Space Debris Tracking Data Association Method Based on Time Error Correction and Multi-Feature Joint Decision, Postprint

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Abstract

For the catalog management of large batches of space debris, the correlation matching between wide-area surveillance orbit measurement data and cataloged targets is a prerequisite and key factor. The correlation accuracy rate not only affects normal catalog processing but also influences observation data utilization efficiency and surveillance system effectiveness. This paper proposes a method to improve the correlation accuracy rate of orbit measurement data for large batches of space debris. First, based on the characteristics of orbit prediction errors, a time error parameter estimation and observation residual correction model is established that converts large-scale orbital spatial position errors into small-scale temporal errors. Then, a correlation decision model is constructed based on the joint use of four characteristic quantities: time error parameters (including constant and linear terms), RMSE statistical values of corrected observation residuals, and a correlation value function, along with a correlation decision threshold setting strategy and correlation processing flow. Finally, simulation and measured data verification using electro-optical telescopes (arrays) were conducted, with results showing that the correlation accuracy rate between orbit measurement data and targets using this method can reach approximately 98%.

Full Text

A Track-Catalogue Correlation Method for Space Debris Utilizing Time Error Correction and Multi-Features Joint Judgements

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Abstract

For the catalog management of large batches of space debris, the correlation between wide-area surveillance tracking data and cataloged targets is a prerequisite and key factor. The correlation accuracy not only affects normal cataloging processing but also influences the utilization rate of observation data and the effectiveness of the surveillance system. This paper proposes a method to improve the correlation accuracy of large-batch space debris tracking data. First, based on the characteristics of orbit prediction errors, a model is established to estimate time error parameters and correct observation residuals, transforming large-scale orbital spatial position errors into small-scale time errors. Then, a correlation judgment model is constructed based on a four-feature joint vector including time error parameters (constant and linear terms), the RMSE statistical value of corrected observation residuals, and a correlation value function, with threshold setting strategies and a correlation processing flow provided. Finally, verification using simulated and actual measured data from optical telescopes (arrays) demonstrates that the track-catalogue correlation accuracy of this method can reach approximately 98%.

Key words methods: data analysis, catalogs: space debris, celestial mechanics: correlation of observations

1 Introduction

Space debris catalog management is a critical foundation for space situational awareness and space traffic management. To catalog tens of thousands or even hundreds of thousands of space debris objects, wide-area detection methods (such as phased array radar and optical arrays) are generally employed to simultaneously measure multiple targets and obtain large batches of tracking data. For the massive amount of unknown target tracking data acquired by equipment, the first problem to be solved is the correlation matching between this data and known targets in the catalog database (i.e., observation data-catalog target correlation, referred to as data-target correlation). Given the enormous daily volume of observation data, further improving the data-target correlation accuracy is of great significance for enhancing the application benefits of tracking data and maintaining stable catalog management.

Currently, two main data-target correlation methods are employed [1−2]. The first method uses orbit parameter-based correlation, where initial orbit determination is performed on observation arcs, and then the initial orbit parameters are compared with cataloged target orbit parameters to select the optimal correlation result through appropriate judgment metrics. This method is limited by the uncertainty of initial orbit results, and its correlation performance is affected when initial orbit determination success rates are low or initial orbit accuracy is unstable. The second method employs observation residual analysis-based correlation, where observation predictions are calculated for each cataloged target during the observation period, residual sequences between actual observations and predictions are extracted, and correlation target judgments are made using thresholds. This method avoids initial orbit constraints and can improve correlation accuracy to some extent. However, due to significant individual differences in orbit prediction errors for space debris, direct correlation judgment based on observation residuals makes threshold setting difficult and imposes high requirements on the timeliness and accuracy quality of cataloged target orbital elements, limiting further improvement in correlation accuracy.

To address these issues, this paper analyzes the characteristics of orbit prediction errors and their impact on data-target correlation accuracy for wide-area detection data. A time error correction method is proposed to transform large-scale orbital spatial position prediction errors into small-scale prediction time errors. Based on this, a correlation judgment method is constructed using multiple features including time error parameters and observation residual statistics, with corresponding threshold setting strategies and target correlation processing flows provided. Verification analysis using large batches of simulated and real data demonstrates that the space debris tracking data correlation accuracy of this method reaches approximately 98%, showing high application value.

2 Correlation Result Classification and Probability Definition

2.1 Correlation Result Classification

When correlating single-pass tracking data obtained by detection equipment with a known target set, five possible correlation results may occur (the correlation matrix is shown in Table):

(1) True Positive (TP): The true target exists in the known target set, and the correlation result (target ID) matches the tracking data.

(2) True Negative (TN): The true target does not exist in the known target set, and the tracking data fails to correlate (no correlation result).

(3) False Positive 1 (FP1): The true target exists in the known target set, but the correlation result ID does not match the tracking data.

(4) False Positive 2 (FP2): The true target exists in the known target set, but the tracking data fails to correlate (no correlation result).

(5) False Negative (FN): The true target does not exist in the known target set, but the tracking data correlates with another target in the known target set.

Reducing erroneous correlations (false correlations and false associations) is essential to prevent introducing incorrect data into subsequent catalog orbit determination processing [3], which would affect the accuracy of catalog orbit generation. Comparatively, missed correlations have less impact, as cataloging interruptions caused by missed correlations can be recovered through dynamic scheduling of supplementary observation data and correlation of "new" targets with known targets.

2.2 Factors Affecting Correlation Accuracy

Based on the classification of correlation results, the probabilities of correct correlation, erroneous correlation, and missed correlation are defined as:

$$P_{\text{true}} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{FP1} + \text{FP2} + \text{FN} + \text{TN}} \tag{1}$$

$$P_{\text{false}} = \frac{\text{FP1} + \text{FN}}{\text{TP} + \text{FP1} + \text{FP2} + \text{FN} + \text{TN}} \tag{2}$$

$$P_{\text{miss}} = \frac{\text{FP2}}{\text{TP} + \text{FP1} + \text{FP2} + \text{FN} + \text{TN}} \tag{3}$$

Correlating tracking data with known targets essentially involves determining whether the spatial parameters of known targets at observation times can exhibit identity with the spatial parameters mapped by the tracking data to some extent. Different correlation methods employ different judgment metrics, but fundamentally all judge the difference between the spatial parameters extrapolated from known target orbits to observation times and the actual measured spatial parameters of targets.

For a given observation quantity y, the subscript o denotes the measured value calculated from tracking data, the subscript c denotes the calculated value from known target orbit parameters, where y_{rc} represents the true calculated observation value and y_{pc} represents the predicted calculated observation value, and ε is the measurement error. The observation error at a certain observation time can be expressed as:

$$(y_o - y_c)_{ri} = y_{oi} - y_{rci} + \varepsilon_i = (y_o - y_{pc})_i + (y_{pc} - y_{rc})_i + \varepsilon_i \tag{4}$$

From this equation, when using known target catalog orbits for target correlation of tracking data, observation prediction errors are introduced because the calculated observation values are obtained through orbit prediction. These introduced errors generally far exceed measurement errors and directly affect correlation judgment accuracy.

Furthermore, observation prediction errors originate from orbital position errors generated by catalog orbit extrapolation prediction. According to orbit prediction error propagation laws [4], for near-circular orbits, prediction errors are mainly concentrated in the along-track direction (along the orbital flight direction) and diverge continuously with the prediction period (the interval from the epoch of the orbital elements to the given prediction time point). Different targets or different prediction period times for the same target exhibit significant differences in orbital position prediction errors, making threshold setting extremely difficult for direct correlation judgment based on orbital position prediction errors. This is the core factor affecting final correlation performance.

3 Correlation Method Based on Time Error Correction and Multi-Feature Joint Judgment

3.1 Basic Concept

Fully utilizing the characteristic that orbit prediction errors exhibit linear slow variation over short time periods, orbital position prediction error variables are transformed into time prediction errors, and observation prediction errors are compensated and corrected based on time prediction errors. On this foundation, a joint judgment model is established by combining multiple features including time prediction errors and corrected observation error statistics to set judgment thresholds and achieve high-accuracy target correlation for tracking data.

3.2 Observation Prediction Error Correction Based on Time Error

The time error of orbit prediction is defined as the ratio of position error of space debris along the orbital flight direction to the flight velocity:

$$\Delta T_i = \frac{\Delta P_{vi}}{v_i} \tag{5}$$

where ΔT_i is the time error of the space debris at a certain observation moment. Since the observation arc duration is generally much shorter than the orbital period, the time error can be assumed to be linear during the observation period and characterized as:

$$\Delta T_i = \Delta T_0 + K(t_i - t_0) \tag{6}$$

Using the observation quantity variation rate and time error, a model for correcting observation prediction errors is established:

$$(y_o - y_c)_{\mathrm{mod}\ i} = \dot{y}_i \Delta T_i = \dot{y}_i \Delta T_0 + \dot{y}_i (t_i - t_0) K \approx \dot{y}_i \Delta T_0 + K(t_i - t_0) \tag{6}$$

where $\dot{y}_i$ is the observation quantity variation rate at time t_i, and ΔT_0 and K are model parameters. Combining equations (4) and (6), a time error parameter estimation model is established:

$$\begin{bmatrix} \dot{y}_1 & \dot{y}_0 \\ \dot{y}_2 & \dot{y}_0(t_2 - t_0) \\ \vdots & \vdots \\ \dot{y}_n & \dot{y}_0(t_n - t_0) \end{bmatrix} \begin{bmatrix} \Delta T_0 \\ K \end{bmatrix} = \begin{bmatrix} (y_o - y_c)_1 \\ (y_o - y_c)_2 \\ \vdots \\ (y_o - y_c)_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix} \tag{7}$$

The corresponding matrix form is:

$$A\vec{x} = \vec{b} + \vec{\varepsilon} \tag{8}$$

where

$$A = \begin{bmatrix} \dot{y}_1 & \dot{y}_0 \\ \dot{y}_2 & \dot{y}_0(t_2 - t_0) \\ \vdots & \vdots \\ \dot{y}_n & \dot{y}_0(t_n - t_0) \end{bmatrix}, \quad \vec{x} = \begin{bmatrix} \Delta T_0 \\ K \end{bmatrix}, \quad \vec{b} = \begin{bmatrix} (y_o - y_c)_1 \\ (y_o - y_c)_2 \\ \vdots \\ (y_o - y_c)_n \end{bmatrix}, \quad \vec{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}$$

The singular value decomposition (SVD) method is used to solve this least squares fitting problem and calculate the time error parameters:

$$\vec{x} = (A^T A)^{-1} A^T \vec{b} \tag{9}$$

Based on this, the corrected observation error time series is obtained:

$$(y_o - y_c)_{\text{final } i} = (y_o - y_{pc})_i - [\dot{y}_i \Delta T_0 + K(t_i - t_0)] \tag{10}$$

3.3 Multi-Feature Joint Target Correlation Judgment

Select the observation quantity time error parameters ΔT_0 and K to construct the correlation judgment feature vector:

$$\vec{d} = [\text{RMSE}, \Delta T_0, K]^T \tag{11}$$

where RMSE is the statistical root mean square error of the corrected observation error sequence.

Using the judgment feature vector, define the initial correlation value function for multi-feature joint judgment:

$$V = \frac{1}{3} \sum_{i=1}^{3} \left(\frac{d_i}{R_i} \right)^2 \tag{12}$$

where d_i are the components of $\vec{d}$, and R_i are the weighted values of each feature quantity.

A two-layer correlation judgment model is adopted for target correlation result judgment of tracking data. The layer I joint judgment conditions are:

$$\begin{cases} |d_i| \le g_i & (i = 1, 2, 3) \\ V \le g_V & (R_i = g_i; i = 1, 2, 3) \end{cases} \tag{13}$$

where g_1, g_2, and g_3 are the threshold values for RMSE, ΔT_0, and K, respectively, and g_V is the threshold value for the initial correlation value function.

For multiple suspected correlation targets satisfying the layer I joint judgment conditions, layer II optimal selection judgment is performed. First, the optimal correlation value functions are calculated separately; then the target with the minimum optimal correlation value function is selected from the suspected correlation targets as the final correlation result. The optimal correlation value function for each suspected correlation target is:

$$V' = \frac{1}{3} \sum_{i=1}^{3} \left(\frac{d_i}{R'_i} \right)^2 \tag{14}$$

where R'_i is the maximum value of feature quantity d_i among the m suspected correlation targets.

3.4 Correlation Judgment Threshold Setting

The correlation judgment thresholds involved in this method are few and relatively convenient to set. The setting methods are described as follows:

(1) **RMSE Threshold Value** g_1: Under ideal conditions, the corrected observation error contains only measurement error. Therefore, the reference quantity for setting the RMSE threshold is the measurement error of the detection equipment corresponding to the tracking data. Considering the nonlinear characteristics of observation prediction errors, this threshold can generally be set to 10 times the measurement error of the observation quantity.

(2) **Time Error Parameter** ΔT_0 **Threshold** g_2: This depends only on the accuracy quality of known target orbital elements and the prediction period (the time interval from the epoch of the elements to the observation time of tracking data). For commonly used Two-Line Element (TLE) data in engineering applications, with a prediction period not exceeding 7 days, the threshold for low-orbit target time error parameter ΔT_0 is generally controlled within 20 seconds.

(3) **Time Error Parameter K Threshold g_3**: This is mainly related to the nonlinear characteristics of orbit prediction errors and the impact of non-flight-direction errors on measurement errors, generally set to 2–3 times the measurement error of the observation quantity.

(4) **Initial Correlation Value Function Threshold g_V**: When calculating the initial correlation value function, the weighted values of each feature quantity can be taken as their corresponding thresholds. Therefore, according to the definition of the initial correlation value function, the corresponding threshold can be set between 0.8–1.0.

3.5 Target Correlation Processing Flow

Target correlation processing for single-pass tracking data includes three parts: initial suspected target screening, layer I joint judgment screening, and layer II optimal selection judgment.

(1) **Suspected Target Initial Screening**: Smooth the tracking data and calculate the measured spatial position (or station spatial pointing) of the unknown target at a reference time (generally the midpoint of the arc). From the known target set, select known target orbital elements satisfying the epoch time range condition; then extrapolate each target's orbital elements to this reference time and calculate the corresponding predicted spatial position (or station spatial pointing). Set an initial screening spatial position difference (or spatial pointing angle difference) threshold, perform correlation initial screening judgment using the spatial position difference (or spatial pointing angle difference) at the reference time, retain known targets within the threshold range, and proceed to the next joint judgment screening.

The purpose of suspected target initial screening is to reduce the target capacity for subsequent correlation processing. The initial screening threshold can be appropriately relaxed, with spatial position difference thresholds generally in the 50–100 km range and spatial pointing angle difference thresholds in the 5°–10° range.

(2) **Layer I Joint Judgment Screening**: For each suspected target after initial screening, first use its orbital elements to calculate observation quantity calculated values and observation quantity variation rates at each observation time, generating $\dot{y}_i$ and residual vector $(y_o - y_c)$; then use equation (9) to calculate time error parameters ΔT_0 and K, use equations (6) and (10) to calculate corrected observation errors and extract RMSE; next use equation (12) to calculate the initial correlation value function V for this suspected target; finally, perform multi-feature joint judgment on this suspected target based on the judgment conditions given in equation (13). If the judgment conditions are satisfied, add this suspected target to the candidate correlation target set.

If no candidate correlation target meets the standards in layer I joint judgment screening, it is judged that there is no correlation result, and the target correlation processing exits. If only one candidate correlation target remains after layer I joint judgment screening, this candidate is considered the correlation result, and the target correlation processing exits. If more than one candidate correlation target remains after layer I joint judgment screening, proceed to the next optimal selection judgment.

(3) **Layer II Optimal Selection Judgment**: For multiple candidate correlation targets, first use equation (14) to calculate each target's optimal correlation value function; then sort the candidate correlation targets in ascending order of optimal correlation value function values, select the first candidate correlation target as the correlation result, and exit the target correlation processing.

4 Simulation and Real Data Verification

4.1 Simulation Data Analysis

Initial orbital element sets for low-orbit targets were read from a publicly available TLE file on the internet (seed element file). A high-precision orbit prediction model was used to propagate large batches of low-orbit targets, and ground-based optical array observation data and space-based optical observation data were simulated separately. The right ascension/declination measurement errors for ground-based optical array astronomical positioning were set to 12.5″, and those for space-based telescopes were set to 5.0″.

Using TLE files released 2 days in advance as the known target element set, large-batch measurement data correlation processing and result analysis were conducted. Table lists the basic information of the optical tracking data simulation scenario, with time standard as UTC (Universal Time Coordinated).

For optical angle measurement tracking data, spatial pointing angles were used as observation quantities for data-target correlation processing. Table lists the target correlation thresholds for the two types of equipment.

Table lists the classification statistics of track-catalogue correlation results for ground-based optical arrays and space-based telescopes. The statistical results show that the track-catalogue correlation accuracy for both detection equipment types is basically close to 98%, with false correlation probabilities not exceeding 1%. Most missed correlations are caused by large prediction errors in known target orbital elements, with 85% of missed detection targets having along-track errors exceeding 100 km.

For the true positive (TP) samples of tracking data from the two detection equipment types, the distribution of correlation judgment parameter values was further statistically analyzed. Figure [Figure 1: see original paper] shows the histogram distribution of the four feature values. The figure indicates that for both ground-based optical array equipment and space-based telescope equipment, the corresponding feature values are concentrated within the set threshold ranges, showing good clustering and demonstrating that the selected judgment quantities in this method facilitate correlation threshold setting.

4.2 Real Data Analysis

Large-batch low-orbit debris target real data obtained by the Changchun 15 cm aperture optical telescope array on August 14, 2023, was used to analyze and verify the target correlation effect.

(1) **Establishment of Correlation Result Benchmark**: For the real data obtained during the observation night of August 14, 2023, post-event elements were selected from publicly released TLE data with element epochs between 2023-08-15 UTC 00:00:00 and 2023-08-16 UTC 00:00:00 (totaling 22,090 targets). Direct observation residuals were calculated between each pass of real data and the selected post-event elements. Combined with TLE element accuracy levels [5–6], post-event element targets with minimum angle residual RMS not exceeding 250″ were selected as the true targets (evaluation benchmark) for each pass of real data. A total of 4,772 passes of real data (test data) and benchmark IDs for 3,206 targets were extracted. Real target tracking observation data without related elements in the post-event elements for these data passes, or false observation data extracted from observation images, would interfere with the calculation of correct correlation probability, false correlation probability, and missed correlation probability, and are temporarily excluded from discussion. The figure below shows the statistical results of angle residuals and post-event element prediction periods for each data pass relative to post-event elements.

(2) **Correlation Threshold Setting**: Considering the astronomical positioning angle measurement error of the Changchun 15 cm aperture optical telescope array is 10″, and combining the threshold setting strategy in Section 3.4, the correlation thresholds for real data testing were set as shown in Table .

(3) **Correlation Processing Analysis**: TLE files released 1 day and 2 days before the observation date were selected as the known target element sets for two groups of correlation processing, and each group's correlation results were compared with the benchmark IDs. Table lists the classification statistics comparing the correlation results of this method with the benchmark IDs. Both test groups obtained the same 7 true negative results because the corresponding target elements did not exist in the known target element set used for testing (post-event elements did not contain these target elements).

From the correlation result classification statistics in Table , it can be seen that: (1) The proportion of correctly correlated arcs using this method can reach over 98%, indicating ideal performance; (2) This method demonstrates strong adaptability to known target elements, with small differences in correlation results (approximately 0.5% difference in total) obtained using elements released 1 day or 2 days before the observation date under the same correlation thresholds, showing stable correlation results.

5 Conclusions and Discussion

The data-target correlation method proposed in this paper, based on time error correction and multi-feature joint judgment, transforms large-scale orbital spatial position errors during observation periods into small-scale prediction time errors, achieving spatial compression of observation errors and facilitating threshold setting. Through multi-dimensional constraint joint judgment, false correlation probability can be effectively reduced while ensuring high correct correlation rates. Verification using simulated and real data from optical telescopes (arrays) demonstrates that the track-catalogue correlation accuracy can reach approximately 98%. Furthermore, even a small number of false correlation results will "contaminate" the normal cataloging data of corresponding targets and affect orbit improvement. Future research should investigate methods for optimizing target correlation results based on orbit improvement outcomes.

References

1. Wu L D. *Artificial Satellite and Space Debris Orbit and Detection*. Beijing: China Science and Technology Press, 2012: 250
2. Yu S, Sun R, Zhang C. Proceedings of the 1st NEO and Debris Detection Conference, Darmstadt, Germany, January 22-24, 2019
3. Pastor A, Escobar D, Sanjurjo-Rivo M, et al. LPI Contributions, Texas, USA, December 9-12, 2019
4. Li Y X, Yu H. *Space Debris Research and Application*, 2012, 12: 12
5. Wei D, Zhao C Y. *Acta Astronomica Sinica*, 2009, 50: 332
6. Wei D, Zhao C Y. *Chinese Astronomy and Astrophysics*, 2010, 34: 69

A Track-Catalogue Correlation Method for Space Debris Utilizing Time Error Correction and Multi-Features Joint Judgements

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ABSTRACT Track-Catalogue correlation is the precondition and foundation of large scale space object cataloging maintenance. The accuracy of correlation not only affects normal cataloging processing, but also affects the utilization of observation data and the effectiveness of space object surveillance system.

In this paper, a method is put forward to improve the correlation accuracy of large-batch orbital track data. Firstly, based on the characteristics of orbit error propagation, a model is constructed to estimate the orbital prediction time error and to correct observation residual, aiming to transfer the large scale spatial error to a small scale time-domain error. Secondly, a correlation judgement model involving a four-parameter-joint feature vector is proposed, with threshold setting guidelines and a data correlation processing flow followed. Finally, some examples with regard to large-batch simulated and actual measured tracks are checked to illustrate the effectiveness of the method.

Key words methods: data analysis, catalogs: space debris, celestial mechanics: correlation of observations

Note: Figure translations are in progress. See original paper for figures.