Applied Research on Precision Orbit Determination of Space Debris Using Photoelectric Array Systems: Postprint

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Abstract

Photoelectric array systems exhibit advantages including large field of view, numerous detector elements, wide spatial coverage, high reliability, and excellent real-time performance, rendering them important in space debris detection. Firstly, to solve the space debris association and matching problem, TLE data combined with the SGP4/SDP4 model were utilized to achieve data association matching for space debris observed by photoelectric arrays. Subsequently, a computational method for space debris ballistic coefficients was studied, establishing the foundation for calculating the mean ballistic coefficient of space debris based on orbit determination results from observational data. Finally, utilizing the photoelectric array system constructed at the Changchun Satellite Laser Ranging Station, the data accuracy, orbit determination precision, and ballistic coefficient calculation accuracy were validated. Experimental results indicate that: the success rate of space debris association and matching reaches 91.19%; observation accuracy achieves 7.65 arcseconds; for cooperative space targets Sentinel-6A and HY-2C equipped with high-precision laser ranging, precise orbit determination was conducted using laser ranging data, and employing these orbit determination results as reference trajectories, the optical data obtained from the photoelectric array observation system underwent precise orbit determination and 3-day prediction accuracy analysis in terms of RMS error, yielding three-dimensional position accuracies of 319.11 m and 107.25 m, and velocity accuracies of 0.26 m/s and 0.09 m/s, respectively; the 3-day prediction RMSE of the new two-line element set generated from the calculated ballistic coefficient of target 36508 is 746.84 m, which represents a 0.25% reduction compared to the RMSE of 748.68 m from publicly available data, with both achieving comparable accuracy. These results demonstrate that the system essentially satisfies the requirements of routine missions.

Full Text

Preamble

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Research on Precision Orbit Determination Applications for Space Debris Based on Photoelectric Telescope Array Systems

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Abstract

Photoelectric telescope array systems offer significant advantages including wide field of view, numerous units, broad spatial coverage, high reliability, and excellent real-time performance, playing a crucial role in space debris detection. To address the challenge of space debris data association, this study employs Two-Line Element (TLE) data combined with the SGP4/SDP4 model to achieve association matching of space debris observations from photoelectric arrays. Subsequently, a method for calculating space debris ballistic coefficients was investigated, establishing a foundation for computing average ballistic coefficients based on orbit determination results from observational data. Finally, using the photoelectric array system constructed at the Changchun Satellite Observatory, we verified the data accuracy, orbit determination precision, and ballistic coefficient calculation accuracy. Experimental results demonstrate that the space debris association matching success rate reaches 91.19%, with observation precision up to 7.65 arcseconds. For cooperative space targets with high-precision laser ranging—Sentinel-6A and HY-2C—precise orbit determination was performed using laser ranging data as reference orbits. Using these reference orbits, the optical data from the photoelectric array observation system underwent precise orbit determination and 3-day prediction, with root-mean-square errors analyzed for accuracy assessment. The three-dimensional position accuracies are 319.11 m and 107.25 m, respectively, while velocity accuracies are 0.26 m/s and 0.09 m/s, respectively. For target 36508, the 3-day prediction root-mean-square error using a newly generated TLE based on the calculated ballistic coefficient is 746.84 m, representing a 0.25% improvement over the publicly available data's error of 748.68 m, with both achieving comparable precision. These results indicate that the system fundamentally meets the requirements of routine operational tasks.

Keywords: space debris; photoelectric telescope array; precise orbit determination; TLE

1 Introduction

Space debris refers to all man-made objects in Earth orbit other than normally functioning spacecraft, including spent satellites and rocket bodies, rocket exhaust products, mission-related debris, and fragments generated from space object collisions. The presence of space debris poses a serious threat to the safety of operational spacecraft, and its continuous generation will severely impact the limited orbital resources. As China's space activities become increasingly frequent, the threat from space debris will intensify correspondingly. As a major spacefaring nation, China currently operates numerous application satellites for communications, meteorology, resource surveys, and military applications. Furthermore, China's manned space program has entered a phase of long-term orbital operations, with space debris posing substantial risks to the space station and crew members. To ensure the safety of space activities and enable the continuous development and utilization of space resources, it is essential to advance space object detection technologies and enhance capabilities for space environment analysis and prediction. Consequently, the development of space debris detection technology holds significant practical importance and application value for the safe operation of spacecraft. With the continuous development of the national aerospace industry, establishing a high-precision civilian space object catalog database carries vital application value.

Radar technology and photoelectric observation represent the primary means of space object monitoring. Radar technology offers the advantage of all-weather, 24-hour operation regardless of weather conditions. However, its limitations include higher operational costs compared to optical methods, limited detection range, inability to detect certain sensitive targets, and the fact that most observation data are not publicly available. As an active detection method, radar emits conspicuous signals and requires large antennas, making it easily detectable by adversarial targets. Photoelectric observation technology offers advantages such as lower operational costs, long detection range, ability to obtain data on sensitive targets, high measurement precision, no signal emission requirement, and no need for large antennas, thus providing good concealment and low detectability. Its primary disadvantage lies in significant environmental constraints, particularly weather conditions, as high-quality observations can generally only be obtained under good seeing conditions. Consequently, photoelectric observation has been widely adopted by research institutions and universities domestically and internationally as a cost-effective technology for space debris detection.

As an important branch of photoelectric detection technology, photoelectric arrays possess numerous advantages including large field of view, multiple units, extensive spatial coverage, high reliability, and excellent real-time performance, playing a significant role in space debris detection. This research is based on the array-structured space debris photoelectric observation system (hereafter referred to as the photoelectric array system) constructed at the Changchun Satellite Observatory of the National Astronomical Observatories, Chinese Academy of Sciences. The space debris arcs observed by this photoelectric array system are all short arcs, typically no longer than 1% of an orbital period, essentially meeting the definition of extremely short arcs. Such observational data presents numerous challenges for space debris orbit determination. Building upon previous research, this paper focuses on three key issues based on observation data from the Changchun Observatory photoelectric array system: the association and matching method for short arcs using space debris optical angle measurement data, precise orbit determination of space debris and the orbit prediction accuracy based on these determination results, and the calculation of ballistic coefficients for large area-to-mass ratio space debris based on orbit determination results from optical angle measurement data. By selecting appropriate targets for calculations related to these three issues, this study provides valuable references for applied research on precise orbit determination of space debris using photoelectric array optical angle measurement data.

In April 2017, the Changchun Satellite Observatory established a photoelectric array system in Jilin City, Jilin Province, consisting of eight 150 mm transmissive wide-field telescopes [Figure 1: see original paper], each equipped with a scientific-grade CCD camera. The system features a complete image acquisition and processing system along with a GPS timing system. Specific technical parameters are detailed in Table 1 . The system monitors a sky area of up to 1,590 square degrees, primarily observing low-Earth orbit space debris with magnitudes brighter than 10.5 mag. Related research analysis indicates that while the system generates large volumes of observation data, the arc lengths are short, with numerous observation arcs approximately 40 seconds in duration. The space debris observation data provides only the observation time for each data point, the right ascension and declination in the station-centric coordinate system (J2000), and the magnitude information. Since this information lacks additional characteristic details about the corresponding space debris, it cannot be directly applied to orbit determination and requires association matching identification processing.

2.2 Association Matching of Space Debris Observation Data

Related research analysis shows that the photoelectric array system produces substantial observation data, acquiring 5,000–9,000 arcs during a single clear night. Unlike conventional photoelectric telescopes, this system's field of view does not track observation targets. Instead, it identifies space debris crossing the fixed field of view from background star images using the three-frame parallax method, then records the observation arc data based on background calibration stars. Consequently, the system obtains short observation arcs but in large volumes, with numerous arcs approximately 40 seconds long. This observation method differs from conventional photoelectric telescopes in that it does not require advance acquisition of target prediction data, but this also results in unidentified space debris for the observed arcs, necessitating association matching identification processing. Currently, the largest publicly available space debris catalog is maintained by the North American Aerospace Defense Command (NORAD), which publishes space debris orbital data primarily in the form of Two-Line Elements (TLE). The TLE represents mean orbital elements, from which the SGP4 (Simplified General Perturbations version 4) model calculates position and velocity parameters of space debris at the epoch time. To accomplish association matching identification and orbit determination for photoelectric array system observations, space debris observation data must be matched with TLE targets. The association matching process for space debris observation data is illustrated in Figure 2 [Figure 2: see original paper].

In Figure 2, O represents observed values, while C represents values obtained by solving TLE data using the SGP4 model. The TEME (True Equator Mean Equinox) coordinate system is an orbital coordinate system with its reference plane being the instantaneous true equatorial plane, where the X-axis points to the projection of the mean vernal equinox at the epoch onto the true equator. TOD (True Equator of Date) is the instantaneous true equatorial geocentric coordinate system, with its reference plane being the instantaneous true equator and the X-axis pointing to the instantaneous true vernal equinox.

2.3 Determining Space Debris Ballistic Coefficient Based on TLE Data

For low-Earth orbit space debris, atmospheric drag is one of the significant non-conservative perturbation forces affecting its orbit, calculated as:

$$F = \frac{1}{2}\rho C_D A v_r^2 \mathbf{e}_{vr}$$

where ρ represents atmospheric density, C_D is the drag coefficient of the space debris, A is the cross-sectional area perpendicular to the velocity direction, v_r is the velocity of the space debris relative to the atmosphere, and $\mathbf{e}_{vr}$ is the unit vector of the relative atmospheric velocity. Therefore, the acceleration due to atmospheric drag can be expressed as:

$$\mathbf{a}_r = \frac{1}{2}\frac{C_D A}{m}\rho v_r^2 \mathbf{e}_{vr}$$

where B is the ballistic coefficient, a parameter describing the physical characteristics of space debris and an important factor in calculating atmospheric drag effects, defined as:

$$B = \frac{C_D A}{m}$$

where m is the satellite mass. Typically, the ballistic coefficient of space debris is unknown, making orbit determination and prediction difficult, particularly for low-Earth orbit debris. Consequently, research on ballistic coefficient determination methods holds practical significance and application value. The ballistic coefficient is primarily influenced by aerodynamics, atmospheric composition at the debris location, and debris material properties. Accurate calculation of the drag coefficient is extremely challenging; therefore, during precise orbit determination, the drag coefficient must generally be estimated. For approximately spherical debris, the drag coefficient is nearly constant at 2.2; thus, if unknown, 2.2 can be used as an initial value. Related research indicates that during periods of weak solar activity ($F_{10.7} < 80$), the primary atmospheric constituent below 500 km altitude transitions from atomic oxygen to helium molecules. The drag coefficient for atomic oxygen is approximately 2.2, while for helium molecules it is approximately 2.8. Above 1,500 km, where hydrogen is the primary atmospheric component, the drag coefficient exceeds 4.0. The area-to-mass ratio (A/m) is a crucial geometric property of space debris. Information regarding cross-sectional area, size, and mass is difficult to obtain. This study utilizes observation data from the photoelectric array system combined with empirical values for orbit determination calculations to obtain position and velocity parameters of target debris, then calculates the ballistic coefficient for orbit determination and prediction, which holds certain application value.

Considering atmospheric drag effects, the time rate of change of the space debris orbit semi-major axis a is expressed as:

$$\dot{a} = \frac{2a^2}{\mu}\mathbf{v}_S \cdot \mathbf{a}_d$$

where μ is the product of the gravitational constant and Earth's mass, $\mathbf{v}_S$ is the space debris velocity, $\mathbf{e}_v$ is the unit vector in the direction of motion, and $\mathbf{a}_d$ is the acceleration vector due to drag, defined as:

$$\mathbf{a}_d = -\frac{1}{2}\rho B\|\mathbf{v} - \mathbf{V}\|(\mathbf{v} - \mathbf{V})$$

where ρ is atmospheric density, $\mathbf{v}$ is the space debris velocity vector, $\mathbf{V}$ is the atmospheric wind velocity vector, and $\mathbf{e}_{(v-V)}$ is the unit vector of space debris relative to atmospheric wind. Substituting Equation (5) into Equation (4) yields:

$$\dot{a} = -\frac{2a^2}{\mu}\rho B v_r^3$$

Integrating Equation (6) gives:

$$\Delta a = -\frac{2a^2}{\mu} B \int_{t_1}^{t_2} \rho v_r^3 dt$$

where Δa represents the change in semi-major axis due to drag from time t_1 to t_2. Assuming the ballistic coefficient is constant, we obtain:

$$B = -\frac{\mu \Delta a}{2a^2 \int_{t_1}^{t_2} \rho v_r^3 dt}$$

Replacing the denominator with numerical integration yields:

$$B = -\frac{\mu \Delta a}{2a^2 \sum_{i=1}^{N} \rho_i v_{r,i}^3 \Delta t}$$

where Δt is the numerical integration time step, and the variable Δa can be obtained by calculating the epoch times t_1 and t_2 from TLE data. Thus, for a given space debris object, specifying the TLE reference epoch, atmospheric density model, and atmospheric wind field model allows solving for the debris ballistic coefficient. In this experiment, a fixed empirical constant was used for the ballistic coefficient in orbit determination, and a fixed empirical constant was also employed for the area-to-mass ratio in solar radiation pressure calculations.

The velocity vector at epoch time t required in Equation (9) can be obtained from orbit determination results; the instantaneous semi-major axis is derived from the position and velocity vectors at that epoch; atmospheric density at the target location is obtained by solving atmospheric density models, with this experiment using the average of three models (J71, NRLMSISE00, and DTM2000); wind field velocity at the target location is obtained by substituting position parameters from orbit determination results into the atmospheric wind field model, with this experiment employing the HWM96 atmospheric wind field model.

2.4 Determination and Prediction of Space Debris Extremely Short Arc Orbits

The motion equation for Earth-orbiting space debris can be expressed as the following second-order differential equation:

$$\ddot{\mathbf{r}} = \mathbf{f}(\mathbf{r}, \dot{\mathbf{r}}, \mathbf{a}, t)$$

where $\mathbf{r}$, $\dot{\mathbf{r}}$, and $\ddot{\mathbf{r}}$ represent the position, velocity, and acceleration vectors of space debris in the Earth-centered inertial coordinate system; $\mathbf{f}$ denotes the vector sum of various forces per unit mass acting on the debris; $\mathbf{a}$ represents dynamic model parameters including atmospheric drag and solar radiation pressure coefficients; and t denotes the time variable. When performing orbit determination and prediction for space debris, the primary perturbation forces considered include Earth's gravity, gravitational attraction from the Sun and Moon, atmospheric drag, solar radiation pressure, Earth tidal forces (solid and ocean tides), and relativistic effects.

Based on observation data from the photoelectric array system, the processing flow for precise orbit determination and extrapolation prediction of space debris is illustrated in Figure 3 [Figure 3: see original paper], with the following main steps:

(1) Data input, including:

1) Physical parameter files such as Earth gravity field model files, ocean tide model files, IERS Earth rotation parameter files, solar radiation and Earth albedo files, atmospheric density model files, and JPL planetary ephemeris files;

2) Space debris information files including target mass, cross-sectional area, and center-of-mass corrections;

3) Observation station information including station name, code, and Earth-fixed coordinate position;

4) Observation data including ground-based photoelectric array system observations (angle measurements).

(2) Force model configuration, including Earth gravity field models, atmospheric density models, and ocean tide models.

(3) Orbit numerical integration and formation of least squares equations, using the Cowell numerical integrator to generate target state vectors and variational equations at observation epochs.

(4) Least squares equation solution to obtain optimal estimates of unknown parameters.

(5) Convergence judgment of the least squares solution, based on whether changes between successive solutions fall within specified limits.

(6) Outlier rejection to ensure no gross errors exist in the observation data participating in orbit determination.

(7) Generation of orbit parameters up to the target epoch and export of directional observations, range observations, and observation residuals based on parameter results and ground station data.

(8) Output of result files including observation residuals, precise orbit determination, and prediction results, which can be exported in various formats

such as CPF (Consolidated Prediction Format) and TOD coordinate system precise ephemeris formats.

The orbit determination convergence condition requires that changes in the initial state are smaller than a given threshold. In this study, the convergence control criterion is that position changes between successive iterations are less than 0.01 m and velocity changes are less than 0.01 m/s.

3.1 Space Debris Association Matching Results

Based on photoelectric array system observation data from August 26 to September 5, 2021, combined with TLE data from the observation period and the SGP4/SDP4 model, this study successfully achieved association matching between space debris observation data from the photoelectric array system and public TLE data, with a success rate of 91.19%. The association matching results are shown in Figure 4 [Figure 4: see original paper].

3.2 Space Debris Precise Orbit Determination and Prediction Results

Currently, the Satellite Laser Ranging (SLR) global network provides predicted data (CPF format) and observation data (NPT format) for over 90 laser-ranging satellites with altitudes ranging from several hundred kilometers to tens of thousands of kilometers. Based on global SLR NPT data, post-precision orbit determination can generally achieve centimeter-level prediction accuracy, serving as standard orbits (theoretical truth values) and providing external accuracy assessment for other equipment or algorithms.

This study selected several SLR satellites and used global SLR NPT data for precise orbit determination to generate standard ephemerides. Using photoelectric array system observation data from August 26 to September 5, 2021, we successfully associated the laser satellite Sentinel-6A (NORAD ID: 46984) with an orbital altitude of 1,339.4 km. First, we performed precise orbit determination using Sentinel-6A NPT data from the global observation network to generate standard orbital data. Subsequently, we converted the Sentinel-6A standard orbital data into right ascension and declination in the station-centric J2000 coordinate system as truth values. Finally, we validated the photoelectric array system observation data in right ascension and declination directions, statistically analyzing observation residuals to determine that the system's observation precision reaches up to 7.65 arcseconds, with no less than 10 arcseconds precision. The observation error distribution is shown in Figure 5 [Figure 5: see original paper].

Analysis of the photoelectric array system observation data precision yields the results presented in Table 2 .

Using photoelectric array system observation data from September 1–5, 2021, we successfully associated the laser satellite HY-2C (NORAD ID: 46469) with an orbital altitude of 957 km. Following the procedure described in Section 2.4, we performed orbit determination and prediction. Using HY-2C NPT data, we generated standard orbital data and validated the prediction data from the orbit determination software against the standard orbit in X, Y, and Z axes. The 3-day prediction achieved three-dimensional position accuracy of 107.25 m and velocity accuracy of 0.09 m/s, as detailed in Figure 6 [Figure 6: see original paper].

Using photoelectric array observation data from September 1–5, 2021, we also successfully associated the laser satellite Sentinel-6A (NORAD ID: 46984) with an orbital altitude of 1,339.4 km. After orbit determination and prediction, we used Sentinel-6A NPT data to generate standard orbital data. Validation against the standard orbit in X, Y, and Z axes yielded 3-day prediction three-dimensional position accuracy of 319.11 m and velocity accuracy of 0.26 m/s, as shown in Figure 7 [Figure 7: see original paper].

3.3 Analysis of Large Area-to-Mass Ratio Ballistic Coefficient Calculation Results

Following the method described in Section 2.3, we calculated ballistic coefficients. Using observation data from August 26 to September 1, 2021, we performed precise orbit determination, derived changes in mean motion parameters from NORAD-published TLE data, back-calculated changes in the mean semi-major axis, computed ballistic coefficients, and generated prediction ephemerides by incorporating them into TLE data.

We compared prediction ephemerides generated from published versus calculated ballistic coefficients for the laser satellite Cryosat2 (NORAD ID: 36508), with results shown in Figure 8 [Figure 8: see original paper]. Data points in Figure 8 are spaced at 50-minute intervals. The dashed circular line represents the TLE generated from experimentally calculated ballistic coefficients:

(1) 36508U 10013A 21242.54996539 .00000056 00000-0 -21976-3 0 9995;

(2) 36508 92.0151 213.6864 0007119 138.5085 221.6664 14.51911344603920.

The solid square line represents the publicly available NORAD TLE:

(1) 36508U 10013A 21242.54996539 .00000056 00000-0 13008-4 0 9995;

(2) 36508 92.0151 213.6864 0007119 138.5085 221.6664 14.51911344603920.

Using precise orbit determination results from ILRS-published laser ranging data as standard orbits, we performed external accuracy assessment of prediction errors. Comparing the one-day prediction root-mean-square errors, the publicly available TLE yields 748.68 m, while the experimentally calculated TLE yields 746.84 m—a marginal 0.25% improvement, with both achieving similar accuracy.

For targets at lower orbital altitudes, optical orbit determination results serve as the accuracy reference. This experiment selected Starlink1561 (NORAD ID: 46056) as the test object. According to public data, this target was launched in August 2020 and re-entered the atmosphere in November 2023.

We compared prediction ephemerides from published versus calculated ballistic coefficients for 46056, with results shown in Figure 9 [Figure 9: see original paper]. Data points in Figure 9 are spaced at 50-minute intervals. The dashed circular line represents the TLE generated from experimentally calculated ballistic coefficients:

(1) 46056U 20055AF 21138.10331013 .00000989 00000-0 -12660-3 0 9998;

(2) 46056 53.0567 82.2445 0001530 74.0988 286.0169 15.06398368 43737.

The solid square line represents the publicly available NORAD TLE:

(1) 46056U 20055AF 21138.10331013 .00000989 00000-0 85294-4 0 9998;

(2) 46056 53.0567 82.2445 0001530 74.0988 286.0169 15.06398368 43737.

Using optical orbit determination results as standard orbits, we performed external accuracy assessment. Comparing one-day prediction root-mean-square errors, the publicly available TLE yields 1,912.60 m, while the experimentally calculated TLE yields 1,430.11 m—a 25.22% reduction in error.

These results demonstrate that using observation results from this equipment combined with publicly available orbital element data yields average ballistic coefficients whose one-day prediction errors are comparable to those of NORAD-published data.

4 Conclusion

Addressing challenges in space debris observation using photoelectric array systems, this study conducted in-depth research on space debris association matching methods, ballistic coefficient calculation methods, and precise orbit determination techniques. By employing TLE data combined with the SGP4/SDP4 model, we successfully implemented space debris observation data association matching. We thoroughly investigated ballistic coefficient calculation methods for space debris. Based on the photoelectric array system constructed at the Changchun Satellite Observatory and utilizing orbit numerical integration and least squares methods, we studied the precision of space debris orbit determination and prediction using photoelectric array observation data.

Experimental results demonstrate that the photoelectric array system achieves observation precision up to 7.65 arcseconds for space debris at 1,339.4 km altitude, with precision no worse than 10 arcseconds for other orbital altitudes. Using this observation data for precise orbit determination with 3-day extrapolation, targets at 957 km altitude achieve prediction accuracy of 107.25 m, while those at 1,339 km altitude reach 319.11 m. Ballistic coefficients calculated using optical data orbit determination results achieve prediction accuracy comparable to publicly available TLE data. These results indicate that the equipment holds substantial application value for practical observation operations.

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