and maintain the constellation configuration. Especially in the event of extreme space weather events, the frequency and amplitude of maneuvers will also increase accordingly; In addition, satellites sometimes maneuver to meet specific mission requirements. By analyzing the orbital parameter changes of constellation satellites, maneuver events can be detected and identified in a timely manner.

In this paper, first the clustering analysis method is used to classify Starlink satellites, then the segmented optimization method is used to detect satellite orbit anomalies. Two typical examples were chosen, one happened in May and June 2022, and the other happened in May 2024 during the space weather event. The results indicate that the classification and anomaly detection methods proposed in this paper are effective.

1 INTRODUCTION

The Starlink plan was announced by the founder of SpaceX in 2015. It plans to build a "Starlink" network consisting of about 42000 satellites in space to provide Internet services. According to the US Space Surveillance Network, as of January 8, 2025, SpaceX has successfully launched 222 batches of Starlink satellites, with a total number of 8038 launched and 7677 in orbit.

The entire mission process of Starlink satellite involves different stages such as orbit insertion, climb, operation, and deorbit. The satellite has strong electric propulsion capability and can continuously propel the satellite to meet the orbit change requirements of different mission stages. The satellites in the working stage are mainly used to compensate for atmospheric drag for the configuration maintenance. When encountering extreme space weather events, the amplitude and frequency of maneuver will also increase significantly, and maneuver events can be identified through abnormal changes in orbit parameters. Therefore, timely detection of their orbital anomalies is of great significance. By analyzing the changes in orbital parameters of constellation satellites, maneuver events can be detected and identified in a timely manner.

When a large number of Starlink satellites encounter extreme space weather events, satellites in different orbits will have different maneuver strategies. At the same time, during the execution of tasks, Starlink satellites will perform frequent maneuvers to complete the mission, but it is difficult to detect them solely by detecting the maneuvers of one or a few satellites. It is necessary to perform maneuver detection on a large number of Starlink satellites and conduct maneuver characteristic statistics. However, a large amount of Starlink satellite data is complex and varies greatly due to the maneuver situation of satellites at different stages. Data needs to be clustered to group similar data into one category. Clustering, as a typical unsupervised learning algorithm, focuses on classifying samples based on their similarity. Due to the different forms of satellite TLE data at different stages, and the fact that satellite TLE data is not in equal time series, clustering has become difficult. The main difficulty lies in the calculation of similarity metrics, although there are many calculation methods for similarity metrics, they all require data consistency. To solve this problem, the Dynamic Time Warping (DTW) algorithm can be chosen to calculate similarity.

On the basis of satellite clustering analysis, the next step is to perform maneuver detection on satellites. This paper adopts an improved orbit anomaly analysis method based on the semi-major axis data of the orbit—the segmented optimization method. This method is based on the idea of dynamic optimization. It randomly segments the semi-major axis data within a time window, a loss function is constructed based on the variance of each segment, and the value of the total loss function is used as the criterion to obtain the distribution of segmentation points that minimize the total loss function through optimization iteration. The segmentation points obtained are the detected anomaly points.

On the basis of the satellite classification and anomaly detection methods, the Starlink constellation is analysed in this paper. Firstly, the DTW algorithm is used to classify the Starlink satellites, and then the segmented

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optimization method is used to detect orbit anomalies or maneuvers of the satellites. Then, two typical examples were analyzed, one was the frequent maneuver events of Starlink satellites in May and June 2022, and the other was the abnormal satellite maneuver during the space weather event in May 2024.

2 ANALYSIS METHOD

2.1 Cluster analysis method

Clustering is an unsupervised learning method that divides a dataset into different classes according to a certain criterion, minimizing intra class differences and maximizing inter class differences. Due to the uneven and unequal distribution of TLE (Two line element) data, traditional clustering algorithms based on Euclidean distance can not be directly applied. This paper chooses the clustering analysis method of dynamic time programming to calculate similarity measurement. Based on the shape of the data, clustering is performed, and satellites with similar orbital changes are grouped together according to the shape similarity of TLE data.

Dynamic Time Warping (DTW) is a commonly used method for calculating temporal similarity. It is based on the idea of Dynamic Programming (DP) and adopts a "one to many" alignment strategy during matching. It uses local optimization to find a curved path that minimizes the distance and maximizes the similarity between two sets of TLE data on this path. A constrained path is found from the matrix through the state transition equation to minimize the cumulative sum of elements on the path, and this cumulative sum is used as the similarity measure between two TLE sequences.

$$DTW(X_A, X_B) = \min_p \sum_{k=1}^{K} D(p_k) \qquad (1)$$

X_A and X_B are the TLE time series of two satellites, and $D(p_k)$ represents the distance of the curved path.

For the convenience of defining and selecting categories, hierarchical clustering is chosen for clustering. There are various methods for calculating inter cluster distances in hierarchical clustering, such as minimum distance, maximum distance, class average distance, centroid distance, and inner squared distance.

The minimum distance method takes the distance between the two nearest data points i and j in class r and class s as the distance between the two classes. The minimum distance is:

$$L_{rs} = min\left(D(S_{ri}, S_{sj})\right) \qquad (2)$$

$S_{ri}$and S_{sj}represent points i in class r and points j in class s, respectively; D (·) represents the distance function, which calculates the distance between two points. The maximum distance method takes the distance between the two farthest data points i and j in class r and class s as the distance between the two classes. The maximum distance is:

$$L_{rs} = max\left(D(S_{ri}, S_{sj})\right) \qquad (3)$$

The class average distance method takes the average of the sum of distances between any two points in class r and class s as the distance between two clusters. The distance is expressed as:

$$L_{rs} = \frac{1}{n_r n_s} \sum_{i=1}^{n_r} \sum_{j=1}^{n_s} D\left(S_{ri}, S_{sj}\right) \qquad (4)$$

Of which, n_r and $n_s$are the number of data points in class r and class s, respectively.

The centroid distance method takes the average value of class r and class s as the center point, and takes the distance between these two means as the distance between the two classes. The centroid distance is expressed as:

$$L_{rs} = D\left(\frac{1}{n_r}\sum_{i=1}^{n_r} S_{ri}, \frac{1}{n_r}\sum_{j=1}^{n_s} S_{sj}\right) \qquad (5)$$

The inner squared distance method takes into account the data points contained in each class and merges the pair of clusters with the smallest distance between them.

In order to evaluate which distance calculation method is suitable for clustering, it is necessary to evaluate the similarity coefficient of clustering effects under different clustering methods. This similarity coefficient can measure how clustering accurately represents the differences between observed values. Therefore, the closer the value is to 1, the more suitable the calculation method is for this clustering. The formula for calculating the corresponding similarity coefficient is as follows:

$$c_{rs} = \frac{\sum_{i<j}(D_{ij}-d)(Z_{ij}-z)}{\sqrt{\sum_{i<j}(D_{ij}-d)^2 \sum_{i<j}(Z_{ij}-z)^2}} \qquad (6)$$

$D_{ij}$is the distance between data i and data j, Z_{ij} is the same phenotype distance between data i and data j (also known as clustering distance, representing the distance corresponding to the common nodes of two objects on the clustering tree), d and z are the average values of D and Z, respectively.

2.2 Anomaly detection methods

There are some analysis methods on anomaly detection. This paper mainly considers anomaly detection based on changes in the semi-major axis, and the segmented optimization method is chosen. The segmented optimization method follows the basic idea of the semi-major axis change statistical analysis method, using the semi-major axis differential data as the anomaly analysis parameter. This method does not rely on the historical data, but segments the data based on assumed anomaly points, a loss function is defined, the loss function of each segment and their sum are calculated, and then the optimization search to minimize the loss function is performed and the anomaly points iteratively are determined. By this method, the anomaly detection can be transformed into an optimization problem. This method relies on setting a threshold that is related to the orbit of the satellite and can be calculated using the historical data or satellite data with the same inclination and altitude to obtain an appropriate threshold.

3 TWO ORBITAL MANEUVER EVENTS ANALYSIS OF STARLINK

3.1 Maneuver detection of Starlink in May-June 2022

3.1.1 Data classification results

Most of the Starlink satellites are in work orbits above 500km, so we mainly extract data above 500km from April to June 2022. The hierarchical clustering based on dynamic time programming are used to classify Starlink satellites. The similarity coefficients are calculated for the five distance methods proposed in Section 2, and the class average distance method is selected with the highest similarity coefficient for the first clustering analysis; Further the centroid distance method is used for the second clustering analysis. After the second clustering, the orbit change characteristics of different classified satellites during the three-month analysis period are shown in Figure 1. From Figure 1, the second and fourth class of satellites with a larger sample size are selected for analysis. These two class of satellites are basically in work orbits near 550km altitude.

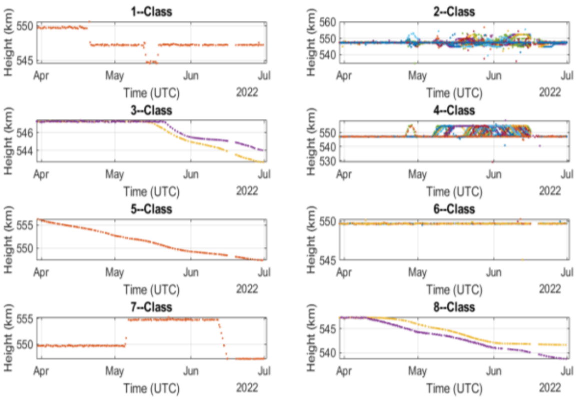

Figure 1. The second classification results of Starlink satellites based on DTW method

3.1.2 Maneuver detection with the segmented optimization method

Based on the results obtained from cluster analysis, the segmented optimization detection method was used to detect orbit anomalies for the 2 and 4 class of satellites, and orbit anomaly of satellites was detected within these three months.

According to the classification results in the previous section, Starlink satellites are divided into two groups. A represents the second class of satellite, with a total of 1461 satellites. B represents the fourth class of satellite, with a total of 185 satellites. See Table 1.

Table 1. Three group numbers of the detected satellites

Class	A	B
Satellite Numbers	1276	85

Three sets of detection results were obtained with the segmented optimization methods to detect abnormal changes in these three groups of satellites. The number of abnormal points detected by each group each month is shown in Table 2. From the table, it can be seen that the number of maneuvers from May to June 2023 has significantly increased compared to April, with the number more than doubling.

Table 2. Number of Anomalous Points for Starlink Satellites in different month

Epoch	A	B
April 2023	610	138
May 2023	1277	373
June 2023	1233	384

According to the anomaly detection results, further statistics were conducted on the changes in the frequency and amplitude of three sets of abnormal changes over time. The statistical results are shown in Figure 2. According to the results in Figure 2, it can be seen that the orbital anomaly frequency in May and June is more frequent and the anomaly amplitude is greater than that in April. It is inferred that the Starlink satellite underwent a large-scale small maneuver between May and June 2022. From the figure, it can be seen that the satellite began orbit adjustment at the end of April and resumed its original orbit in mid June. During this period, there were no significant changes in the space environment. It is speculated that the Starlink satellite's orbit adjustment might be for some specific mission.

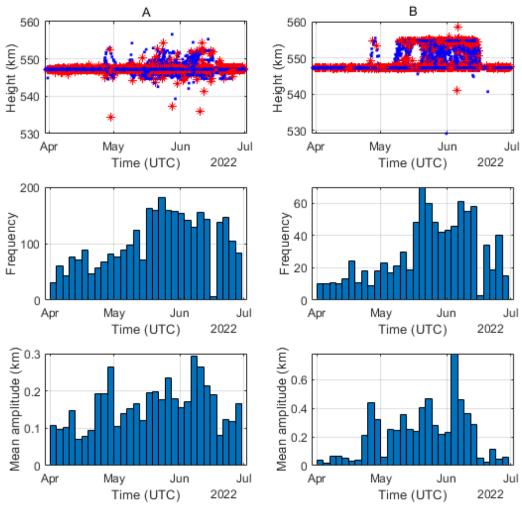

Figure 2. Maneuver detection results of Starlink satellites based on DTW method

3.2 3Maneuver Detection of Starlink Satellite in May 2024

At 4:24 on May 8, 2024 UTC, the Sun erupted an X1.0 class X flare, accompanied by a coronal mass ejection (CME). And from May 10-12, 2024, there was a strong disturbance in the geomagnetic field, with a total of 18 hours of Kp index reaching the strongest red alert level (Kp=9), 15 hours reaching the level of geomagnetic storm (Kp=7,8), and on the 11th, the Ap index reached 273 and the geomagnetic Dst index reached -412nt. On February 3, 2022, only 11 of SpaceX's 36th batch of 49 Starlink satellites entered working orbit during a small geomagnetic storm on February 4, and the remaining 38 decayed. So what impact will this geomagnetic storm event have on Starlink satellites?This section analyzes the orbital changes of Starlink satellites caused by this incident.

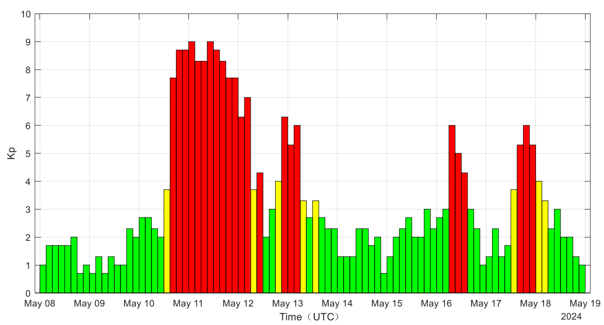

Figure 3. Changes in Kp Index in May 2024

3.2.1 Data classification results

Extracting TLE orbit data of Starlink satellites in May 2024, the dynamic time programming method is first used to classify Starlink satellites. The corresponding correlation coefficients for the five clustering methods are calculated,. the centroid distance method for clustering is chosen which is the most suitable. However, as the TLE data belongs to non monotonic cluster trees, the centroid distance method may not be suitable. Therefore, the maximum distance method is chosen for clustering.

Based on the clustering results of satellites, further the descending orbit changes is removed. the Starlink satellites in the orbit segment are chosen for is chosen for maneuvering detection. These satellites are basically maintained in orbit, grouped according to altitude, and 18 different satellite classifications are given. Figure 4 shows the changes in Starlink at different altitudes from May 3-19, 2024. From the figure, it can be seen that most satellites experienced significant abnormal orbital changes on May 11 and were subsequently maneuvered back into orbit.

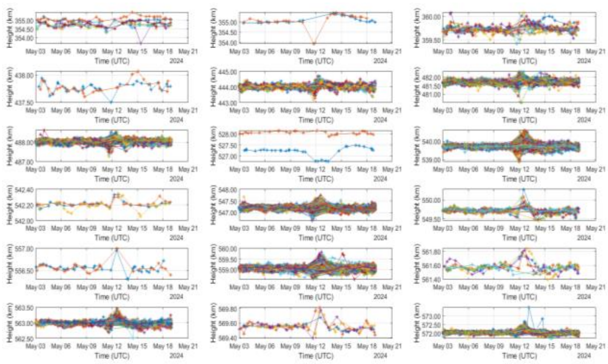

Figure 4. The orbit changes of classified Starlink satellites at different altitudes from May 3-19, 2024

3.2.2 Maneuver detection with the segmented optimization method

On the basis of satellite classification, this section uses the segmented optimization anomaly detection method to detect maneuvers. Figure 5 shows the statistical results of the maneuver frequency. From the figure, it can be seen that during the space weather event on May 11th, the maneuver frequency of satellites showed a significant increase for all analysis altitude. For satellites with an altitude less than 450km, the maneuver frequency increases from 30 to 100 ; For satellites at altitudes of 450-500km, the maneuver frequency increases from around 80 to 180; For satellites with an altitude greater than 500km, they are already in working orbit. In order to maintain their configuration to meet mission requirements, irregular maneuvers need to be performed. The number of maneuvers of the satellite itself is already high, increasing from 800 to 1000 during space weather events. When the satellite orbit is higher, it is relatively less affected by space weather. The satellite's maneuvering frequency did not show a very obvious sudden change, which also indicates that the impact of space weather events on the high altitude satellites on is not significant.

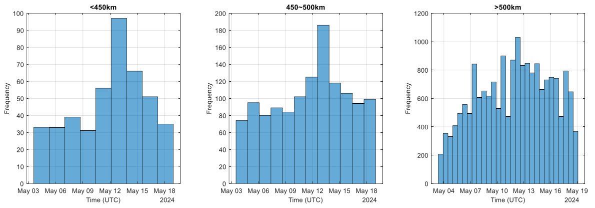

Figure 5. Statistical results of maneuver frequency

The above results of maneuver frequency only show the changes in the number of maneuvers, and Figure 6 provides the statistical results of maneuver amplitude. From the graph, it can be seen that the maneuver amplitude of the satellite began to increase significantly on the evening of May 11th, and it can also be seen that satellites with different orbital heights have different response to the maneuver amplitude of this event. The lower the orbital altitude, the more significant the increase in maneuver amplitude, which also indicates that the satellite's maneuver on May 11th was to cope with the abnormal decay of the satellite orbit caused by space weather events. The higher the altitude, the greater the decay amplitude, and the greater the maneuver amplitude required to compensate for atmospheric drag.

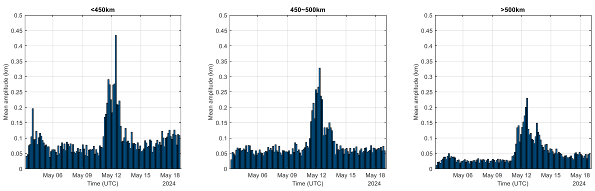

Figure 6. Statistical Results of Maneuver Amplitude

4 SUMMARY

In order to analyze the maneuver characteristics of a large number of Starlink satellites and their responses to space weather events, this paper uses hierarchical clustering based on dynamic time planning, combines the orbital height distribution of Starlink, classifies satellites based on TLEs orbital data, and further the segmented optimization method is used to detect orbital maneuver. According to the statistics of the detection results, the maneuver amplitude and frequency of satellites are given. The analysis were conducted on two typical cases of satellite maneuver on Starlink. One was the frequent maneuver in May and June 2022, and the other was the satellite anomaly caused by space weather events in May 2024.

Based on satellite clustering analysis, the anomaly points of orbit changes were identified, and the frequency and amplitude of maneuvers were given for the May and June 2002 event. The satellite returned to its original orbit after maneuver, and there were no abnormal changes in the space environment during this period. Analysis suggests that the orbit adjustment may have been caused by the mission requirements of Starlink.

The space weather event on May 11, 2024 led to a rapid descent of satellite orbits. In order to maintain the orbits, a large number of Starlink satellites performed orbital maneuvers to cope with the rapid decay of their orbits caused by this event, quickly returning to their original orbits. Combined with changes in space environment parameters, it can be seen that the detection results are reliable. The amplitude and frequency of maneuvers began to increase on May 11, when environmental parameters suddenly changed, and it can be seen that the satellites orbits in the lower height are more sensitive to changes in the space environment. After the start of a geomagnetic storm, the satellite's orbit rapidly descends for about 0.5 days and then rises. It continues to rise for about 1 day before descending and returning to its task orbit. The time when it stops rising is very close to the end time of geomagnetic activity. The results indicate that the clustering analysis and anomaly detection methods proposed in this paper are effective.

5 REFERENCES

1.https://www.space-track.org

2.Cao,J.F.(2024).Orbit Anomaly Detection Technology Based on Segmentation Optimization. Chin.J.Space Sci.44(5):917-927.

3.Wang R.L.(2014). An orbital anomaly analysis method based on TLE data. Chin.J.Space Sci. 34(2): 208-213.