

Article

Research on the Laser Ranging of Runaway Space Objects

Guanyu Wen ^{1,*}, Shuang Wang ², Yukun Zeng ¹, Tingyu Liu ¹, Mingliang Zhang ³, Zhipeng Liang ¹, Makram Ibrahim ⁴ , Xingwei Han ¹ and Chengzhi Liu ¹

¹ Changchun Observatory, National Astronomical Observatories, Chinese Academy of Sciences, Changchun 130117, China

² School of Mechanical Engineering, Jilin Communications Polytechnic, Changchun 130012, China

³ Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

⁴ National Research Institute of Astronomy and Geophysics, Helwan 11421, Cairo, Egypt

* Correspondence: wengy@cho.ac.cn

Abstract

With the increase in human space activities, there is a significant amount of space debris as well as defunct satellites that seriously threaten the safety of spacecraft in their orbits. The laser ranging technique is one of the most accurate methods of ground-based space target observation. Therefore, it is very meaningful to study efficient tracking and observation methods for defunct satellites and space debris. In this paper, time bias, which is in advance of the actual observation, was added by analyzing the deviation of the orbit prediction such as the time bias and range bias of the runaway space objects. A new method was used for the determination of the TB and RB in real-time tracking and in data processing. The data produced from the observation of the out-of-control targets, such as the Topex satellite and CZ-2C Long March Launch Vehicle, were presented and analyzed. Taking the laser ranging data of the Topex satellite obtained on 19 November 2019, as an example, the result of the first observation circle provided the initial time bias value for the second observation circle, proving that the laser ranging method for runaway space objects is effective. The results of this paper can effectively improve the acquisition efficiency of the defunct satellites.

Keywords: space debris; laser ranging; Changchun SLR station; orbit prediction; defunct satellites; acquisition efficiency

1. Introduction

With the continuous development of science and technology, human space activities are increasing; thus, there is a significant amount of space debris and defunct satellites in orbit. The space debris and the out-of-control satellites threaten the safety of spacecraft. Due to the potential harm of the space debris and the out-of-control objects, many countries all over the world are making great efforts to study the detection and recognition technology of space debris [1,2]. In the space object monitoring system, radar technology and electro-optical observation technology form the two fundamental pillars. Electro-optical technology itself encompasses various branches. Electro-optical arrays excel at wide-area search and initial orbit determination through passive angle measurement, whereas the laser ranging technology focused on in this paper represents another core branch within this system, dedicated to high-precision distance measurement. The innovation of this work lies in developing a laser ranging strategy for the real-time, precise tracking of non-cooperative targets like defunct satellites. This strategy is based on the real-time estimation and



Academic Editor: Paolo Tortora

Received: 15 January 2026

Revised: 8 February 2026

Accepted: 10 February 2026

Published: 14 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

closed-loop correction of time bias (TB) and range bias (RB). Advancements in ground-based laser ranging for non-cooperative targets continue to focus on improving detection sensitivity, real-time data processing, and prediction accuracy. Concurrently, the exploration of novel architectures and methodologies has expanded the field's horizon. For instance, intelligent mission-planning algorithms, such as the critical task aggregation-based NSGA-II algorithm for multi-satellite systems, are being developed to optimize the efficiency of surveillance and early-warning networks [3]. Furthermore, the conceptual and technical feasibility of space-based laser ranging systems for resident space object (RSO) detection is under active investigation, promising potential advantages in coverage and observational geometry [4]. These developments highlight a dual-track evolution: enhancing existing ground infrastructure while pioneering next-generation surveillance concepts. The present study, focusing on real-time tracking strategy optimization for ground-based SLR stations, contributes directly to the first track. It addresses a core operational challenge—the efficient initial acquisition of uncooperative targets—by refining in situ data utilization, thereby complementing broader advances in system-level planning and novel sensor architectures.

At present, space debris detection mainly relies on ground-based detection; however, the accuracy of the observation of the ground-based radar is about 100 m. Thus, it is impossible to conduct precise orbit determination [5,6]. Therefore, it is necessary to find a new method for the observation of out-of-control objects to carry out research on low-orbit and small-scale space debris tracking technology. It is known that the laser ranging technique is considered to be one of the most accurate methods to track artificial Earth satellites [7–12]. Many countries have been paying more and more attention to the space debris laser ranging (DLR) technique. Satellite laser ranging (SLR) is a high-precision space-geodetic technique. Beyond its application to space debris monitoring—the focus of this study—SLR fundamentally underpins modern earth science. It is essential for defining the International Terrestrial Reference Frame, measuring tectonic plate motions and geocenter motion, and deriving Earth orientation parameters. SLR data also contribute to determining Earth's gravity field, solid Earth tide parameters, and testing fundamental physics such as general relativity [13–15]. This robust scientific legacy, upheld by the global ILRS network, provides the foundation for its advanced adaptation to tracking non-cooperative targets like defunct satellites (debris laser ranging, DLR). Our work on real-time tracking strategies directly leverages this heritage to address pressing operational challenges in space situational awareness. In the United States, the 3.5 m telescope system located in the Starfire Optical Range of Cortland Air Force Base in New Mexico has carried out research in this field, including imaging and tracking space targets by laser ranging. In 1994, Fugate claimed to be able to carry out diffuse reflectance ranging for satellites 1000 km away [16]; in October 2002, Ben Greene of Australia announced that the Mt. Stromlo laser ranging station in Canberra has realized the ranging of 15 cm space debris that was 1250 km away by using a high-energy laser and large aperture telescope [2,17,18]. Since 2000, Chinese observatories, such as Shanghai Observatory, Yunnan Observatory, and Changchun Observatory, have successively carried out research on laser ranging technology for space debris that is conducive to enhancing the ability to analyze and predict space debris [12,19,20].

The Changchun station started space debris laser ranging at the end of 2013, using the 60 cm aperture laser ranging system. One of the main applications of the data is to prepare a database for space debris. Such a database will be very useful for the newly launched satellites as well as to prevent the working satellites from colliding with space debris [20].

The DLR with a high repetition system in Changchun has stable and reliable observational data; the observation results have reached a leading level internationally. By analyzing the observation characteristics of out-of-control satellites, this paper summarizes

the methods based on adjusting time bias and range bias. The correctness of the laser ranging method of the defunct Topex satellite was verified by taking the observation of the defunct Topex satellite, on 19 November 2019, as an example. This method can provide the research basis for the laser ranging of near-Earth space debris and other defunct satellites.

To this end, in order to obtain laser ranging data, it is necessary to analyze the main factors affecting the success rate of space debris laser ranging, as discussed in Section 2. In Section 3, the orbit preprocessing and estimation of deviations for the defunct satellites are explained. In Section 4, the determination method of the TB and RB used in the real-time tracking and in data-processing is explained. Finally, the methods used for the laser ranging experiment of Topex and the CZ-2C Long March rocket are given as examples; the results are given in Section 5.

2. Analysis of Laser Ranging Characteristics for the Defunct Satellites

The defunct satellites can be regarded as space debris; thus, the principle of laser ranging is basically the same as that of satellite laser ranging. The basic principle of the space debris laser ranging is to measure the round-trip time of the laser signal from the ground station to the space target. Only a few laser signals can return to the ground station. However, the defunct satellites are equipped with reflector mirrors; thus, the satellites have a stronger diffuse reflection signal and are easier to detect.

According to the lidar equation of a non-cooperative target, the average number of photoelectrons received by the detector n_0 is given by Equation (1) [2,21,22], as follows:

$$n_0 = \frac{\lambda \eta_q}{hc} \times \frac{E_t A_r \rho S \cos \theta}{\pi \theta_t^2 R^4} \times T^2 \times \eta_t \times \eta_r \times \alpha \quad (1)$$

where λ is the wavelength of the laser; η_q is the quantum efficiency of the detector; h is the Planck constant; c is the speed of light; E_t is the energy of the laser pulse; ρ is the reflectivity of the target surface; $\rho = 1$. S is the effective area of the reflective target; A_r is the effective area of the receiving telescope; $\cos \theta$ is the incident angle of the laser that reaches the reflector on the satellite; θ_t is the divergence angle of the laser beam; R is the range of the space target; T is the atmospheric transmission efficiency; η_t is the efficiency of transmitting optics; η_r is the efficiency of receiving optics; and α is the attenuation factor mainly caused by atmospheric effects.

The main factors affecting the success of the space debris laser ranging can be summarized as follows.

- Performance of the laser

One of the main important parameters is the energy E_t of a single laser pulse. It determines the number of photons emitted by a single pulse from the laser, which is proportional to the number of returned photons. The divergence angle θ_t of the laser is the embodiment of the energy distribution of the laser beam. The smaller the divergence angle, the more concentrated the energy distribution of the laser beam. On 19 November 2019, the defunct Topex satellite was about 1340 km away from the station. It is equipped with an angle reflector; for this reason, the satellite laser ranging system at Changchun can complete the observation without using a high-power laser;

- The detector

The detector is used to convert the optical signal to an electrical signal. It is a compensated single photo avalanche diode (C-SPAD) with a quantum efficiency of $\eta_q = 20\%$ [20];

- Effective reflection area of the target

This represents the area in which the target can receive the laser signal and reflects the reflection ability of the target to the laser, which is proportional to the number of returned photons. The range, R , is the height of the satellite's orbit, which reflects the flight distance of the laser beam from the ground station to the target. The number of returned photons decreases with the increase in distance. The retroreflector array of the defunct Topex satellite (as an example) has a diameter of 150 cm and therefore has better reflection characteristics;

- Effective area of receiving telescope

The effective area of the receiving telescope, A_r , indicates the ability of the telescope to collect the returned photons, which is an important index with which to measure the receiving ability of the telescope. The number of returned photons is directly proportional to the area of the receiving telescope. The effective aperture of the telescope used at the Changchun SLR station is 60 cm, which can meet the requirements of satellite ranging;

- The efficiency of laser energy in telescope transmission and atmosphere transmission

This refers to the laser energy loss caused by the laser beam passing through the telescope receiving/transmitting system and the atmospheric transmission system. It is a fixed consumption that must be considered in laser ranging and is proportional to the number of returned photons.

On 19 November 2019, the defunct Topex satellite was about 1340 km away from the station. According to the above analysis and substituting the values into equation 1, the average number of returned photoelectrons from a single pulse is computed to be 0.4. It indicates that the laser ranging of the defunct Topex satellite can be carried out by using the conventional satellite laser ranging system from the Changchun SLR station. However, due to the fact that the Topex satellite is close to the ground and out of control, it has some problems, including a fast transit speed and certain rotation. In the actual observation, we are required to do rapid acquisition and laser alignment. Therefore, this paper deals with the preprocessing and deviation estimation, and it also proposes the laser ranging method for the defunct satellites.

3. Orbit Preprocessing and Estimation of Deviations for Defunct Satellites

Firstly, according to the perturbation models used for the orbit prediction, the deviation value of laser ranging was estimated and analyzed. The simplified perturbed motion of a space object can be described by the two-body problem; the Earth's gravity becomes the only force that affects the motion of the spacecraft.

According to Newton's law of motion, the satellite's acceleration can be written as Equation (2):

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3} \mathbf{r} \quad (2)$$

where $\mathbf{r}^0$ represents the unit vector of the spacecraft pointing to the Earth's center and G is the gravitational constant, $G = 6.67259 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$ [23]. According to Equation (1), the prediction of the orbit under the two-body problem can be carried out through the initial conditions. The main perturbation models consist of the perturbations due to non-spherical perturbation of the Earth, tide, three-body gravitational, atmospheric drag, solar radiation pressure, and Albedo [23,24]. The second-order differential motion can be obtained from the perturbation acceleration of the spacecraft, as given by Equation (3):

$$\ddot{\mathbf{r}} = \mathbf{a}(t, \mathbf{r}, \dot{\mathbf{r}}) \quad (3)$$

where $\mathbf{r}$ and $\dot{\mathbf{r}}$ are the position and velocity vectors of the spacecrafts, respectively.

The acceleration of the spacecraft's perturbation is a nonlinear function of time. The nested Runge–Kutta–Fehlberg (RKF) numerical integration method was used to solve Equation (3) and the position and velocity of the spacecraft at the undetermined time was obtained [24].

Due to the special kinds of materials of the spacecrafts and the changing space environment, the parameters of the perturbation model are very complex. In this paper, the parameters, such as solar radiation pressure, damping coefficient, and area-to-mass ratio, were set as typical constants. The data of solar radiation flux $F_{10.7}$ are given as published by the National Geophysical Data Center of the United States. The main perturbation models [25–27] and their parameters are classified and presented in Table 1.

Table 1. Perturbation force models.

No	Perturbation Force	Model	Model Parameter
1	Nonspherical gravity of the Earth	EGM96	(1) Gravity parameter $\mu = 389,600.4415 \text{ km}^3/\text{s}^2$ (2) Earth radius $r = 6378.1363 \text{ km}$ (3) Earth rotation velocity $\omega = 7.292158553 \times 10^{-5} \text{ rad/s}$
2	Tide	solid tide, sea tide	IERS Convention 2003
3	Three-body perturbations	Earth, moon	(1) Gravitational constant of the sun: $1.327122000000 \times 10^{11} \text{ km}^3/\text{s}^2$ (2) Gravitational constant of the moon: $4.902801076000 \times 10^3 \text{ km}^3/\text{s}^2$
4	Solar pressure	shadow model: dual cone	(1) $C_R = 1.2$ (2) $S/M = 0.04 \text{ m}^2/\text{kg}$
5	Atmospheric drag	air density model: Jacchia–Roberts	(1) $C_D = 2.2$ (2) $A/M = 0.04 \text{ m}^2/\text{kg}$ (3) $F_{10.7} (2014) = 140; F_{10.7} (2015) = 125$

The Jacchia–Roberts model, with better comprehensive performance, was selected as the atmospheric density model. When the prediction time is more than 24 h, the position offset caused by solar radiation pressure and the three-body gravitational perturbation reaches 100 m, which shows strong periodic characteristics and large amplitude. In addition, the prediction itself has uncertainty, which may produce zero to hundreds of deviation values. Topex, as an example, has some characteristics of laser joint measurement; thus, it can be preprocessed by using the mathematical method of satellite laser ranging. Suppose that the observed value and the computed value at time t_i are $\rho_0(t_i)$, $\rho_c(t_i)$, respectively, then the residuals can be shown, as follows, in Equation (4):

$$\Delta\rho_i = \rho_0(t_i) - \rho_c(t_i) \quad (4)$$

To provide the correction of the real time for subsequent observation, the error of the predicted orbit can be roughly calculated by using the preprocessed data. These errors can be divided into two parts, the range bias (RB) and the time bias (TB). The range bias (RB) represents a fixed constant deviation between the predicted target range value and the actual range value at a given reference time. It primarily stems from inaccuracies in orbital dynamic models—such as atmospheric drag and solar radiation pressure coefficients—as well as the projection of errors like station coordinates onto the radial direction. The time bias (TB) indicates a time lag or advance in the predicted target position along the orbital track. TB mainly arises from along-track drift caused by errors in the initial state of

orbit integration, atmospheric density models, and similar factors. The solution process essentially involves fitting the optimal values for TB and RB through linear regression, based on a series of discrete observation residuals and their corresponding predicted range rates. Thus, Equation (4) can be rewritten, as given in Equation (5), where ρ_i is the satellite range variability and $\dot{\rho}_i$ is the satellite range rate:

$$\Delta\rho_i = RB + \dot{\rho}_i TB \quad (5)$$

According to Equation (5), the deviation of the orbit of the defunct satellites is composed of the time bias and range bias. In actual laser ranging, in order to make the defunct satellite more stable in the field of view, the time bias is used to modify the satellite position first in order to place it in the center of the imaging field of the CCD; that is, the satellite will be kept in the field of view during the observation by adding time bias manually. Then, the laser is launched, so that the laser tip can be aligned to the target. Finally, the range bias is adjusted to receive the echo signal from the laser. The values of the TB and RB in the real-time tracking and in the data-processing are explained in detail in the next section. The details of the method used for the laser ranging of the defunct satellites are explained in Section 5. The advantage of adding time bias in advance in the observation is that it avoids the movement of the satellite in the field of view caused by the time deviations, thus leading to the acquisition and tracking of the defunct satellites using the laser ranging technique.

4. The TB and RB Values in Real-Time Tracking and in Data-Processing

4.1. The Linear Regression Theory

In Equation (5), the pair of the time bias and range bias (TB, RB) is fitted for $\Delta\rho$ and $\dot{\rho}$ series by a linear regression approach. In general, there are usually formulas to fit the equation $y_i = ax_i + b$, $i = 1, 2, 3, \dots, n$, in which the coefficients a and b can be calculated as:

$$a = \frac{n\sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{n\sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2}, b = \frac{1}{n} \left(\sum_{i=1}^n y_i - a \sum_{i=1}^n x_i \right) \quad (6)$$

In fitting the TB and RB pairs, let $y_i = \Delta\rho_i$ and $x_i = \dot{\rho}_i$, so that the TB and the RB can be calculated as expressed in the formulas a and b , respectively.

4.2. The Application of the Linear Regression on Data

In order to explain the application of the linear regression on the used data, let us first clarify the used data, which are given in Table 2, which is an excerpt of the whole. The first column is the modified Julian date (MJD), the second column is the second of day (sod); the range residuals o-c (m) are the observed range minus the calculated range. $\dot{\rho}_i$ is the range rate of the target in (m/s), as given in Column 4. During the earlier (rising) half of the pass, the range rate is negative. During the latter (sinking) half, the range rate is positive. In the last column, the range in meters is given.

Table 2. Data sample produced from applying the linear regression of the target, CZ-2C, observed on 15 November 2019 at UTC 10 h.

MJD	Sod	o-c (m)	$\dot{\rho}_i$ (m/s)	Range (m)
58802	38,971.868000910021	35.1697	1581.8330	1,583,552.001
58802	38,971.889000905176	35.2246	1582.4680	1,583,585.285
58802	38,971.913000908462	35.2897	1583.1930	1,583,623.347

Table 2. *Cont.*

MJD	Sod	o-c (m)	$\dot{\rho}_i$ (m/s)	Range (m)
58802	38,972.106000904510	35.7892	1589.0260	1,583,930.000
58802	38,972.116000911024	35.8181	1589.3280	1,583,945.927
58802	38,972.121000908090	35.8173	1589.4790	1,583,953.869
58802	38,972.166000906655	35.9364	1590.8380	1,584,025.549

4.3. The Method Used in the Determination of TB and RB Values in Real-Time Tracking and in Data-Processing

To provide the orbital correction for subsequent observations, the error of the predicted orbit can be roughly calculated by using the preprocessed data. These errors can be decomposed into two variables, nominally the range bias (RB) and the time bias (TB), as given in Equation (5).

According to Equation (5), the deviation of the orbit of the defunct satellites is composed of TB and RB. In actual laser ranging, the system provides an interface for TB input in order to adjust and keep the target image centered in the field of view. This visual adjustment corresponds to the orbital along-track error of the target. Let us denote it as visual TB (TBV).

When the target is centered, the laser will be fired, so that the laser tip can be aligned to the target and the system will try to obtain echo signals from the target. When echo data are acquired, the system will be solved for temporary TB (TBT) and temporary RB (RBT) so as to correct the orbital range error and make it easier to acquire range data. In Changchun's case, the required data amount is 150 entries and the system will repeat the solution every one second.

After the acquisition of the whole pass, the TB and RB will be solved again in the preprocessing stage, when normal point data are generated. We denote them as preprocessed TB (TBP) and RB (RBP), corresponding to the satellite orbit error, observed in the station-implemented time and coordinate frame. This means that TBP and RBP contain the station clock and coordinate error.

Finally, in data centers where the satellite orbit is fit over the global station network, the data pass will be validated against the fitted reference 'true' orbit, so that the error will give other TB and RB values, which we denote as reference TB (TBR) and RB(RBR).

We can summarize the method as follows:

The TB and RB are components of the observed orbit error. The TBV is estimated from visual tracking of the target. The TBT and RBT are fit from the first bits of range data. The TBP and RBP are fitted from the whole range of data, as shown in Table 3. The above are compared against the predicted orbit. The TBR and RBR are fitted from the whole pass, against the reference orbit, as shown in Figure 1. In this paper, we use the TBP and RBP of the previous pass as the TBV of the current pass. This method showed a good output in the experiments. We noted that:

- The TBV cannot be recovered due to the lack of image capture and data logging in the system;
- The TBT/RBT can be recovered by fitting selected subsets of range data;
- The TBP/RBP can be recovered by fitting the whole pass;
- The TBR/RBR is not available in the case of defunct satellites.

Table 3. TBT/RBT data of a CZ-2C pass with piece size = 150 entries.

Target: CZ-2C No. 28480		Pass Time: 15 November 2019 UTC 10 h	
		TBP = 90.03 ms	RBP = −110.37 m
Piece Time in Seconds of the Day	Piece TBT in ms	Piece RBT in m	
38,971.868~38,995.957	86.59	−101.83	
38,995.971~38,997.379	87.56	−104.03	
38,997.381~39,000.410	87.81	−104.59	
39,000.447~39,001.533	87.84	−104.67	
39,001.534~39,002.888	88.09	−105.28	
39,002.889~39,004.298	88.06	−105.21	
39,004.300~39,005.286	88.28	−105.77	
39,005.293~39,006.147	87.84	−104.64	
39,006.148~39,007.220	88.29	−105.78	
39,007.227~39,009.058	88.4	−106.07	
39,009.062~39,010.531	88.48	−106.28	
39,010.532~39,011.525	88.68	−106.81	
39,011.527~39,013.013	88.69	−106.82	
39,013.014~39,013.979	88.64	−106.68	
39,013.980~39,015.638	88.99	−107.65	
39,015.642~39,016.675	89.04	−107.79	
39,016.680~39,017.475	89.16	−108.13	
39,017.476~39,018.147	89.22	−108.31	
39,018.149~39,019.223	89.27	−108.43	
39,019.252~39,019.867	89.42	−108.87	
39,019.870~39,020.996	89.4	−108.82	
39,021.028~39,021.987	89.33	−108.61	
39,021.992~39,023.237	89.53	−109.21	
39,023.242~39,023.875	89.39	−108.78	
39,023.881~39,024.537	89.76	−109.88	
39,024.540~39,025.734	89.82	−110.06	
39,025.741~39,026.551	89.3	−108.49	
39,026.560~39,027.566	90.12	−111	
39,027.571~39,028.774	90.23	−111.33	
39,028.777~39,029.839	89.78	−109.93	
39,029.840~39,031.046	90.23	−111.32	
39,031.064~39,032.415	90.65	−112.68	
39,032.479~39,033.799	90.15	−111.07	
39,033.807~39,035.110	90.63	−112.64	
39,035.113~39,036.500	90.57	−112.43	
39,036.520~39,037.640	90.72	−112.91	
39,037.648~39,041.013	90.9	−113.5	

Table 3. Cont.

Target: CZ-2C No. 28480	Pass Time: 15 November 2019 UTC 10 h	
	TBP = 90.03 ms	RBP = −110.37 m
Piece Time in Seconds of the Day	Piece TBT in ms	Piece RBT in m
39,041.018~39,042.439	91.33	−114.97
39,042.451~39,043.477	91	−113.86
39,043.478~39,045.134	91.5	−115.58
39,045.184~39,047.808	91.57	−115.82
39,047.817~39,049.221	91.59	−115.9
39,049.250~39,052.401	91.87	−116.9
39,052.412~39,054.475	91.95	−117.21
39,054.480~39,056.172	92.26	−118.33
39,056.173~39,058.250	92.27	−118.36
39,058.251~39,062.462	92.61	−119.66
39,062.488~39,066.034	92.89	−120.72
39,066.039~39,068.766	93.12	−121.65

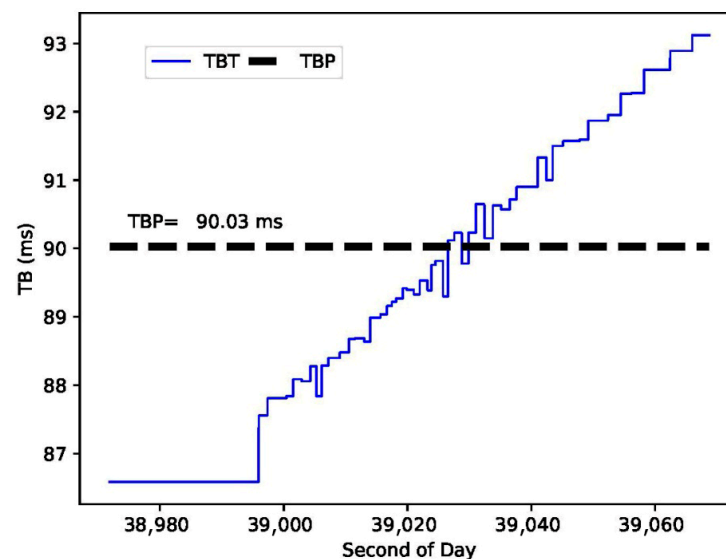


Figure 1. Progressive TBT vs pass-average TBP for the satellite CZ-2C, as observed on 15 November 2019 during the first transit, at 10 h, UTC.

The TBTs are evaluated progressively, with real-time range data, in pieces of 150 entries, while the TBP is batch-evaluated with whole-pass data.

5. The Laser Ranging Experiment of the Defunct Satellites

The process of the specific experiment for the observation of the defunct satellites can be described as follows.

Firstly, the time bias is adjusted to move the spot to the middle of the display. Then, the laser tip is used to align the spot of the satellite. The value of the time bias of the spot is adjusted to the center position of the pre-processing adjusted time bias. Finally, the laser ranging data of the defunct satellite are obtained. The standard points can be obtained by fitting using the cubic spline method [28]. Then, by comparing with the predicted data results, we can obtain the time bias and range bias.

The results of the experiment were applied many times for the defunct Topex satellite and the CZ-2C Long March rocket; the results are given in Table 4. Figure 2 shows the laser ranging experiment for Topex, which was observed on 19 November 2019. The time and range biases of the satellite during the first transit are shown in Figure 3. Applying a time bias to the observational process makes it easier to receive the echo signal from the laser and obtain the observational data. The standard points can be obtained by fitting using the cubic spline technique. Then, the time bias and range bias are obtained by comparing the predicted data. Figure 4 shows the observed range. After processing the results of the data, it can be seen that the Topex satellite has an obvious out-of-control rotation phenomenon. The time bias of the data-processing is 127.09 ms, which is very close to the 120 ms of the pre-processing adjusted time bias; the range bias is -275.02 m, as shown in Figure 5. Moreover, the Topex satellite did not significantly move in the imaging system, which proves that adding the time bias in advance can improve the tracking of the defunct satellite. Calibration system delay represents the actual, measured instrumental system delay in nanoseconds (ns). It is a constant for the Changchun SLR system during the campaign, determined through regular calibration procedures against known ground targets and satellite passes.

Table 4. Time bias and range bias produced from two defunct satellites through November 2019.

Sat.	Date	S. T (UTC)	P (mb)	T °(c)	H %	Calibration System Delay (ns)	Nr of Points for Process	TB (ms)	RB (m)
Topex	15 November 2019	17:00	989.1	−9.3	73	209.65	10,321	62.17	−163.19
Topex	15 November 2019	18:50	989.9	−9.0	59	209.64	53,124	56.21	−141.1
Topex	19 November 2019	18:23	996.2	−13.3	66	209.68	45,218	127.09	−275.02
Topex	19 November 2019	20:21	996.1	−14.2	82	209.62	62,085	123.89	92.58
Topex	20 November 2019	16:52	996.7	−11.0	86	209.65	101,970	40.73	−100.65
Topex	20 November 2019	20:45	995.9	−11.5	90	209.65	15,163	48.21	2.45
Cz-2C	15 November 2019	10:42	988.4	−7.3	47	209.67	7415	90.03	−110.37
Cz-2C	15 November 2019	12:21	988.9	−6.9	72	209.67	8307	97.58	−4.86
Cz-2C	18 November 2019	11:07	984.3	−9.4	57	209.64	3097	90.13	−166.24
Cz-2C	18 November 2019	12:47	984.5	−10.3	55	209.62	4345	101.52	16.25



Figure 2. The laser ranging experiment for Topex on 19 November 2019.

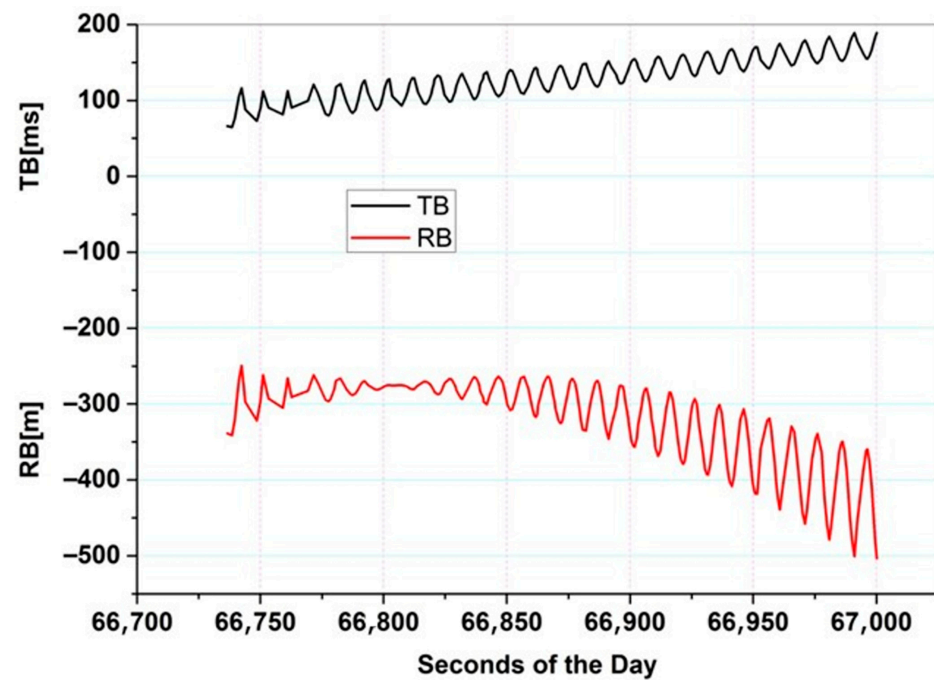


Figure 3. The time bias and range bias of the Topex satellite during the first transit.

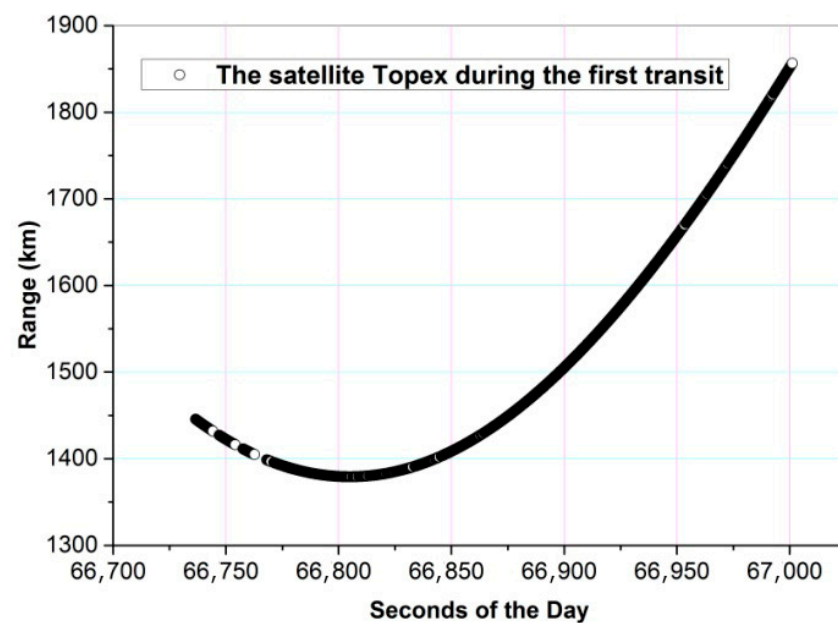


Figure 4. The range of Topex during the first transit.

For the second transit, by applying the value of the time bias that we obtained from the first pass, the system in the second pass recognized the data more quickly. The experimental results indicate that during the second pass, applying the prior TB value from the first pass reduced the initial data acquisition time by approximately 60%, on average. Specifically, the first pass typically required about 30–60 s for manual adjustment and signal search to obtain stable echoes, whereas the second pass shortened this process to within 10–20 s, significantly extending the effective observation arc and improving data acquisition efficiency. Although, in the second pass, the object is invisible (not illuminated by the sun), the data are acquired easily. In the second transit of Topex, which starts at 20:21 (nearly two hours later than the first transit), the time bias to 120 ms of the second round of data-processing in advance is adjusted when the angle is low; then, the laser is launched. The operation of the laser

ranging of Topex during the second transit is shown in Figure 6. The observational data after partial noise filtering for Topex during the second transit are shown in Figure 7.

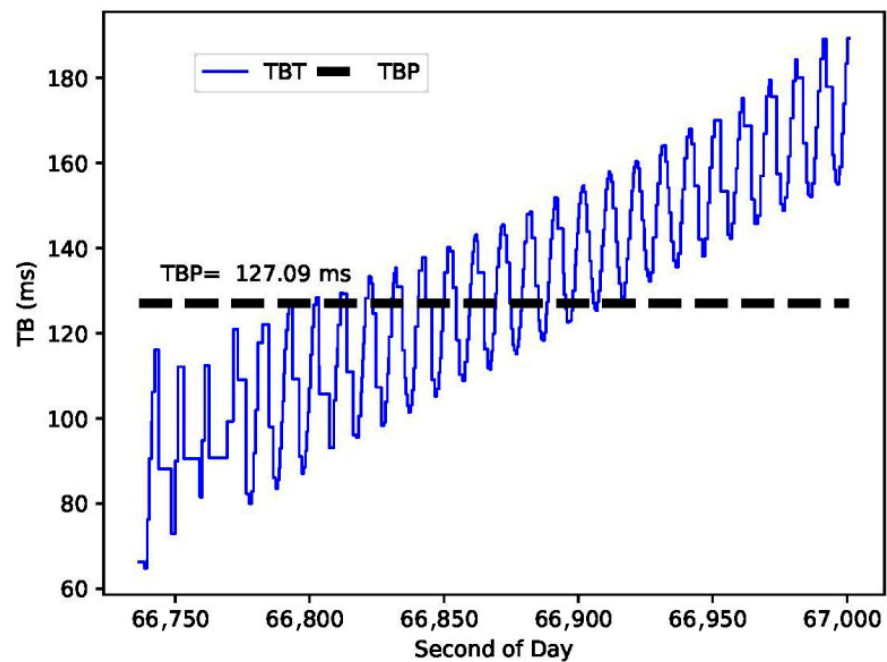


Figure 5. The time bias of the data-processing result is 127.09 ms and the range bias is -275.02 m, according to Topex during the first transit.

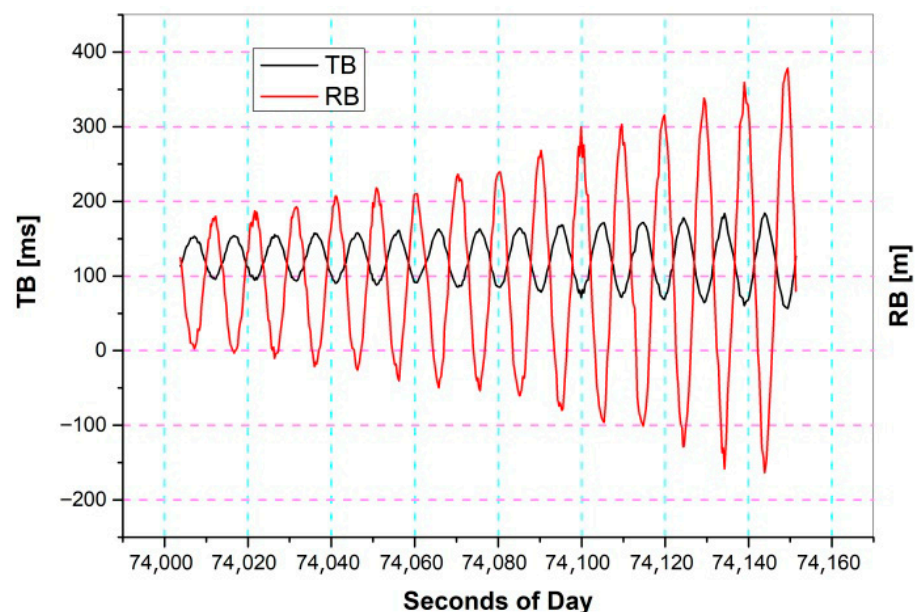


Figure 6. The time bias and range bias of the Topex satellite during the second transit.

After the data-processing, the time bias of the second round of the Topex satellite is 123.89 ms and the range bias is 92.58 m, when the Topex satellite was added in advance, as shown in Figure 8. The value of the deviation between them is helpful to reduce the distance threshold, and the system can easily identify the data. That is, from the fitting of the second pass; few changes in are seen in the time bias from the first pass. Therefore, use of the first-time bias on the second pass will help the orbit correction of Topex.

Meanwhile, on 15 November 2019, the same method was applied for the CZ-2C Long March rocket. In the first transit, the time bias was 90.03 ms, which is very close to the

85 ms of the pre-processing adjusted time bias, and the range bias was -110.37 m. In the second transit, CZ-2C's time bias was adjusted in advance by using the data provided for the first time when it was not visible. Through the method, the experimental data were obtained. At this time, the time bias was 97.58 ms and the range bias was -4.86 m, which proved that the method has a strong practical value for the laser ranging observation of the runaway space targets.

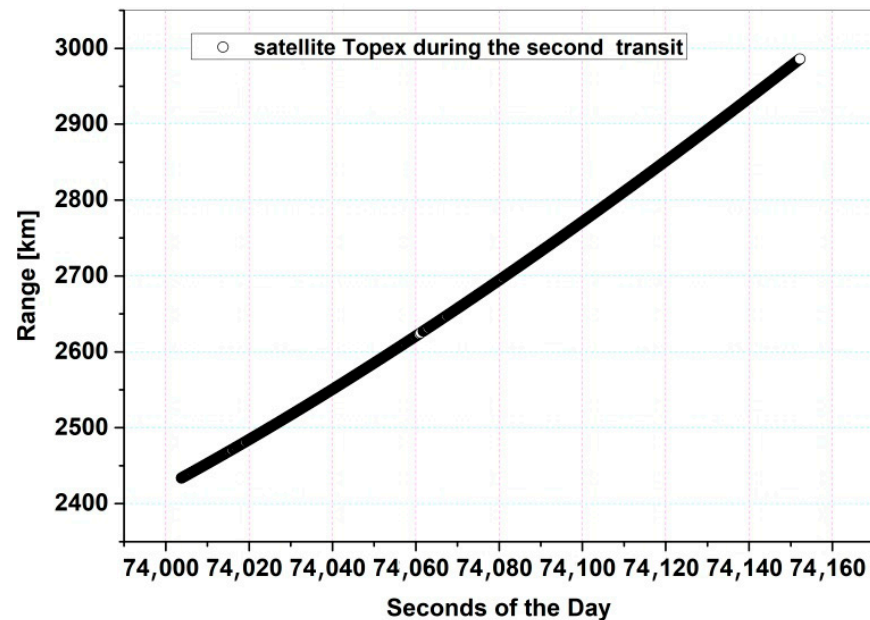


Figure 7. The laser ranging measurement data of Topex during the second transit.

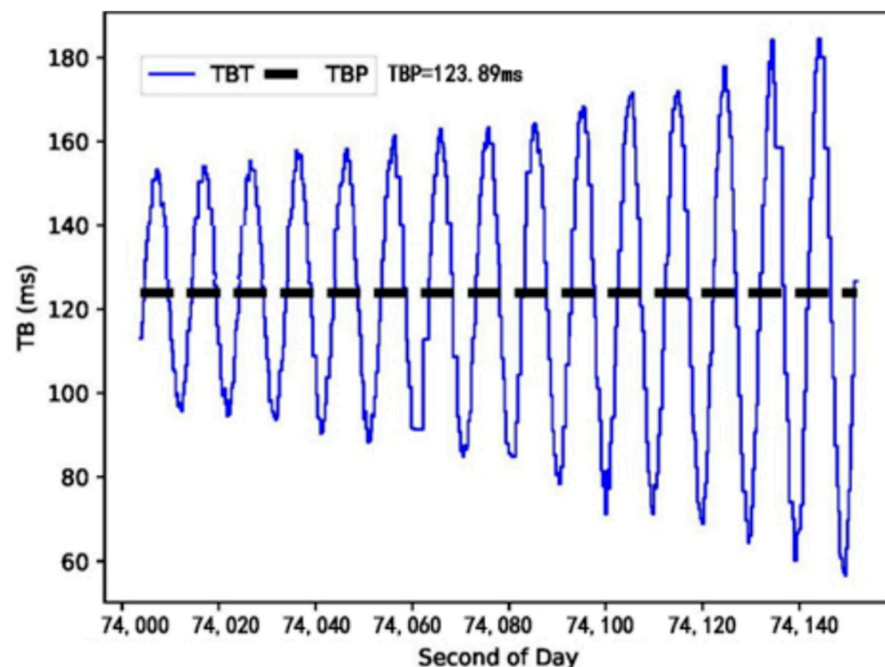


Figure 8. The time bias of the data-processing result is 123.89 ms and the range bias is 92.58 m, according to Topex during the second transit.

Generally, the described method was applied to two defunct satellites, Topex and CZ-2C, as two examples. The first transit and the second transit were applied with a nearly two-hour time difference. The results obtained for the trials of Topex and CZ-2C were computed; the results are given in Table 4. The first column shows the name of the object,

the date of the observation, the starting time of tracking, the pressure, temperature, and the humidity at the time of tracking, the system delay of the calibration, the number of points used for processing the results, the time bias, and the range bias, respectively.

In the table, we can notice that the methods were applied three times for Topex on 15, 19, and 20 November 2019, and two times for the CZ-2C on 15 and 18 November 2019. The range bias and the time bias are given in the last two columns for the first transit and the second transit, respectively.

6. Conclusions

We introduced a method to observe defunct satellites and the runaway space objects. The method uses the laser ranging technique, as applied to the known method of satellite laser ranging (SLR). In this method, the time bias produced from analyzing the deviations of the orbit prediction of the runaway space objects is added in advance. Then, the observational data from the out-of-control objects (defunct satellites or space debris) are obtained. We applied this method to the defunct Topex satellite and CZ-2C Long March rocket body; the observational data were obtained many times by adding time bias in advance. The results are given in Table 4.

As an example, by applying the laser ranging for the defunct Topex satellite on 19 November 2019, we found that the time bias of the data-processing result is 127.09 ms, which is very close to the 120 ms of the pre-processing time bias, and the range bias is −275.02 m. For the second transit, by applying the time bias we obtained from the first pass, the system in the second pass can recognize the data more quickly. Although the second pass is invisible, the data can be acquired easily. In the second transit of Topex, which starts at 20:21, the time bias of the second round of the Topex satellite is 123.89 ms, and the range bias is 92.58 m. It is clear that the value of the deviations between them is helpful to reduce the distance threshold; the system can easily identify the data. This means that using the first-time bias on the second pass will help in the orbit correction. It proves that the laser ranging method for runaway space targets is effective. The method proposed in this paper achieves rapid acquisition and high-precision ranging of defunct space targets by decomposing orbit prediction deviations into time bias (TB) and range bias (RB) in real time and applying them collaboratively during observation and data processing. The core advantage of this approach lies in its use of observational results from a prior pass to optimize tracking parameters for the next pass in real time, forming an enhanced closed-loop cycle of “observation–processing–correction–reobservation.” Practical applications show that this strategy effectively addresses challenges, such as inaccurate orbit prediction and short transit times for defunct targets, thereby improving target acquisition efficiency. It holds significant engineering value for safeguarding in-orbit spacecraft and constructing space debris databases.

Author Contributions: Conceptualization, G.W. and S.W.; methodology, Y.Z.; software, M.Z.; validation, G.W., T.L. and M.I.; formal analysis, M.Z.; investigation, Z.L.; resources, X.H.; data curation, S.W.; writing—original draft preparation, G.W.; writing—review and editing, Y.Z.; visualization, X.H.; supervision, C.L.; project administration, C.L.; funding acquisition, G.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Jilin Provincial Department of Science and Technology under the Science and Technology Development Plan Project of Jilin Province. Grant numbers and project titles are as follows: Grant No. 20240404064ZP (“Telescope Laser Ranging and Communication Integration Transformation Project”, Innovation Guidance—Research Infrastructure and Condition Support Program, Large-Scale Scientific Instrument Function Development Project). Grant No. 20250201093GX (“Autonomous Driving System for Sightseeing Buses in Scenic Areas”, Key R&D

Program—High-tech Field, Advanced Manufacturing—Key Technologies for Automobiles and Rail Transit Vehicles).

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to the data policy of Changchun Observatory, National Astronomical Observatories, CAS, which restricts public dissemination of satellite observation data for institutional and operational reasons.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. No external funding, personal relationships, or competing interests influenced the design, execution, or reporting of this study. All authors have reviewed and approved this declaration, and confirm that no conflicts of interest exist.

References

1. Maag, C.R.; Deshpande, S.P.; Stevenson, T.J.; Mitzen, P.S. Orbital debris environment as measured at the Mir space station. In *Characteristics and Consequences of Orbital Debris and Natural Space Impactors*; SPIE: Bellingham, WA, USA, 1996; Volume 2864, pp. 69–75.
2. Zhang, Z.; Yang, F.; Zhang, H.; Wu, Z.; Chen, J.; Li, P.; Meng, W. The use of laser ranging to measure space debris. *Res. Astron. Astrophys.* **2012**, *12*, 212–218. [\[CrossRef\]](#)
3. Gu, Y.; Li, Z.; Liu, H.; Luo, Q.; Liu, H.; Wu, G. Multi-objective early warning mission planning by multiple satellites using a critical task aggregation-based NSGA-II algorithm. *Adv. Space Res.* **2025**, *in press*. [\[CrossRef\]](#)
4. Ediger, W.M.; Ferguson, P.A. Feasibility of Space-Based Laser Ranging for Resident Space Object Detection. In *AIAA SCITECH 2025 Forum*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2025.
5. Liang, Z.; Han, X.; Fan, C.; Liu, C. Laser ranging observation and orbit determination of rotating reflective CZ-2C rocket stage. In *Proceedings of the 20th International Workshop on Laser Ranging*, Potsdam, Germany, 9–14 October 2016.
6. Sang, J.Z.; Bennett, J.C. Achievable debris orbit prediction accuracy using laser ranging data from a single station. *Adv. Space Res.* **2014**, *54*, 119–124. [\[CrossRef\]](#)
7. Han, X.; Dong, X.; Song, Q.; Zhang, H.; Shi, J. Fulfillment of KHz SLR daylight tracking of Changchun Station. In *Proceedings of the 17th ILRS Meeting*, Fujiyoshida, Japan, 11–15 November 2013.
8. Ibrahim, M.; Hanna, Y.S.; Samwel, S.W. Statistical and comparative studies for the observations of Helwan-SLR station. *Int. J. Nonlinear Sci. Numer. Simul.* **2004**, *5*, 135–147. [\[CrossRef\]](#)
9. Ibrahim, M. 17 years of ranging from the Helwan-SLR station. *Astrophys. Space Sci.* **2011**, *335*, 379–387. [\[CrossRef\]](#)
10. Kirchner, G.; Koidl, F. Graz KHz SLR system: Design, experiences and results. In *Proceedings of the 14th International Workshop on Laser Ranging*, San Fernando, Spain, 7–11 June 2004.
11. Pearlman, M.R.; Degnan, J.J.; Bosworth, J.M. The International Laser Ranging Service. *Adv. Space Res.* **2002**, *30*, 135–143. [\[CrossRef\]](#)
12. Zhao, Y.; Fan, C.; Han, X.; Liu, C.; Li, Z.; Song, Q.; Dong, X. Design and development of an optoelectronic detecting system for space debris. In *Proceedings of the International Conference on Optical Instruments and Technology: Optical Systems and Optoelectronic Instruments*, Beijing, China, 16–19 November 2008; SPIE: Bellingham, WA, USA, 2009; Volume 7156, p. 71560O.
13. Arnold, D.; Montenbruck, O.; Hackel, S.; Sosnica, K. Satellite laser ranging to low Earth orbiters: Orbit and network validation. *J. Geod.* **2019**, *93*, 2315–2334. [\[CrossRef\]](#)
14. Otsubo, T.; Matsuo, K.; Aoyama, Y.; Yamamoto, K.; Hobiger, T.; Kubo-Oka, T.; Sekido, M. Effective expansion of satellite laser ranging network to improve global geodetic parameters. *Earth Planets Space* **2016**, *68*, 65. [\[CrossRef\]](#)
15. Rutkowska, M.; Jagoda, M. Estimation of the elastic earth parameters using slr data for the low satellites STARLETTE and STELLA. *Acta Geophys.* **2012**, *60*, 1213–1223. [\[CrossRef\]](#)
16. Kirchner, G.; Koidl, F.; Friederich, F.; Buske, I.; Völker, U.; Riede, W. Laser measurements of space debris from Graz SLR station. *Adv. Space Res.* **2013**, *51*, 21–24. [\[CrossRef\]](#)
17. Myrtille, L.; Sebastien, W.; Florent, D. First astrometric observations of space debris with the MEO telescope. *Adv. Space Res.* **2011**, *49*, 603–611.
18. Sang, J.; Smith, C.; Zhang, K. Towards accurate atmospheric mass density determination using precise positional information of space objects. *Adv. Space Res.* **2012**, *49*, 1088–1096. [\[CrossRef\]](#)
19. Gong, Z.Z.; Xu, K.; Mu, Y.; Cao, Y. The space debris environment and the active debris removal techniques. *Spacecr. Environ. Eng.* **2014**, *31*, 129–135.
20. Liang, Z.; Dong, X.; Ibrahim, M.; Song, Q.; Han, X.; Liu, C.; Zhang, H.; Zha, G. Tracking the space debris from the Changchun Observatory. *Astrophys. Space Sci.* **2019**, *364*, 201. [\[CrossRef\]](#)

21. Ibrahim, M.; Abd El-Hameed, A.; Attia, G. Analytical studies of laser parameters for ranging and illuminating satellites from H-SLR station. *Space Res. J.* **2010**, *4*, 71–78. [[CrossRef](#)]
22. Ibrahim, M.; Abd El-Hameed, A.; Liang, Z.; Han, X. Analytical investigation for the satellite ranging data of Changchun SLR station. *NRIAG J. Astron. Geophys.* **2020**, *9*, 321–329. [[CrossRef](#)]
23. Montenbruck, O.; Gill, E. Satellite Orbits-Models, Methods and Applications. *Appl. Mech. Rev.* **2002**, *55*, B27–B28. [[CrossRef](#)]
24. McCarthy, D.; Petit, G. (Eds.) *IERS Technical Note No.32*; IERS Conventions Centre: Paris, France, 2003.
25. Combrinck, L.; Suberlak, V. Earth-tide as parameter of crustal motion correction for SLR station displacement. *S. Afr. J. Geol.* **2007**, *110*, 203–210. [[CrossRef](#)]
26. Li, Y.; Wang, X.; Zhong, S.; Xi, K. The influence of considering atmospheric wind field for atmospheric drag on SLR orbit determination. *Adv. Space Res.* **2024**, *74*, 975–986. [[CrossRef](#)]
27. Panzetta, F.; Blossfeld, M.; Erdogan, E.; Rudenko, S.; Schmidt, M.; Mueller, H. Towards thermospheric density estimation from SLR observations of LEO satellites: A case study with ANDE-Pollux satellite. *J. Geod.* **2019**, *93*, 353–368. [[CrossRef](#)]
28. Hanna, Y.S.; Ibrahim, M.; Samwel, S.W. On using Chebyshev polynomials for fitting SLR data of artificial satellites. *Appl. Math. Comput.* **2004**, *158*, 655–666. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.