RCS Historical Data Screening Method Based on Spatial Observation Geometric Relationship

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Abstract. Selecting accurate Radar Cross Section (RCS) sequence historical data has an important impact on RCS-based spatial target attitude anomaly detection. RCS is related to factors such as satellite shape size, attitude and radar observation angle, and is a sensitive function of observation angle variation. In this paper, the influence of spatial observation geometric relationship on spatial target RCS sequence is analysed. Aiming at the orbital regression characteristics unique to spatial targets, a spatial target RCS historical data screening method based on dynamic time programming (DTW) distance is proposed. According to the relationship between the azimuth and the elevation angles of the radar line of sight, the orbit data with similar spatial geometry is found from the historical data. The orbital data of the system. This method can reduce the impact of Earth's rotation on data observation and establish a more efficient database. The variational mode decomposition (VMD) of RCS is carried out, and the fractal box dimension of each component is extracted as the data feature, and the BP neural network is used as the classifier for the anomaly detection. The simulation results prove that compared with the traditional historical data collection method, this method can improve the attitude detection rate of space targets and has better robustness.

1. Introduction

Today, satellites play an indispensable role in navigation and positioning, communications and other fields. The anomaly detection of space targets is mainly to quickly analyse the operational status of space targets such as satellites and spacecrafts, to confirm the possible abnormalities of the targets and the causes of the anomalies, and to provide a basis for rescue and emergency re-issue [1], which is an important part of ensuring the normal operation of the satellites. The attitude control mode of satellite can be the basis for judging the working state of the satellite. The literature [2-4] discriminates the attitude pattern of the satellite based on the simulated RCS data, and has achieved certain results. However, the influence of the radar observation angle change on the RCS value is not considered in the experiment. In this paper, based on the change of radar line-of-sight angle, the method of screening RCS historical data under similar spatial geometric relationship based on DTW distance is proposed. The detection process was analysed, and the improvement effect of the method combined with the traditional detection method was compared based on the simulation experiment.

2. Geometric relationship between ground-based monitoring radar and space targets

The RCS value is affected by the radar line of sight. The difference in spatial geometry makes the surface of the radar observation space target different, so that the RCS data obtained by the ground-based radar is different for the same spatial target.
2.1. Spatial geometric observation angle
Define the centroid orbit coordinate system O-XYZ of the space target. The origin of the coordinate system is in the centroid of the space target, the X axis points to the velocity direction, the Z axis points to the zenith direction, and the Y axis is orthogonal to the X and Z axes and satisfies the right-hand rule, which is presented in Figure 1. Under the O-XYZ, define the elevation angle between the radar line of sight and the +Z axis, and the azimuth angle between the projection of the radar line of sight at XOY and the +X axis, which is presented in Figure 2.

![Figure 1. Space target centroid orbit coordinate system.](image)

![Figure 2. Spatial geometric relationship.](image)

2.2. The influence of spatial geometry on RCS
Simulation was conducted to verify the influence of spatial geometry on RCS, and satellites with orbital roots as shown in Table 1 were established in STK software.

| Orbital elements     | The parameter value |
|----------------------|---------------------|
| Semimajor axis       | 7378.14km           |
| Eccentricity         | 0                   |
| Inclination          | 98°                 |
| Argument of periapsis| 120°                |
| Longitude of node    | 110°                |
| Mean anomaly at epoch| 0°                  |

Radar station location set to 29.6° north latitude and longitude 100.5°, observation time is UTCG 00:00:00 on January 1, 2018, 000 and 2018 on February 1, 00:00:00. 000. The trajectory of sub-satellite points is shown in Figure 3. As can be seen from the figure 3, the rotation of the earth causes the deviation of the trajectory of the sub-satellite point, which causes the observation surface of the radar line of sight Angle to change, and the obtained RCS data changes in the numerical value and sequence length, stretching and translation in time and space.

![Figure 3. Sub-satellite trajectory change.](image)

RCS under different observation angles of the same target are compared, as shown in Figure 4.
The traditional anomaly detection method ignores the influence of earth rotation on the RCS data in time and space. The influence can be reduced to a certain extent by screening RCS data with similar spatial geometric relations in historical data.

3. Theory of Dynamic Time Warping

The Dynamic Time Warping (DTW) algorithm was first used in the field of speech recognition. It is an algorithm for calculating distance by dynamic time planning and judging sequence similarity [5]. The similarity between time series is generally judged by calculating distances, such as Euclidean distance and Markov distance [6], but there is a problem that only sequences of the same length can be calculated. The DTW algorithm is generated to deal with the problem of similarity between unequal long time series [7], and it is applicable to calculate the similarity between time series of spatial targets that vary due to the earth rotation.

There are two one-dimensional time series and, whose lengths are n and m respectively. The distance matrix D is calculated.

\[ D_{i,j} = d(x(i), y(j)) \]  

Where, d is called local distance, and Euclidean distance is used in this paper.

The regular path W is used to describe the mapping mode between two sequences.

\[
\begin{align*}
W &= (w_1, w_2, \ldots, w_t) \\
w_t &= d(x(i), y(j))
\end{align*}
\]  

Where, wt is the t element on the structured path W, and the length of the structured path W satisfies \( t \in [\max(n, m), n + m - 1] \).

In addition, the following conditions shall be met for the structured path:

- boundary: the two time series to be tested are corresponding at the beginning and end points, that is, the calculation of W starts from \((x(1), y(1))\) and ends from \((x(n), y(m))\).

- monotonicity and continuity: for the adjacent elements \( w_t = d(x(i), y(j)) \), \( w_{t+1} = d'(x(i'), y(j')) \) in W, which satisfy \( |x(i) - x(i')| \in [0,1] \) and \( |y(j) - y(j')| \in [0,1] \), the distance between any point at any time and the point at the nearest time can only be calculated, and it should be carried out monotonically along the time axis, and the mapping between points at different time points cannot exist intersection.

Under the above conditions, the optimal path should be found so that the minimum value of the sum of the distances is the DTW distance, as shown in Figure 5.
The distance accumulation matrix $S$ is constructed to solve the DTW distance.

$$
\begin{align*}
S(1, 1) &= d(x(1), y(1)) \\
S(i, j) &= d(x(i), y(j)) \min(\{S(i-1, j), S(i, j-1), S(i-1, j-1)\}) 
\end{align*}
$$

(3)

4. Simulation and analysis

4.1. Method of screening RCS

Track parameters are set through STK toolbox, as shown in Table 1. The location of radar station is set at 29.6 degrees north latitude and 100.5 degrees east longitude. The observation time is from 00:00:00.000 on January 1, 2018 to 00:00.000 on February 1, 2018 at UTCG. Because the detection time of each circle of space target to ground station varies, the attitude motion information contained in too short RCS sequence is incomplete, so only RCS sequence whose length is longer than 300s is retained in this paper. The space target assumes a three-axis stable attitude, and the changes of the azimuth angle $a$ and the elevation angle $e$ under the space target centroid coordinate system O-XYZ are deduced from the time series three-dimensional coordinates. The screening process is as follows:

- Establish the historical observation arc database: including RCS sequence set, azimuth data set $a$, and elevation angle data set $e$.
- Measure the current observation target data: including RCS sequence, azimuth angle $a'$ and elevation angle $e'$ of the current observation target.
- Establish the database 2: The DTW distances between the azimuth angle $a'$ of the current observation target and the azimuth angle of each observation arc in the historical data set $a$ are calculated and sorted from small to large. The RCS sequence set arranged in the first $K_1$ historical observation arcs and the high and low angle data set of radar line of sight are selected to form the database 2. $K_1$ is the parameter that determines the size of the database 2.
- Establish the database 3: The DTW distances between the elevation angles of the current observation target $e'$ and the high and low angles of each observation arc in database 2 are calculated and sorted according to the distance from small to large. The RCS sequence sets arranged in the first $K_2$ historical observation arcs are selected to form the database 3. $K_2$ is the parameter that determines the size of the database 3.

The results of DTW distance screening are shown in Figure 6. Through simulation, it can be found that RCS curves observed under similar spatial geometric relationships have high similarity, as shown in Figure 7.
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4.2. Effect validation

4.2.1. Establishing target sample data. Simulation object space target model: A, B, C as shown in Figure 8.

Figure 6. Azimuth, elevation angle before and after screening.

Figure 7. Comparison of RCS in similar spatial geometry.

Figure 8. Spatial target model of the sample.
Simulation of four different motion postures:
- Rotate around Z axis at a rate of 3.5 revs/min.
- Rotate around Z axis at 6.5 revs/min.
- Rotate around Z axis at a rotation rate of 5 revs/min and precession rate of 5 revs/min.
- The Z-axis is aligned with the sky-bottom direction, and the X-axis is constrained by the normal direction of the orbit surface.

The number of orbital elements is shown in Table 1. The location of radar stations is set at 29.6 degrees north latitude and 100.5 degrees east longitude. There are few abnormal data in anomaly detection, so the observation time of three-axis stable attitude is from 00:00:00.000 on January 1, 2018 to 00:00.000 on January 1, 2019 at UTCG. The observation time of three different rotational speed rollover postures is from 00:00:00.000 on January 1, 2018 to 100:00.000 on March 1, 2018 at UTCG. The sampling frequency is 1 Hz, and the minimum height angle of radar observation is 15 degrees. Screening is carried out according to the flow shown in Figure 6. Choose 100 for K1 and 60 for k2.

After screening, the number of three-axis stabilized attitude orbits is 60, and the number of orbits is 27 from the simulated rollover attitude data, which constitute the test set 1 under the similar geometric relationship. In order to ensure that the base of the test set is the same, 60 three-axis stabilized attitude orbits are selected from the simulated data continuously, and nine of the three rollover attitude orbits are selected successively, respectively. The test set 2 under the conventional method is constituted.

4.2.2. Extraction feature. Variational mode decomposition (VMD) is a signal processing method that determines the bandwidth and center frequency of each intrinsic mode function (IMF) by seeking the optimal solution of the variational model and realizes adaptive signal decomposition. Fractal dimension is an important index to measure fractal, which can describe the complexity of signal. Box dimension is widely used because of its simple calculation and high efficiency. RCS is decomposed into variational modes to obtain multiple IMF components, and the box dimensions of each IMF component are obtained as features.

Among them, the initialization mode number $K=8$, penalty factor $\alpha$ and bandwidth $\tau$ use default values: $\alpha=2000$, $\tau=0$ the box edge length is 1024. The box dimensions of $K$ IMF components are calculated and the eigenvectors are formed.

4.2.3. BP Neural Network. The current mature pattern recognition toolbox of MATLAB neural network is used as classifier, in which the dimension of input parameters is used 10, the dimension of output is 1, the number of neurons is 10, the excitation function is sigmoid function, the learning method is elastic gradient descent method, the test set is 50% as training set, 20% as verification set, and 30% as test set. The remaining training parameters are shown in Table 2.

| Parameter name                  | parameter values |
|---------------------------------|------------------|
| Number of training cycles       | 1000 times       |
| Training Accuracy Requirements  | 1e-4             |
| Maximum number of failures      | 6 times          |
| Minimum gradient requirement    | 1e-6             |
| Maximum training time           | Inf              |

Three different roll postures are regarded as abnormalities. The results of abnormal detection are shown in Figure 9.
From the recognition results, it can be seen that the anomaly detection rate of RCS sequence after screening has been improved by 3.4%, 12.5% and 8.1%, respectively. Compared with the training model directly using historical data, the training of model after screening historical data according to the spatial geometric relationship of current observation data has better adaptability, which has practical physical and geometric significance. It has better robustness.
5. Conclusion
The RCS sequences of space targets with different space target models and different attitude motion modes are simulated. The historical data are screened based on the spatial geometry of the current observation data. The results are compared with the conventional methods using continuous historical data training model. The following conclusions can be drawn.

- The observation mechanism of RCS sequence of space target is studied. It is found that the selection of historical data in traditional methods does not take into account the influence of different spatial geometric relations. According to the motion characteristics of space target, a method of selecting historical data based on DTW distance is proposed and verified by simulation experiments. The results show that this method can improve the anomaly detection rate and provide a reference for fast detection of on-orbit target anomalies based on RCS data.
- RCS has a large amount of historical data, which requires more efficient screening methods. DTW algorithm has high complexity and time-consuming in large amount of data. Therefore, it is necessary to optimize the algorithm to improve the computational efficiency. Spatial target motion has regression characteristics. It is also a research direction to improve the efficiency of filtering by clustering the similar spatial geometric relations of historical data or calculating the regression period of spatial target.

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