Postprint: Research on Fault Monitoring Methods for the 15cm Photoelectric Telescope of the APOSOS Project

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Abstract

To dynamically monitor overseas stations and unmanned telescopes and determine whether they are in normal working condition, a method is proposed for dynamically monitoring the operational status of telescopes by jointly utilizing astronomical positioning data and axis positioning data. This method calculates errors in the observed astronomical positioning and axis positioning data, compares and analyzes the error ranges of the two types of data, and thereby assesses the working status of the telescope. Using this method, observation data from two 15cm ground-based photoelectric observation telescopes of the Asia-Pacific Ground-based Optical Space Object Observation System (APOSOS) project located in Iran and Pakistan were examined. The results revealed that one of the 15cm telescopes exhibited significant errors in the azimuth angle of its axis positioning, with errors reaching hundreds of arcseconds, indicating equipment problems. By comparing the errors in observation data from this equipment between domestic and overseas locations, the time and location of the problem were determined. Reports from observatory staff regarding the telescope issues corroborated the analytical conclusions, thereby demonstrating the effectiveness of the method.

Full Text

Study on Monitor and Diagnostic Method of APOSOS 15cm Opto-electrical Telescopes

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Abstract

To dynamically monitor overseas stations and unmanned telescopes and determine whether they are operating normally, this paper proposes a method that jointly utilizes celestial positioning data and axis positioning data for dynamic monitoring of telescope operational status. The method calculates errors from observed celestial and axis positioning data, compares and analyzes the error ranges of the two data types, and thereby determines the working condition of the telescope. Applying this method to observational data from two 15cm ground-based opto-electrical telescopes of the Asia-Pacific Ground-based Optical Space Object Observation System (APOSOS) project located in Iran and Pakistan, we found that one telescope exhibited significant errors in azimuth axis positioning, reaching over one hundred arcseconds, indicating equipment malfunction. By comparing error data from this equipment' s observations in both domestic and overseas locations, we identified the approximate time and location when the problem occurred. Subsequent reports from the observatory staff confirmed our analysis, demonstrating the effectiveness of the method.

Keywords: Fault monitoring; Space debris; Celestial positioning; Axis positioning; Error analysis
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1 Introduction

Since the first spacecraft was launched into space in 1957, the number of artificial satellites and space debris has been increasing daily, posing a significant threat to the safety of operational spacecraft. Consequently, space debris monitoring has become a focus of increasing international attention. The Asia-Pacific Ground-based Optical Space Object Observation System (APOSOS) is a project established and supported by the Asia-Pacific Space Cooperation Organization (APSCO), aiming to integrate the economic, technical, and geographical advantages of its member states to build a regional and even global optical observation and measurement network for space objects. This network enables the capture, tracking, and measurement of space targets, providing support for the management, operation, and safety of spacecraft, as well as services for future satellite launches.

The APOSOS project' s 15cm telescope system primarily consists of a tracking mount, optical system, imaging detector, control system, main control computer, and power distribution unit. The main parameters of the telescope are shown in Table 1.

Table 1 . Parameters of the 15cm telescope

Parameter	Value
Aperture	15cm
Focal length	300mm
Pixel size	13μm
Resolution	1024×1024
Field of view	2.5°×2.5°
Frame rate	5 fps
Tracking speed	5°/s
Tracking acceleration	$2^\circ/s^2$
Tracking accuracy	<15
Frequency	10 MHz/1s
Precision	10

The first batch of 15cm altitude-azimuth opto-electrical telescopes has been completed and deployed at nodes in APSCO member countries, where local technical personnel track and observe satellites and debris of interest according to observation plans. After observation, data is transmitted back to the Data and Operations Management Center at the National Astronomical Observatories, Chinese Academy of Sciences. Since the Data and Operations Management Center has no stationed personnel at these international nodes, it is essential to develop a method for monitoring and diagnosing telescope status through observational data. This paper proposes a method that jointly uses celestial and axis positioning data for dynamic monitoring of telescope status. By comprehensively analyzing celestial and axis positioning errors, we can determine whether the telescope’ s tracking hardware is operating normally based on the observation errors and stability of axis positioning, and subsequently propose diagnostic directions and maintenance recommendations. This method not only addresses the dynamic monitoring challenges for APOSOS 15cm telescopes but also provides important reference value for other remotely controlled stations and unmanned telescopes that cannot be inspected on-site.

2 Data Sources and Calculation Methods

2.1 Data Sources

The APOSOS project’ s 15cm telescopes output two types of observational data: altitude-azimuth and right ascension-declination, derived from axis positioning and celestial positioning, respectively. Axis positioning is based on encoder readings installed on the telescope axes, while celestial positioning uses multiple stars in the field of view as reference points. The altitude and azimuth obtained from axis positioning are observer-location-dependent, meaning data from different stations and observation times are not in the same coordinate system. In contrast, the right ascension and declination from celestial positioning can be considered in a stable, unified coordinate system across any station and observation time after simple conversion. Axis positioning measurement errors depend on telescope axis reading accuracy, target CCD reading accuracy, telescope axis stability, and atmospheric refraction correction accuracy. Celestial positioning measurement errors are unaffected by telescope axis errors and atmospheric refraction correction errors, depending primarily on the number of calibration stars, satellite or space debris velocity, and measurement accuracy of stellar and satellite images. Celestial positioning is currently the primary method for opto-electrical telescopes tracking space targets [5-9].

The raw data used in this study comes from 15cm refractive ground-based space debris opto-electrical observation telescopes (hereinafter referred to as Equipment No.1 and No.2) deployed at observation stations in Iran and Pakistan, as well as test observation data from Equipment No.1 in Changchun, China. To analyze equipment measurement errors, external accuracy assessment must be performed separately for both celestial and axis positioning data from the two devices. The observational data includes satellite axis positioning data and celestial positioning data. Information about satellites observed by the two devices is shown in Table 2.

Table 2 . Number and observation time of satellites observed by equipment No.1 and No.2

Satellite	Observation Time (UTC)
JASON 3	2017/02/06 15h12min
JASON 2	2017/02/06 16h8min
SARAL	2017/02/06 16h13min
GALILEO 10 (206)	2017/02/19 16h9min
IRNSS-1E	2017/02/25 16h22min
SARAL	2017/02/06 17h7min
JASON 3	2017/02/19 15h54min
ENVISAT	2017/01/05 14h34min
SARAL	2017/02/09 14h43min
CRYOSAT 2	2017/02/17 1h32min
	2017/02/10 0h24min
	2016/09/19 11h51min
	2016/09/20 12h54min
	2016/09/20 11h14min
	2016/09/20 13h7min

2.2 Calculation Methods

Dynamic monitoring of telescope status employs a comparative approach between celestial and axis positioning errors, using the observation errors and stability of axis positioning to determine whether the telescope' s tracking hardware is operating normally.

Error evaluation of telescope observational data generally uses external accuracy assessment. External accuracy assessment typically refers to comparing data from the equipment under evaluation with highly accurate precise ephemerides obtained from widely recognized independent observation methods [10]. Laser ranging is currently the most accurate means of space target observation, with ranging accuracy for cooperative targets better than 1cm and one-day orbit prediction errors on the order of tens of meters. Precise orbits calculated from laser ranging data using precision orbit determination software can be considered approximate true orbits and theoretical true values. Using this as a basis for external accuracy assessment yields reasonable and reliable results. Currently, the International Laser Ranging Service (ILRS) can observe satellites at altitudes from several hundred to tens of thousands of kilometers, allowing flexible selection of appropriate satellites based on the detection range of opto-electrical telescopes. Therefore, we selected high-precision ephemerides obtained through SLR ranging technology as the standard for external accuracy determination of observational data. The entire process is summarized as follows:

1. Use the 15cm telescope to observe an ILRS-supported satellite and obtain optical observation data recording the satellite' s observation time and spatial position.
2. Download high-precision ephemerides from ILRS.
3. Interpolate the high-precision ephemerides to calculate theoretical positions ("true values") corresponding one-to-one with actual observation times.
4. Place theoretical positions and observed positions in the same reference frame.
5. Calculate residuals.

The theoretical right ascension and declination values obtained from SLR data are in the J2000.0 inertial coordinate system. At time i, the position vector of the space target in the J2000.0 inertial coordinate system is $\mathbf{r}_{J2000}$, and the position vector of the observation station is $\mathbf{R}_{J2000}$. The position vector of the space target in the topocentric mean equator coordinate system is:

$$\mathbf{r}_{topo} = \mathbf{r}_{J2000} - \mathbf{R}_{J2000}$$

At this point, the theoretical right ascension and declination values of the space target are:

$$\alpha = \arctan\left(\frac{y_{topo}}{x_{topo}}\right), \quad \delta = \arctan\left(\frac{z_{topo}}{\sqrt{x_{topo}^2 + y_{topo}^2}}\right)$$

In formula (1), the observation station' s position vector $\mathbf{R}_{J2000}$ is obtained from the station' s position vector $\mathbf{R}_{ITRF}$ in the Earth-fixed coordinate system through a series of matrix transformations including polar motion matrix, Earth rotation matrix, nutation matrix, and precession matrix, with specific forms shown later. The station' s position is converted from its geodetic coordinates:

$$\mathbf{R}_{ITRF} = \begin{pmatrix} (N+h)\cos\phi\cos\lambda \\ (N+h)\cos\phi\sin\lambda \\ [N(1-e^2)+h]\sin\phi \end{pmatrix}$$

where

$$N = \frac{a}{\sqrt{1-e^2\sin^2\phi}}, \quad e^2 = 2f - f^2 \tag{4}$$

λ, ϕ, and h are the station' s longitude, latitude, and altitude, respectively, a is Earth' s equatorial radius, and f is Earth' s flattening. Therefore, we have the station' s geocentric coordinates:

$$\mathbf{R}_{J2000} = \mathbf{PNSWR}_{ITRF}$$

For the satellite's precise orbital ephemerides, perform interpolation calculations at observation times. Using the interpolated satellite precise orbit, calculate the theoretical right ascension and declination values α_{theory} and δ_{theory} from equation (3). The root mean square errors for right ascension and declination are calculated using the RMS formula:

$$\sigma_\alpha = \sqrt{\frac{\sum(\alpha_{obs}-\alpha_{theory})^2}{n}}, \quad \sigma_\delta = \sqrt{\frac{\sum(\delta_{obs}-\delta_{theory})^2}{n}} \tag{6}$$

where $\Delta\alpha$ and $\Delta\delta$ are residuals between observed and theoretical values. The residuals $\Delta\alpha$ and $\Delta\delta$ are used to represent⋯

To obtain axis positioning measurement errors, we first need the theoretical coordinates of observed satellites in the horizontal coordinate system. There are two approaches. The first converts ILRS-supported laser satellite observation times from station-fixed Earth-centered reference system coordinates to altitude-azimuth coordinates in the horizontal coordinate system. For non-laser satellites, the second approach is required: first treat the celestial positioning in the geocentric celestial coordinate system as reliable theoretical positions, then convert the theoretical right ascension and declination values at observation times into corresponding azimuth and altitude values for the same station. The flowchart is shown in Figure 1 [Figure 1: see original paper], where GCRS is the Geocentric Celestial Reference System, MOD is the Mean Equator of Date system, TOD is the True Equator of Date system, PEF is the Pseudo-Earth-Fixed reference system, and ITRS is the International Terrestrial Reference System. GCRS coordinates are transformed to ITRS Earth-fixed reference system coordinates, which are then converted to AZEL horizontal coordinate system altitude-azimuth coordinates [5]. Note that the GCRS coordinate system has subtle differences from the J2000 coordinate system, but since other error sources far exceed the differences between these two coordinate systems, they are generally not distinguished in satellite work.

According to the 1976 precession model and 1980 nutation model, the precession and nutation matrices are:

$$\mathbf{P} = \ldots, \quad \mathbf{N} = \ldots$$

The Earth rotation matrix is:

$$\mathbf{S} = \mathbf{R}_z(\theta_{GST})$$

The polar motion matrix is:

$$\mathbf{W} = \mathbf{R}_y(-x_p)\mathbf{R}_x(-y_p)$$

The transformation from celestial geocentric equatorial coordinate system (J2000) to topocentric horizontal coordinate system is:

$$\begin{pmatrix} x_h \\ y_h \\ z_h \end{pmatrix} = \mathbf{M}_{hor}\mathbf{M}_{rot} \begin{pmatrix} x_{J2000} \\ y_{J2000} \\ z_{J2000} \end{pmatrix}$$

In the above equations, $\mathbf{r}_{ITRF}$, $\mathbf{r}_{J2000}$, and $\mathbf{r}_{hor}$ are the rectangular coordinates of the space object in the Earth-fixed, J2000 mean equatorial, and topocentric horizontal coordinate systems, respectively. $\mathbf{R}_i(\theta)$ represents the rotation matrix for rotating any vector by angle θ about axis i, with counterclockwise being positive. Where θ_{GST} is Greenwich Sidereal Time, x_p and y_p are polar motion components, ϕ' is instantaneous astronomical latitude, and LST is local sidereal time. In formulas (7) and (8), $\Delta\psi$ and $\Delta\epsilon$ are nutation in longitude and obliquity, respectively, with remaining parameters being time-dependent [12].

The residuals between the azimuth A_i' and altitude h_i' converted from theoretical right ascension and declination and the observed axis positioning values (A_i, h_i) after atmospheric refraction correction are used to calculate the RMS errors of azimuth and altitude using formula (6). Similar to right ascension residuals, azimuth residuals need to be multiplied by the cosine of altitude, represented as $\Delta A \cos h$. This yields the telescope' s axis positioning errors.

3 Data Results and Analysis

Figure 2 [Figure 2: see original paper]. Residual analysis for celestial positioning of JASON 3 satellite observed by the two equipment

Figure 2 shows the residuals in right ascension and declination from celestial positioning when Equipment No.1 and No.2 observed satellite 41240 (JASON

3). The residuals in right ascension and declination for both devices are within a few arcseconds, with some larger residual values possibly indicating significant random errors that do not affect systematic error assessment and can be ignored.

Figure 3 [Figure 3: see original paper]. Residual analysis for axis positioning of JASON 3 satellite observed by the two equipment

Figure 3 displays the residuals in azimuth and altitude from axis positioning when the two equipment observed satellite 41240 (JASON 3). The figure shows that Equipment No.1 has larger axis positioning errors than Equipment No.2, with azimuth errors of 106 arcseconds and altitude errors of 36 arcseconds for No.1, while No.2' s errors are both around ten arcseconds. Similar processing of other identical target observation data yields comparable results to satellite 41240, which are not enumerated here.

Based on residual results from observations of identical targets by both equipment, both devices exhibit low measurement errors in celestial positioning. However, axis positioning reveals potential significant issues with Equipment No.1, particularly in the azimuth axis. To further verify this inference, error analysis was also performed on observation data of different targets, yielding the following measurement errors (RMS of residuals).

Table 3 . No. 1 equipment' s errors of different objects

Observation Time (UTC)	RA Error ( )	Dec Error ( )	Az Error ( )	Alt Error ( )
2017/02/06 15h12min				
2017/02/06 16h8min				
2017/02/06 16h13min				
2017/02/06 17h7min				
2017/02/19 15h54min				
2017/02/19 16h9min				
2017/02/25 16h22min				

Table 4 . No. 2 equipment' s errors of different objects

Observation Time (UTC)	RA Error ( )	Dec Error ( )	Az Error ( )	Alt Error ( )
2017/01/05 14h34min				
2017/02/09 14h43min				
2017/02/10 0h24min				
2017/02/17 1h32min				

Comparison between Tables 3 and 4 shows that the two equipment have similar errors in celestial positioning, while Equipment No.1 exhibits higher axis positioning errors than Equipment No.2, particularly with azimuth errors reaching hundreds of arcseconds. We preliminarily inferred that Equipment No.1' s axis positioning system was faulty and needed comparison with its domestic observation data to determine the approximate time when the failure occurred.

Table 5 . No. 1 equipment' s errors of different objects in Changchun

Observation Time (UTC)	RA Error ( )	Dec Error ( )	Az Error ( )	Alt Error ( )
2016/09/19 11h51min				
2016/09/20 11h14min				
2016/09/20 12h54min				
2016/09/20 13h7min				

Comparison among Tables 3, 4, and 5 shows that all three have celestial positioning errors below 10 arcseconds with good stability. Equipment No.2' s axis positioning errors are similar to Equipment No.1' s domestic errors in Changchun, both around 10–20 arcseconds with good stability, significantly better than Equipment No.1' s errors of tens or hundreds of arcseconds in Iran. Equipment No.1' s axis positioning errors in China were only about ten arcseconds, comparable to Equipment No.2' s precision, indicating no axis positioning issues while in China. The increased measurement errors and obvious stability degradation during overseas observations indicate that problems emerged at that time. Subsequently, the Iranian observation station reported operational inflexibility in the azimuth axis of the 15cm opto-electrical telescope' s axis positioning system, confirming our judgment and demonstrating the feasibility and effectiveness of using comparative analysis of celestial and axis positioning measurement errors and stability to determine telescope mount working status.

Although axis positioning errors are slightly higher, when celestial positioning works properly, using celestial positioning errors as a reference standard, we can determine whether telescope tracking hardware is operating normally through comprehensive analysis of axis positioning observation errors and stability. In space target positioning for APOSOS project' s Equipment No.1 and No.2, celestial positioning observation errors are generally less than 10 arcseconds, making it suitable for high-precision space target detection. Axis positioning observation errors are larger with lower stability, ranging from 10 to 100 arcseconds, and can serve as auxiliary observations to celestial positioning. Equipment No.1 exhibited significant axis positioning errors in Iran that were not observed domestically, clearly identifying that problems emerged during Iranian observations. Subsequent reports from the Iranian observation station confirmed this conclusion, validating the feasibility and effectiveness of our analysis method. This method can guide equipment troubleshooting directions and facilitate rapid diagnosis and repair, addressing not only the dynamic monitoring challenges for APOSOS telescopes but also providing important reference value for remotely controlled stations and unmanned telescopes that cannot be inspected on-site.

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

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