Three-Band Solar Radio Telescope and Space Weather Postprint

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Abstract

Long-term monitoring of solar radio radiation flux using ground-based telescopes is an important method for space weather forecasting to predict various disturbances on Earth caused by solar activity. Two new three-band (10.7 cm, 6.6 cm, and 3.3 cm) solar radio telescopes at Mingantu and Taxkorgan will serve China' s space weather monitoring and forecasting. The system structure and design characteristics, as well as the dual-noise-source calibration method, are introduced. The system stability is better than 1% (10 hours), and the sensitivity is better than 1 s.f.u. Preliminary results from the 2017 trial observations of the Mingantu Solar Radio Telescope are presented.

Full Text

Research on Real-time Correction Method of Laser Ranging Prediction for Non-cooperative Targets

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Abstract

Laser ranging predictions for non-cooperative targets are typically extrapolated from Two-Line Element sets (TLE) and often exhibit significant deviations that substantially impact laser ranging success rates. Based on orbital theory for space targets and analysis of actual measurement data, we identify that prediction errors primarily stem from discrepancies between the mean anomaly of the space target in its orbit as extrapolated by the prediction model and the actual mean anomaly. By utilizing the miss distance of non-cooperative targets within the telescope' s tracking field of view, relevant algorithms can determine an optimal time element deviation to correct the target' s mean anomaly. After correction, the apparent position deviation of the space target is significantly improved, with distance deviations reduced from several hundred meters to tens of meters. This enhancement improves the accuracy of expected echo arrival times, enabling higher-precision distance gating for single-photon detectors and increasing ranging success rates.

Keywords: real-time correction; time element deviation; non-cooperative target; orbit prediction

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Laser ranging technology is a comprehensive discipline encompassing laser physics, electronics, astronomical measurement, and satellite orbit calculation. The actual operation is a highly complex process influenced by multiple factors including target characteristics, telescope pointing errors, distance, and receiver aperture size. Among these factors, the accuracy and stability of space target orbit predictions directly affect whether the laser pulses emitted by the ranging telescope can continuously reach the target surface and whether the single-photon detector at the receiver can promptly detect echo photons, thereby significantly impacting laser ranging success rates.

Satellite laser ranging systems widely employ range gating technology—a form of temporal filtering that effectively prevents noise interference. This technique involves sending an opening pulse to the single-photon detector just before the expected echo arrival time, minimizing the probability of noise interference and making it possible to detect single photons that would otherwise be drowned out by numerous noise sources [**?**].

Laser ranging predictions for non-cooperative targets loaded into tracking telescopes are generally extrapolated from Two-Line Element (TLE) sets using the Simplified General Perturbations Version 4 (SGP4) orbit propagator [**?**]. These predictions often exhibit substantial deviations during target tracking, primarily manifesting as position errors in the telescope' s field of view and distance errors between the station and the target. Excessive apparent position deviation prevents laser pulses from hitting the target, while large predicted distance deviations between the station and target cause significant mismatches between expected and actual echo arrival times, resulting in the single-photon detector' s range gate failing to capture echo photons.

The real-time correction method for non-cooperative target laser ranging predictions proposed in this paper operates as follows: First, the original TLE-based prediction is used to track visible non-cooperative targets for several minutes to obtain miss distance data in the telescope' s tracking field of view. Based on this information, the time element deviation is solved, and the orbit prediction is corrected using this deviation before being reloaded into the telescope to continue tracking the target. Laser ranging satellites (such as Ajisai, Beacon-

C, Starlette, Stella, etc.) have both TLE and CPF (Consolidated Prediction Format) predictions. Reference [?] compared CPF ephemerides for medium-low orbit satellites with precise orbits determined from global laser tracking station observations, showing CPF ephemeris accuracy within the meter level. Reference [?] analyzed that when using the SGP4 model for near-Earth objects, orbit determination accuracy is at the hundred-meter level. To exclude the influence of telescope pointing errors and other ranging system errors and theoretically prove the effectiveness of this method, this paper treats medium-low orbit laser ranging satellites as non-cooperative targets for research and analysis, using the CPF predictions of visible laser satellites during a certain period as reference values (i.e., simulated observations). The target' s miss distance is represented by the azimuth and elevation angle deviations between TLE predictions and CPF predictions at the same epoch, followed by time element deviation calculation and orbit prediction correction.

1.1 Time System Conversion

Coordinated Universal Time (UTC) is a corrected atomic time system used as the input and output time parameter for space target states and observation data. Greenwich Sidereal Time (GST) θ_G is a key parameter for coordinate system conversion, thus requiring calculation of θ_G from UTC, as detailed in Reference [?].

1.2 Conversion Between TEME and Station Local Coordinate Systems

Position information for space targets extrapolated by prediction models is expressed in the True Equator Mean Equinox (TEME) coordinate system, while laser ranging telescopes use orbit predictions expressed in the station local coordinate system. Therefore, conversion from TEME to station local coordinates is necessary, as illustrated in [Figure 1: see original paper].

The transformation involves several steps. First, the rotation matrix $R_z(\theta_G)$ is defined as:

$$R_z(\theta_G) = \begin{pmatrix} \cos\theta_G & -\sin\theta_G & 0 \\ \sin\theta_G & \cos\theta_G & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

where $\vec{R}$ is the position vector of the space target in the TEME coordinate system, $R_z(\theta_G)$ is the transformation matrix, θ_G is Greenwich Sidereal Time, $\vec{r}$ is the position vector of the space target in the Earth-fixed coordinate system, $\vec{\rho}$ is the position vector in the station local coordinate system, and $\vec{r}_{sta}$ is the position vector of the laser ranging telescope in the Earth-fixed coordinate system. The complete transformation matrix (M_{LT}) is given by:

$$(M_{LT}) = R_x(-\phi)R_z(\lambda + \theta_G) \tag{2}$$

where

$$R_x(-\phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix} \tag{3}$$

and

$$R_z(\lambda + \theta_G) = \begin{pmatrix} \cos(\lambda + \theta_G) & -\sin(\lambda + \theta_G) & 0 \\ \sin(\lambda + \theta_G) & \cos(\lambda + \theta_G) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4}$$

Here, ϕ and λ represent the latitude and longitude of the laser ranging telescope station, with $R_x(-\phi)$ and $R_z(\lambda + \theta_G)$ being transformation matrices.

1.3 Aberration Correction

For laser ranging of medium-low orbit space targets, the distance between the station and target often reaches several thousand kilometers. During the laser pulse' s uplink and downlink propagation, the space target moves significantly relative to the station. Therefore, laser ranging typically uses the emission epoch to generate tracking files, meaning the telescope' s real-time pointing includes a lead amount. For this application, due to downlink aberration, the target' s visibility corresponds to a lagged prediction, using the laser reception direction as the simulated observation value. The CPF prediction's lead amount algorithm is as follows:

For a given epoch T, let the position vectors of the space target and station in the Earth-fixed coordinate system be $\vec{r}(X, Y, Z)$ and $\vec{r}_{sta}(X_0, Y_0, Z_0)$, respectively. The relative distance between station and target is $D = |\vec{r} - \vec{r}_{sta}|$. Without considering aberration, the laser pulse emission direction corresponds to the target' s predicted position at epoch T. The uplink propagation time is $T_{out} = D/c$, where c is the speed of light, and the target' s position vector in the station local coordinate system is $\vec{\rho}(\rho_x, \rho_y, \rho_z)$. When accounting for aberration, the laser pulse emission direction corresponds to the target' s predicted position at epoch $T_B = T + T_{out}$. The target's position vector in the station local coordinate system is $\vec{\rho}_B(\rho_{Bx}, \rho_{By}, \rho_{Bz})$. Special attention must be paid to the fact that the Earth-fixed coordinate system is a rotating frame, requiring appropriate corrections in calculations.

This yields the uplink aberration-induced lead amount for laser emission:

$$dA = A - A_B = \tan^{-1}\left(-\frac{\rho_y}{\rho_x}\right) - \tan^{-1}\left(-\frac{\rho_{By}}{\rho_{Bx}}\right) \tag{5}$$

$$dE = E - E_B = \tan^{-1}\frac{\rho_z}{\sqrt{\rho_x^2+\rho_y^2}} - \tan^{-1}\frac{\rho_{Bz}}{\sqrt{\rho_{Bx}^2+\rho_{By}^2}} \tag{6}$$

For the downlink aberration-induced lag amount in laser reception, geometric considerations show it is also dA, dE.

2.1 Theoretical Formulation

The orbital diagram of a space target in elliptical motion around Earth is shown in [Figure 2: see original paper]. The shaded area represents the fundamental plane (XY plane) of the geocentric celestial coordinate system O-XYZ, which approximates the J2000.0 mean equatorial plane, with the X-axis pointing near the J2000.0 mean equinox and the Z-axis pointing toward Earth' s north pole. Here, r is the orbital radius of the space target, $\vec{h}$ is the normal vector of the orbital plane, $\vec{N}$ is the vector through the orbit' s ascending node, and $\vec{e}$ is the vector through the orbit' s perigee. Ω is the longitude of the ascending node measured from the X-axis direction, i is the inclination between the orbital plane and fundamental plane, ω is the argument of perigee, and θ is the polar coordinate variable. The orbital polar equation is:

$$r(t) = \frac{a(1-e^2)}{1+e\cos(\theta-\omega)} \tag{7}$$

where a is the semi-major axis and e is the eccentricity. Both the argument of perigee ω and the polar coordinate variable θ are measured from the ascending node direction. Under perturbation, the elliptical orbit changes with time, and the ascending node direction also varies. The argument of perigee ω should be measured from this changing ascending node direction, while the polar coordinate variable θ remains measured from a defined invariant direction.

The mean anomaly M is defined as:

$$M = n(t-\tau) \tag{8}$$

measured from perigee, where n is the mean motion angular velocity. The mean anomaly of a space target is a time-dependent parameter that determines the target' s position on the elliptical orbit within the orbital plane at a given epoch. When $t=\tau$, $M=0$, and correspondingly, the space target is at perigee where r reaches its minimum value, making τ the epoch of perigee passage.

Space targets experience various perturbing forces during orbital operation, including Earth' s non-spherical gravitational effects, lunar and solar gravitational forces, atmospheric drag, and solar radiation pressure. For medium-low orbit space targets, atmospheric drag effects are particularly significant. Two-Line Elements account for long-term and periodic perturbation effects from Earth' s non-spherical gravity and lunar-solar gravitational forces, as well as gravitational resonance and orbital decay from atmospheric drag models. TLEs are "mean" elements that remove periodic perturbation terms using specific methods, with the SGP4 prediction model reconstructing these periodic terms using the same approach [**?**]. During observations, space targets often exhibit significant deviations from the telescope' s pointing center in the along-track direction, appearing either ahead of or behind the predicted position. The primary cause is that the SGP4 model' s atmospheric model is simplified to a single drag parameter B^*, and the along-track deviation can be simplified and attributed to time element τ deviation.

If the value of τ is appropriately adjusted during target tracking, the offset between the space target and telescope pointing center can be reduced, the distance between the target and station can be corrected, and tracking stability can be improved.

The algorithm for solving the time element τ deviation is as follows. Let the azimuth of the space target in the station local coordinate system be A, the elevation angle be E, and the distance from the station be s. The measured sequence is denoted as (t_i, A_i, E_i, s_i), where $i = 1, 2, 3, \dots, n$. When calculating predictions, the value of τ is appropriately adjusted by replacing τ with $\tau + \Delta\tau$, where $\Delta\tau$ is the adjustment amount. This means using the position vector $\vec{R}_i(X_i, Y_i, Z_i, t_i + \Delta\tau)$ in the TEME coordinate system instead of $\vec{R}_i(X_i, Y_i, Z_i, t_i)$:

$$\vec{r}(t) = R_z(\theta_G(t))\vec{R}(t + \Delta\tau), \quad \vec{\rho}(t) = (M_{LT})[\vec{r}(t) - \vec{r}_{sta}]$$

This yields the predicted sequence (t_i, A'_i, E'_i, s'_i) for $i = 1, 2, 3, \dots, n$. Let $\Delta A_i = A'_i - A_i$ and $\Delta E_i = E'_i - E_i$. When the following quantity reaches its minimum value over the tracking period:

$$RMS^* = \sqrt{\sum(\Delta A_i \cos E_i)^2 + \sum \Delta E_i^2}$$

the corresponding $\Delta\tau$ is the time element deviation of the prediction. This is a complex nonlinear problem that is difficult to solve directly. However, since the time element deviation only needs to be accurate to the millisecond level, a simple and direct approach is to perform a search within a certain range.

When the pointing information of the space target is corrected, the distance information is correspondingly corrected, thereby improving the precision of the single-photon detector' s range gate and increasing the probability of receiving echo photons.

2.2 Case Study

Laser ranging satellites such as Ajisai, Beacon-C, Starlette, and Stella are in near-Earth orbits with orbital heights similar to most non-cooperative targets and experience similar space environments, making them excellent proxies for studying non-cooperative targets that only have TLE predictions.

This paper analyzes the transit of the Stella laser ranging satellite. Stella has an orbital altitude of 792.3–803.1 km, placing it in the dense region of non-cooperative targets. When performing laser ranging on space targets, the distance between station and target often exceeds a thousand kilometers. During the laser pulse' s uplink and downlink propagation, the space target moves significantly relative to the station. The pointing lag amount is shown in [Figure 3: see original paper], where the horizontal axis represents seconds of the day and the vertical axes represent azimuth and elevation deviations. The lag amount fluctuates considerably, reaching up to several tens of arcseconds at its peak—a non-negligible factor when solving for time element deviation.

[Figure 4: see original paper] displays the time element deviation search results for Stella using tracking data from the first 1, 2, 3 minutes and the entire pass segment. The horizontal axis represents the time element deviation $\Delta\tau$, while the vertical axis shows the corresponding RMS^*. The search range for the time element is $[-100, 200]$ ms. As shown in the figure, whether using data from the first 1, 2, 3 minutes or the entire pass segment, each search yields a minimum value corresponding to time element deviations of 26 ms, 27 ms, 29 ms, and 32 ms, respectively, with no significant differences. For other laser ranging satellites, the time element deviation results based on different tracking durations are shown in .

**** The time element deviations of some Laser Ranging Satellites by using different duration of the tracking data.

Satellite	Orbital Altitude (km)	Pass Duration	First Minute (ms)	First Two Minutes (ms)	First Three Minutes (ms)	Full Pass (ms)
Ajisai	1479×1497	12min20s	-	-	-	-
Beacon-C	928.6×1305	8min30s	-	-	-	-
Starlette	805.5×1107	6min9s	-	-	-	-

Table 1 demonstrates that for these three laser ranging satellites during their visible pass periods, the time element deviations solved using the first 1, 2, 3 minutes and the entire pass segment show no significant differences. According to the principle of searching for time element deviation, longer tracking data segments yield more precise solutions, with the full pass segment theoretically providing the most accurate result. Considering the short pass durations of medium-low orbit targets, using the first minute of data to solve the time element deviation is ideal for application across the entire pass.

[Figure 5: see original paper] shows the deviations in elevation angle (a) and azimuth angle (b) between Stella' s orbit prediction corrected with different time element deviations (0 ms uncorrected, 26 ms, 27 ms, 29 ms, 32 ms) and the reference orbit.

[Figure 6: see original paper] illustrates the deviation amounts of Stella' s orbit prediction corrected with 0 ms (uncorrected) and 26 ms (first minute) compared with the reference orbit, plotted with $\Delta A \cos E$ on the horizontal axis and ΔE on the vertical axis.

After correction, the apparent position deviation of laser satellite Stella is significantly reduced, with minimal fluctuation amplitude. In Figure 5: see original paper, the solid line represents the residuals between the azimuth angle in Stella' s original TLE prediction and CPF reference values as a function of observation time, while the dashed lines below represent residuals between azimuth angles from TLE predictions corrected with 26 ms, 27 ms, 29 ms, and 32 ms and CPF reference values. Similarly, in Figure 5: see original paper, the solid line shows residuals between elevation angles in the original TLE prediction and CPF reference values, while the middle dashed lines represent residuals from predictions corrected with the aforementioned time element deviations.

[Figure 6: see original paper] plots $\Delta A \cos E$ versus ΔE for the entire tracking pass using corrections of 0 ms (uncorrected) and 26 ms (first minute). The results comprehensively demonstrate that after TLE prediction correction using time element deviation, the apparent position deviation is significantly reduced, fluctuating within a small range around a fixed value on the order of several arcseconds.

**** The mean value of the deviations of some Laser Ranging Satellites'corrected orbit predictions in azimuth angle and elevation angle and corresponding RMS^*.

Satellite	$\overline{\Delta A_0 \cos E_0}$	$\overline{\Delta E_0}$	$\overline{\Delta A_1 \cos E_1}$	$\overline{\Delta E_1}$	$\overline{\Delta A_2 \cos E_2}$	$\overline{\Delta E_2}$
Ajisai	-	-	-	-	-	-
Beacon-C	-	-	-	-	-	-
Starlette	-	-	-	-	-	-
Stella	-	-	-	-	-	-

Table 2 presents the mean deviations and corresponding position deviation RMS^* in azimuth and elevation angles between TLE predictions (uncorrected and corrected using time element deviations solved from the first minute and full pass) and CPF reference orbits for four near-Earth laser satellites. $\overline{\Delta A_0 \cos E_0}$ and $\overline{\Delta E_0}$ represent the mean deviations between original TLE predictions and the reference orbit across the entire pass. $\overline{\Delta A_1 \cos E_1}$, $\overline{\Delta E_1}$, $\overline{\Delta A_2 \cos E_2}$, and $\overline{\Delta E_2}$ represent mean deviations after correction using time element deviations solved from the first minute and full pass, respectively. The results show that the latter two RMS^* values are smaller than those of the original TLE predictions, indicating they are closer to the actual trajectory. The mean deviations in azimuth and elevation are also very similar, further demonstrating that the time element deviation solved from the first minute of tracking data can replace that from the full pass for orbit prediction correction.

[Figure 6: see original paper] shows the distance deviation between Stella' s predicted range and reference values after correction with different time element deviations (26 ms, 27 ms, 29 ms, 32 ms). The distance deviation is reduced from over 200 meters to several tens of meters, with more stable variation range.

**** The mean value of the deviations of some Laser Ranging Satellites'corrected orbit prediction in range and corresponding RMS.

Satellite	$\bar{D}_0$	RMS_0	$\bar{D}_1$	RMS_1	$\bar{D}_2$	RMS_2
Ajisai	-	-	-	-	-	-
Beacon-C	-	-	-	-	-	-
Starlette	-	-	-	-	-	-
Stella	-	-	-	-	-	-

Table 3 presents the mean deviations $\bar{D}_0$, $\bar{D}_1$, $\bar{D}_2$ and corresponding RMS values (RMS_0, RMS_1, RMS_2) for four near-Earth laser satellites' orbit predictions (uncorrected and corrected using time element deviations from the first minute and full pass) compared to CPF reference orbits. The mean range deviation is reduced from hundreds of meters to tens of meters or even several meters, with the RMS value decreasing by an order of magnitude, indicating significantly enhanced deviation stability. These results demonstrate that correcting TLE predictions based on time element deviation can improve the precision of single-photon detector range gating.

This paper introduces a real-time correction method for non-cooperative target laser ranging predictions. During the time element deviation search process, the $\Delta\tau$ value that minimizes RMS^* is adopted as the time element deviation for correcting the space target' s TLE prediction. Time element deviations searched using different tracking data durations show no significant differences, and the deviation solved from the first minute of data can be applied to the entire pass. The corrected TLE predictions are closer to the actual trajectory of space targets, with predicted distance deviations reduced from hundreds of meters to tens of meters or even several meters, enabling higher-precision range gating for single-photon detectors. The apparent position and predicted distance deviations of several space targets selected in this study are significantly improved after correction using this method.

References

[1] Li Zhulian, Xiong Yaoheng, He Miaochan, Zheng Xiangming, He Shaohui,

Fu Honglin. Principle of 1.2m Telescope Satellite Laser Ranging System[J]. *Astronomical Research & Technology*, 2008(03):248-252.

[2] Hoots F R, Roehrich R L. *Space Track Report No. 3—Models for Propagation of NORAD Element Sets*. Peterson: NORAD, 1980.

[3] Zhai Dongsheng, Tang Rufeng, Li Zhulian, Li Yuqiang, Xiong Yaoheng. A Study into Laser Pulse' s Impact on the Precision and Accuracy of the Diffuse Laser Ranging System[J]. *Astronomical Research & Technology*, 2016,13(03):326-332.

[4] Tang Meirong, He Lijuan, Zhai Dongsheng, Li Yuqiang, Tang Rufeng, Li Zhulian. Research on the Distribution of Echo Photons in Laser Ranging System[J]. *Astronomical Research & Technology*, 2017,14(01):32-38.

[5] Chen Guoping, He Bing, Zhang Zhibin, Dong Xiaojun. Precision analysis of CPF ephemeris[J]. *Publications of Shanghai Observatory of Chinese Academy of Sciences*, 2010(00):35-44.

[6] Wei Dong, Zhao Changyin. Precision analysis of SGP4/SDP4 model[J]. *Astronomical Journal*, 2009,50(03):332-339.

[7] Huang Cheng, Liu Lin. *Reference Coordinate System and Space Applications*[M]. Beijing: Electronic Industry Press, 2015.

[8] Li Yuqiang, Li Rongwang, Li Zhulian, Zhai Dongsheng, Fu Honglin, Xiong Yaoheng. Application research on space debris laser ranging[J]. *Infrared and Laser Engineering*, 2015,44(11):3324-3329.

[9] Liu Lin, Hu Songjie. *Theory and Application of Spacecraft Orbit Determination*[M]. Beijing: Electronic Industry Press, 2015.

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