Postprint of Xinjiang SLR Mobile Station Coordinate Solution and Application

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Abstract

The precise determination of ground station coordinates based on satellite laser ranging (SLR) technology is of great significance for establishing and maintaining various reference frames, establishing global ocean tide and solid tide models, and monitoring global plate motions and seismic activities. Using a small amount of observation data of the Lageos2 satellite from August 17 to 26, 2023, collected by the Xinjiang SLR mobile station, station coordinate estimation and accuracy analysis were performed using two methods: precise orbit determination and reference orbit checking. The new coordinates were then applied to the orbit validation of the Haiyang-2D satellite. The results show that the mean difference between the coordinates obtained by the two coordinate estimation methods is approximately 3 cm, and the difference in range bias is approximately 3 cm. After adopting the new coordinates, the standard deviation of the data residuals decreased from the meter level to approximately 1 cm, and the mean value decreased from approximately 18 m to approximately 1 cm. SLR orbit validation of the Haiyang-2D satellite observation data yielded a residual mean of approximately −0.35 cm and a standard deviation of approximately 2.5 cm.

Full Text

Preamble

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Coordinate Determination and Application for the Xinjiang SLR Mobile Station

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摘要

The precise determination of ground station coordinates using Satellite Laser Ranging (SLR) technology is of great significance for establishing and maintaining various reference frames, developing global ocean tide and solid earth tide models, and monitoring global tectonic plate motion and seismic activity.

In this study, a small amount of observation data from the Lageos-2 satellite, collected by the Xinjiang mobile SLR station between August 17 and August 26, 2023, was utilized to solve for station coordinates and analyze their precision. Two distinct methods were employed: precise orbit determination (POD) and reference orbit validation. The newly derived coordinates were subsequently applied to the orbit validation of the Haiyang-2D (HY-2D) satellite.

The results indicate that the mean difference between the coordinates obtained by the two calculation methods is approximately 3 cm, with a corresponding range bias difference of about 3 cm. After adopting the new coordinates, the standard deviation of the data residuals improved from the meter level to approximately 1 cm, while the mean residual decreased from approximately 18 m to about 1 cm. Furthermore, SLR orbit validation performed on the HY-2D satellite data using these updated coordinates yielded a mean residual of approximately -0.35 cm and a standard deviation of approximately 2.5 cm.

关键词

Satellite Laser Ranging; Mobile SLR Station; Station Coordinates

CLC Classification Number: P123.46

Figure 1

Figure 1: Figure 1

1. Introduction

Satellite Laser Ranging (SLR) is currently one of the most accurate space geodetic techniques. It provides high-precision measurements of the distance between a ground station and a satellite by measuring the round-trip time of flight of short laser pulses. These measurements are fundamental for determining the Earth' s gravitational field, monitoring crustal deformation, and maintaining the International Terrestrial Reference Frame (ITRF).

While fixed SLR stations provide long-term stability and continuous data, mobile SLR stations offer the flexibility required for targeted regional studies and the densification of geodetic networks. The determination of precise station coordinates for these mobile units is critical for integrating their observations into global and regional reference frames.

2. Methodology and Data Processing

The precision of SLR station coordinates depends on several factors, including the quality of the laser ranging data, the accuracy of the orbital models, and the stability of the local site environment. For mobile SLR stations, additional considerations such as the stability of the temporary platform and the precision of the local tie surveys must be addressed.

The observation model for the range ρ can be expressed as:

$$\rho = \frac{1}{2}c\Delta t + \Delta\rho_{cor}$$

where c is the speed of light, Δt is the measured round-trip time, and $\Delta\rho_{cor}$ represents various corrections, including atmospheric refraction, relativistic effects, and center-of-mass offsets.

To solve for the station coordinates (X, Y, Z), we utilize a least-squares estimation process based on the linearized observation equations:

$$\Delta\rho = \frac{\partial\rho}{\partial X}\Delta X + \frac{\partial\rho}{\partial Y}\Delta Y + \frac{\partial\rho}{\partial Z}\Delta Z + \epsilon$$

where ϵ represents the measurement noise and unmodeled errors.

3. Results and Analysis

Data collected from the mobile SLR station were processed using state-of-the-art orbital determination software. The analysis focused on the repeatability of the station coordinates over several observation sessions.

Figure 1

Figure 2: Figure 1

As shown in

, the short-term repeatability of the horizontal components is typically within the range

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Document Classification Code: A

Satellite Laser Ranging (SLR) calculates the distance between a ground observation station and a satellite equipped with retroreflectors by precisely measuring the round-trip travel time of laser pulses. Based on its fundamental measurement principles, SLR can achieve a ranging accuracy of up to 1 cm. Furthermore, SLR technology is unaffected by carrier phase ambiguity, clock offsets, or ionospheric delays. Due to these technical characteristics [?, ?, ?], SLR has been applied across various scientific and engineering fields—including precise satellite orbit determination [?, ?], validation of orbit accuracy, establishment of terrestrial reference frames, monitoring of geocenter motion, and determination of the Earth' s gravity field—demonstrating its unique advantages.

Currently, there are approximately 40 fixed SLR stations globally. Within China, there are five regular SLR observation stations: Changchun (7237), Beijing (7249), Shanghai (7821), Kunming (7819), and Wuhan (7231). Through rapid and precise orbit determination of the geodetic satellites Lageos-1 and Lageos-2, the observation accuracy of these domestic stations has reached within 1 cm, which is comparable to the performance levels of international stations.

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With the increasing demand for high-precision fundamental research and engineering applications, the current number of fixed domestic SLR stations is insufficient. Additional stations are required to address the sparse and uneven distribution of SLR sites in mainland China. In particular, there is a critical need to fill the observational gaps in western China, optimize the layout of the Chinese laser ranging network, and improve the overall observational efficiency of the national network.

TROS1000 is a new generation of mobile satellite laser ranging system independently developed by the Institute of Seismology, China Earthquake Administration. In August 2019, the TROS1000 system was deployed to the Nanshan Observatory of the Xinjiang Astronomical Observatory to begin SLR observations in the western region, achieving a measurement precision of 1 cm. Because precise eccentric centering measurements were not initially performed for the station' s coordinates, and considering the influence of the mobile station' s external environment, it is necessary to recalculate the station coordinates to better utilize the station for high-precision scientific research and satellite navigation. Given that the Lageos-2 satellite is spherical, orbits at an altitude of approximately 6,000 km, possesses a high area-to-mass ratio, and provides a large number of Normal Point (NP) data, this study first utilizes a small amount of Lageos-2 NP data collected by the mobile station between August 17 and August 26, 2023, to solve for the station coordinates and ranging biases. Subsequently, the reliability of these calculated results is verified by performing orbit validation on SLR NP data from China' s HY-2D (Haiyang-2D) satellite.

2.1 观测数据

The Xinjiang SLR mobile station (Station ID: 7343) conducted observations across two arcs in August 2023. The first arc spanned from August 17 to August 21, 2023. During this period, a total of 25 SLR stations worldwide observed the Lageos-2 satellite, yielding 1,058 normal points. Among these, Station 7343 contributed 35 normal points. The second arc took place from August 24 to August 26, 2023, during which 20 global stations observed the Lageos-2 satellite, collecting a total of 666 normal points.

Within this second observation period, Station 7343 provided 32 normal points. The distribution of normal points obtained by the global network of stations observing the Lageos-2 satellite is as follows:

2.2 数据处理方法

SLR data processing utilizes the one-way distance from the ground station to the satellite as the primary observable. The observation equation is expressed as:

$$\rho = \rho' + \Delta\rho_{td} + \Delta\rho_{rf} + \Delta\rho_{rel} + \Delta\rho_{mc} + \Delta\rho_{ro}$$

In this equation, ρ represents the actual observed distance, while ρ' denotes the geometric distance between the station and the satellite. The remaining terms represent various physical and instrumental corrections: $\Delta\rho_{td}$ accounts for the tropospheric delay, $\Delta\rho_{rf}$ is the correction for atmospheric refraction, $\Delta\rho_{rel}$ represents the relativistic effect correction, $\Delta\rho_{mc}$ refers to the center-of-mass correction for the satellite, and $\Delta\rho_{ro}$ accounts for the station' s receive-system offset and other instrumental biases.

In this context, ρ represents the observed range from the satellite to the ground station, while ρ' denotes the theoretical range, defined as

$\rho' = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$. Here, (x_1, y_1, z_1) are the coordinates of the Satellite Laser Ranging (SLR) station, and (x_2, y_2, z_2) represents the satellite position.

The model accounts for several correction terms: $\Delta\rho_{td}$ is the ranging error caused by tidal variations at the station location; $\Delta\rho_{rf}$ is the ranging error resulting from atmospheric refraction effects; $\Delta\rho_{rel}$ is the ranging bias due to general relativistic effects within the gravitational field; $\Delta\rho_{mc}$ represents the offset between the laser reflection point on the satellite surface and its center of mass; and $\Delta\rho_{ro}$ is the ranging bias caused by station coordinate offsets. This paper employs two distinct methods for coordinate solution and calculation.

The first method is precise orbit determination (POD), which involves processing normal point (NP) data from global Satellite Laser Ranging (SLR) stations for the Lageos-2 satellite to obtain parameters such as satellite positions and station coordinates. By applying dynamic statistical methods for precise orbit determination, Equation (1) is linearized as:

$$y_i = H_i x_0 + \epsilon_i \tag{2}$$

In this expression, i represents the observation epoch, ϵ_i denotes the measurement error, and y_i is the observation residual vector $(n \times 1)$. The vector x_0 represents the parameters to be estimated (7×1), which include the satellite' s state vectors and other relevant physical constants.

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The provided text " ㄉ皺　　踝" appears to be a sequence of corrupted characters or an encoding error (often referred to as "mojibake"). It does not contain coherent academic content, technical terminology, or translatable scientific text in any standard language.

As per the instructions to skip garbage text and meaningless fragments, no translation can be performed on this input.

SLR ㄉ

Distribution of the number of normal points observed by globally distributed stations for the Lageos2 satellite.

The state vector $\mathbf{x}_0$ includes the position, station coordinates, and range bias, where $\mathbf{H}_i$ is the coefficient matrix $(n \times 7)$:

$$\mathbf{H}_i = \begin{bmatrix} \frac{x_{1i} - x_{2i}}{\rho_i} & \frac{y_{1i} - y_{2i}}{\rho_i} & \frac{z_{1i} - z_{2i}}{\rho_i} & \cdots \end{bmatrix}$$

$$\mathbf{x}_0 = [x_1, y_1, z_1, x_2, y_2, z_2, \Delta\rho_{RO}]^T$$

The least squares solution for Equation (2) is given by:

$$\mathbf{x} = (\mathbf{H}^T \mathbf{P} \mathbf{H})^{-1} (\mathbf{H}^T \mathbf{P} \mathbf{y})$$

In this expression, $\mathbf{P}$ represents the weight matrix. This method is suitable for scenarios characterized by a sufficient number of stations, a high volume of normal points, and high data quality. By applying this approach to two observation arcs from mobile station 7343, it is possible to independently solve for a set of station coordinates and range biases.

The second method is the reference orbit validation method, which involves fixing the precise orbit of the Lageos2 satellite to solve for station coordinates and range biases. In this case, the coefficient matrix $\mathbf{H}_i$ $(n \times 4)$ is defined as:

$$\frac{x_1 - x_2}{\rho}, \frac{y_1 - y_2}{\rho}, \frac{z_1 - z_2}{\rho}$$

The state vector $\mathbf{x}_0$ (4×1) represents the station coordinates and the range bias:

0 = 1

1 Δ RO

According to the least squares method shown in Equation (2), the 7343 mobile station can solve for a set of station coordinates and range biases for each of the two observation arcs.

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By employing the reference orbit validation method and integrating the coefficient matrices from both arcs, a single set of station coordinates and two distinct range biases (totaling five parameters) can be resolved. In this case, the coefficient matrix $H_{(m+n)\times 5}$ is expressed as:

11 − 21 1 − 2 = 1 +1 − 2 +1 +1 −

11 − 21

11 − 21

1 − 2 1 +1 − 2 +1 +1

1 − 2 1 +1 − 2 +1 +1

1 − 2

1 − 2

1 0 1 0 1 0 0 1 0 1

In this formulation, m represents the number of observation epochs in the first arc, while n denotes the number of observation epochs in the second arc. The state vector $\mathbf{x}_0$ (5×1) consists of the station coordinates and the range biases for the two arcs: $\mathbf{x}_0 = [x_1, y_1, z_1, \Delta\rho_{RO1}, \Delta\rho_{RO2}]^T$. Unlike traditional precise orbit determination (POD) methods, the reference orbit check method does not involve satellite orbit determination or observations from other stations.

Figure 2

Figure 3: Figure 2

Figure 2

Figure 4: Figure 2

Consequently, it is suitable for calculating station coordinates even when the number of normal points is limited. The detailed processing strategies used for data analysis are summarized in .

Data Processing and Estimation Strategy

N-body perturbation; Earth gravity field model; Earth orientation parameters (EOP); Station coordinate reference frame.

Station-to-satellite distance; JPL DE405; EGM2008 (up to degree and order 120); IERS2010; FES2004 model; IERS2010; IERS2010; SLRF2014; Marini model.

Solar radiation pressure model parameters; Periodic RTN empirical forces.

One set of parameters estimated per orbit determination arc; One set of positions and velocities solved per orbit determination arc; One set estimated per arc; One set of range biases estimated per arc; One set of station coordinates estimated per arc.

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3.1 精密定轨法

Using the Lageos2 normal points from global stations during the first arc, the initial coordinates for station 7343 were set to the values provided by the mobile station without precision centering measurements. The initial orbit utilized the precision orbit products from ILRS, with an orbit determination arc length of 5 days. ILRSA and ILRSB represent the integrated orbit products generated by the two ILRS combination centers (CCs), ASI and JCET, respectively. For the Lageos1/2 satellites, the RMS of the difference between the ILRSA and ILRSB integrated orbit products is approximately 1 cm. The time series of the station normal point residuals calculated using the initial coordinates is shown in

. The mean and standard deviation of the residuals calculated from the initial coordinates were −17.97 m and 5.23 m, respectively, whereas the mean and standard deviation of the residuals calculated using the updated coordinates were 1.3 cm and 2.4 cm.

As illustrated in

, the residuals calculated using the initial coordinates are relatively large, with a mean of approximately −18.0 m and a standard deviation of approximately 5.0 m. The calculated station coordinate corrections and range biases are presented in . After applying the new coordinates and range biases, the mean residual decreased to 1.3 cm and the standard deviation decreased to 2.4 cm. A comparison between the estimated satellite orbit and the precision orbit provided by ILRSA was conducted. The time series of the orbit differences in the RTN directions is shown in [FIGURE:3], indicating a radial RMS difference of approximately 1.0 cm and a three-dimensional RMS of approximately 5.0 cm.

Residual sequences corrected using initial coordinates (a) and updated station coordinates (b)

Coordinate corrections and range biases calculated for the two arcs (Coordinate corrections in meters)

−4.208 −4.216

−4.823 −4.772

Range Bias/m −19.239 −18.977

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Residuals of Range Measurements/cm

Time series of orbit differences between Lageos2 and ILRSA precision orbits

Using the Lageos2 normal points from global observation stations during the second arc, the initial coordinates for station 7343 were set identical to those in the first arc. The initial orbit similarly utilized the ILRSA precision orbit, with an orbit determination arc length of 3 days. The time series of station normal point residuals calculated using the initial coordinates is shown in Figure 4 [FIGURE:4]. The mean and standard deviation of the residuals calculated from the initial coordinates were −16.94 m and 2.28 m, respectively. In contrast, the mean and standard deviation of the residuals calculated using the new coordinates were 0.6 cm and 1.0 cm, respectively. As illustrated in Figure 4, the residuals calculated with the initial coordinates are significantly larger, with a mean residual of approximately −17.0 m and a standard deviation of approximately 2.0 m. After applying the new coordinates and range bias, both the mean residual and standard deviation were reduced to within 1.0 cm. A comparison between the determined satellite orbit and the precision orbit provided by ILRSA yielded the orbit difference time series in the RTN directions, as shown in Figure 5 [FIGURE:5]. The RMS of the radial difference is better than 1.0 cm, while the RMS of the three-dimensional difference is approximately 5.0 cm. The results from both arcs indicate that, compared to the residuals obtained using initial coordinates, the precision of the solution residuals is significantly improved after adopting the new coordinates and range bias.

As shown in Table 2, the coordinate corrections for both sets of stations are at the meter level, and the range bias is approximately 20.0 m. This is primarily due to the use of initial station coordinates without performing precision eccentric surveys. The difference in coordinate corrections between the two arcs is less than 5 cm, and the difference in the calculated range bias between the two arcs is approximately 26 cm. These discrepancies arise because the number of normal points in the two arcs is relatively small; with a sufficient number of normal points, the solution accuracy would increase, and these differences would decrease.

3.2 参考轨道检核法

Station coordinates were solved using the reference orbit check method, utilizing a small number of Lageos-2 normal points from the first arc, the second arc, and a combined two-arc solution. The resulting coordinate corrections and range biases are presented in . Based on the results in Section 3.1, for the first arc, the difference in coordinate corrections between the reference orbit check method and the precise orbit determination method is less than 3 cm, with a range bias difference of less than 1 cm. For the second arc, the difference in coordinate corrections between the two methods is less than 3 cm, while the range bias difference is approximately 3 cm. These results demonstrate that the two methods achieve comparable levels of accuracy.

Using the reference orbit check method, the difference between the coordinate corrections derived from the first arc and those from the combined two-arc solution is less than 2 cm, with a range bias difference of less than 2 cm. Similarly, the difference between the coordinate corrections derived from the second arc and the combined solution···

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Residual sequences corrected using initial coordinates (a) and updated station coordinates (b).

Reference orbit residual/cm

/cm

Analysis of the time series of differences between the computed satellite orbits and ILRSA precise orbits

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Coordinate corrections and range biases calculated using the orbit validation method (Coordinate corrections / cm)

−4.234 −4.211 −4.234

−4.830 −4.760 −4.815

Ranging Bias/cm: First Arc Segment, Second Arc Segment

Residual/cm: Mean, Standard Deviation

−19.240 −19.221

−18.943 −19.021

The ranging bias variation is less than 7 cm. This discrepancy is primarily due to the fact that the first arc segment utilized 5 days of observation data, whereas the second arc segment utilized only 3 days. This smaller data volume introduced errors into the solution results; however, it is expected that these differences will diminish as the volume of data increases.

The mean residuals and standard deviations for the new coordinates and ranging biases were calculated separately using the first arc segment, the second arc segment, and a combination of both segments (as shown in). The corresponding residual time series are presented in [FIGURE:6]. As indicated in and [FIGURE:6], the standard deviation of the residuals is better than 1 cm, which is comparable to the precision achieved by precise orbit determination (POD) methods.

Residual time series for the first arc segment (a)), the second arc segment (b)), and the combined two-arc solution (c)).

4 台站新坐标在海洋二号 D 卫星中的应用

On May 19, 2021, the National Satellite Ocean Application Service launched the fourth Haiyang-2D (HY-2D) satellite. As a key component of China' s marine dynamic environment monitoring constellation, the satellite is equipped with dual-frequency GNSS receivers and SLR corner reflectors. Currently, the precise orbit determination (POD) for the HY-2D satellite achieves a radial accuracy of approximately 0.8 cm and a three-dimensional accuracy of about 3 cm. Utilizing high-precision Satellite Laser Ranging (SLR) data···

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···to perform external validation of satellite orbit determination results is an essential method for evaluating orbital accuracy. The SLR orbital validation residual is defined as the difference between the station-to-satellite distance directly measured by SLR and the distance calculated from the satellite's precise orbit determination solution.

The mobile station conducted effective observations of the HY-2D satellite on August 19, 21, 25, and September 9, 2023 (corresponding to Day of Year 231, 233, 235, and 252, respectively). SLR orbital validation was performed for the HY-2D satellite using three sets of coordinates: the initial station coordinates, coordinates solved via the POD method, and coordinates solved via the reference orbit verification method. The resulting residual means and standard deviations are presented in , and the residual time series are shown in [FIGURE:7]. As indicated in and [FIGURE:7], the residual accuracy using initial coordinates is poor, with a mean of approximately 16 m and a standard deviation of about 3 m. In contrast, the new station coordinates derived from both the POD method and the reference orbit verification method yielded comparable SLR orbital validation accuracy, with a mean residual of approximately −0.35 cm and a standard deviation of about 2.5 cm. This represents a significant improvement in accuracy compared to the results using initial coordinates. Tao Enzhe et al. utilized international SLR core stations to perform orbital validation on HY-2D SLR observation data and obtained a residual RMS of 1.5 cm. The slight discrepancy with the results of this study is due to the limited number of normal points available from the mobile station during this session, which affects the precision of the coordinate solution and subsequently impacts the laser validation accuracy for the HY-2D satellite.

shows that the initial coordinate solution yielded a mean residual of 16.28 m and a standard deviation of 3.19 m. The results above demonstrate that the two methods employed in this study for solving station coordinates—the POD method (−0.35 cm mean, 2.15 cm SD) and the reference orbit verification method (−0.38 cm mean, 2.73 cm SD)—significantly improved the accuracy of the HY-2D laser orbital validation. This confirms that the station coordinate solution methods proposed in this paper are feasible and the results are reliable.

···SLR validation residuals for HY-2D calculated using the new coordinate POD method (b) and the reference orbit verification method (c).

5 结

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In this study, we utilize a limited number of normal points (NPs) from the Lageos-2 satellite collected by the Xinjiang Satellite Laser Ranging (SLR) mobile station to solve for station coordinates and range biases. Two distinct methods are employed: precise orbit determination (POD) and reference orbit validation. Furthermore, the derived coordinates are applied to validate the orbit of China's HY-2D satellite using SLR normal points. The results are summarized as follows: (1) Within the same temporal arc, the coordinate precision achieved by both methods is comparable. (2) The difference between the coordinate corrections obtained by the two methods is approximately 3 cm, and the difference in range bias is also approximately 3 cm. After adjustment, the standard deviation of the data residuals was reduced from the meter level to approximately 1 cm, and the mean residual decreased from approximately 18 m to approximately 1 cm. (3) The variation in station coordinates calculated across different arcs is 5 cm, while the variation in range bias is approximately 26 cm. These discrepancies are attributed to errors resulting from the limited volume of available data.

(4) The station coordinates and range biases obtained from both methods were used to perform SLR orbit validation for the HY-2D satellite. The resulting residual precisions were comparable, with a mean of approximately −0.35 cm and a standard deviation of approximately 2.5 cm. These results demonstrate the reliability of the station coordinates determined by

the two methods proposed in this paper.

The station coordinate determination methods presented in this paper provide technical support for the positioning of newly established stations. When a sufficient number of normal points are available, both methods yield equivalent precision. However, in cases where the number of normal points is relatively small—making a global network solution unfeasible—the reference orbit validation method is recommended as the preferred approach.

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Computation and Application of the Coordinate of Xinjiang SLR Mobile Station

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Abstract

Using Satellite Laser Ranging (SLR) technology, the precise determination of ground station coordinates is of great significance for establishing and maintaining various reference frames, developing global ocean tide and solid Earth tide models, and monitoring global plate motion and seismic activity. Using a small set of observation data from the Xinjiang mobile SLR station for the Lageos2 satellite, collected from August 17 to 26, 2023, we determine and analyze the accuracy of the station coordinates using two methods: precise orbit determination and reference orbit verification.

The newly derived coordinates are then applied to the orbit validation of the HY-2D satellite. The results show that the mean coordinate difference obtained by the two solution methods is about 3 cm, and the range-bias difference is about 3 cm. After adopting the new coordinates, the standard deviation of the data residuals is reduced from the meter level to about 1 cm, and the mean value is reduced from about 18 m to about 1 cm. For the SLR orbit verification of the HY-2D satellite observations, the mean residual is approximately −0.35 cm, and the standard deviation is about 2.5 cm.

Key words: satellite laser ranging; SLR mobile station; station coordinate