Laser ranging observation and orbit determination of rotating reflective CZ-2C rocket stage

Zhi-peng LIANG*,　Xing-wei HAN,　Cun-bo FAN,　Cheng-zhi LIU

(Changchun Observatory, National Astronomical Observatories of Chinese Academy of Sciences, Jingyuetan Lake, Changchun Jilin China, 130117)

*Corresponding: LIANGZP@CHO.AC.CN

ABSTRACT

Changchun Observatory discovered a CZ-2C rocket stage to be highly reflective, and later tracked it with kilo-hertz satellite laser ranging (SLR) technique. We carried out an experiment of laser ranging and precise orbit determination of the CZ-2C rocket stage. Firstly, we used two line element (TLE) for tracking prediction and acquired data. Then we performed orbit improvement with single-station orbit determination method. Finally, prediction is generated from the improved orbit, and orbit verification is done with new observation data. Experiment results showed that the accuracy of improved orbit to be 0.33 km. The experiment realized kilo-hertz laser ranging to CZ-2C rocket stage in full daylight low SNR conditions, and data analysis exhibits rotation of the rocket stage. We conclude that single-station orbit improvement satisfies the required accuracy of space debris laser ranging, and is sufficient for single laser ranging station to track space debris sustainably and independently.

Key words: Satellite laser ranging (SLR); Space debris; Orbit determination; Rocket stage; Astrodynamics;

1. Introduction

Space debris or orbital debris, are by-products of space operations. Types of space debris include abandoned vehicles, rocket bodies and collision fragments, etc.. Space debris with size greater than 10cm are over 16,000 pieces[1], posing threat to space operations. Current measures taken to big space debris pieces are collision forecast and vehicle maneuver, the latter would consume fuel and reduce vehicle life span. The quality of collision forecast depends on the orbit of space debris, which is publicly provided with two line elements or TLE calculated by AFSPC of US department of defense, with kilometer accuracy. Collision forecast based on TLE orbits would produce too much false alarm, making it necessary to generate more accurate orbits [2-3].

Some institutes did research on using satellite laser ranging technique on space debris. Satellite laser ranging (SLR) is a technique that measures laser pulse travel time between ground station and satellite. For those satellites bearing dedicated retro-reflectors, the range resolution can be centimeter level. But laser pulse reflection on space debris is diffusive and range resolution depends on target shape. The first known to declare space debris laser ranging results was the Electro Optical Systems (EOS) of Australia, in 2002. The EOS target was about one thousand

kilometers away, in 10 cm size [4]. New results about sparse data orbit determination were reported from EOS in recent years [5,6]. In Europe, Graz station in Austria tracked space debris targets about 0.3 square meters small and 3000 km far [7,8]. In China, Shanghai Astronomical Observatory performed laser ranging to debris target far as 1000 km, giving 0.6-0.8 m precision [9,10]. Yunnan Observatory began their research in 2008, and acquired data in 2010 [11]. Other institutes in China, like National Observatory of Chinese Academy of Sciences and Beijing Institute of Tracking and Telecommunications Technology (BITTT), also did research on this topic [12,13].

Changchun Observatory in National Observatories of Chinese Academy of Sciences, is experienced in satellite laser ranging techniques. The SLR system of Changchun Observatory uses high repetition rate pico-second pulse laser, and 0.6 m aperture telescope as receiver. Since 2012, Changchun Observatory builds and improves space debris laser ranging system (SDLRS) with high repetition laser, working at 500 Hz with 60 mJ pulse energy and 10 ns pulse width. The beam quality is better than 1.5 (M square) and divergence angle compressed to 8 arc-seconds. During its first campaign from February to May in 2014, the system acquired over four hundred passes from more than two hundred space debris pieces.

Due to high maintenance cost of big lasers, debris laser ranging systems like the one of Changchun Observatory is not likely to run in routinely basis but in experimental campaigns. The routinely run SLR system is economically feasible, but even if it acquired space debris data, to determine orbit from the data is considered difficult. In the following sections, we describe the discovery of a rotating reflective space debris target, which is a CZ-2C rocket stage, and the consequent observations on it. We also developed orbit improvement method to track it more accurately.

2. CZ-2C laser tracking and orbit improvement

During its 2014 campaign, the Changchun Observatory space debris laser ranging system discovered a highly reflective CZ-2C rocket stage target that produced strong echo pulses in laser tracking. Hypothesis emerged that the target may carry laser retro-reflector. In September 2015 we started a campaign to try normal KHz SLR system on the target, and acquired range data successfully. As data accumulating, we committed effective orbit improvement, and successfully performed daytime laser tracking on the target.

2.1 The CZ-2C rocket stage target

The mentioned target is numbered 28480 in TLE catalog. It was launched in Xichang satellite launch center of China, in 18th November 2004, as the second stage of CZ-2C launch vehicle. The stage is 3.35 meter in diameter, 8.9 meter in height, and weighs 4 ton while emptied [14]. Function of the stage is to insert the payload to LEO orbit, then it leaves the payload to enter adjacent LEO orbit becoming space debris. During our research, the target was in an orbit with apogee height 910 km, perigee height 704 km, inclination 98.11 degrees and period 101 minutes. A news picture of the mentioned launch is shown in Figure 1, highlighting the second stage with circle mark.
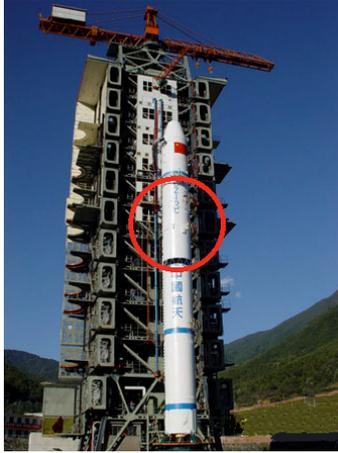
Figure 1. The news photo of CZ-2C rocket before the launch on November 18th, 2004. Payload of the launch, the Shiyan-2 satellite, was inserted to a sun-synchronous orbit.

2.2 Laser Tracking of the CZ-2C rocket stage target

Changchun Observatory first tracked the target in March 9th 2014 with SDLRS. It was found to produce much stronger echo than normal debris targets. In April 12th 2014, the target was tracked again, giving high return rate and high range precision as 0.34 m, near to the theoretical limit of the system, which was impossible for diffusive reflection range measurements. We then believed that a retro-reflection corner cube or similar structure exists on the target, and that the normal KHz SLR system might be able to perform ranging to the target. In September 2015, Changchun Observatory started a campaign to experiment normal KHz SLR system on the CZ-2C stage target, and first acquired range data on September 2nd 2015. During the full pass tracking, the target exhibited highly variable luminosity.

Orbit improvement was carried out with the laser range data, using the so called 'hybrid orbit determination' or HOD technique to promote tracking efficiency [15]. For example, three passes were acquired on September 7th 2015, including one invisible and two in earth shadow. In the local afternoon on September 14th 2015 at 6:15 UTC, the KHz SLR system acquired range data of the target in full daylight, giving 4.8 minute length of range data. It was the first known success of daylight KHz laser ranging to orbiting rocket stages. The success implies the feasibility of standalone SLR station to keep track of space debris targets and to improve orbits, producing accuracy similar to those of normal ILRS missions.

During 2nd to 17th in September 2015, a total of 22 passes of range data were acquired for the CZ-2C stage target. The SLR team was instructed to track the target with highest priority, and acquire data until the target descends to 5 degree elevation. Although the continuity was interrupted in September 9th-12th, the acquisition resumed in September 13th and the daylight tracking success appeared in September 14th.

After the September campaign, we added two CZ-2C rocket stages to normal tracking list, which are No.28480 and No.31114 in TLE catalog. Since then, more than two hundred data passes have been produced of these two targets.

2.3 Orbit improvement of CZ-2C rocket stage target

Orbit improvement, also known as precise orbit determination, is fundamental in modern space operations. Orbit determination with laser range data and other observation data is a mathematical optimization problem that minimizes the statistical difference between the real and projected observations by adjusting orbit parameters:

$$\min_{\sigma}(Y - HX(\sigma))^{\mathrm{T}} W (Y - HX(\sigma))$$

…………(1)

Where Y is the vector of all observations, H is the observation matrix, containing observation functions on every observation epochs. $X(\sigma)$ represents the satellite states on every epoch, with σ the orbit parameter set. W is weight matrix, which assigns weight for every individual observation. In general, higher accuracy leads to greater weight value.

It is common to adopt weighted least square method to solve this problem. The normal equation can be written as:

$$(H^{\mathrm{T}}WH)X(\hat{\sigma}) = H^{\mathrm{T}}WY$$

…………(2)

The existence of a solution requires $H^{\mathrm{T}}WH$ to be positively determined. In turn it requires H full rank, that means observations to distribute widely in both space and time dimensions. Orbit improvement of normal satellites would require widely distributed station network to provide redundant observation data and to ensure existence of solution of the problem [16]. But for the CZ-2C rocket stage target, only Changchun Observatory took part in the tracking, and that single station data would lead to stiffness of the problem. We use TLE-aided hybrid orbit determination technique to improve target orbit from the sparse observation data we got from Changchun Observatory, in order to guarantee a solution of the problem [15].

The TLE aided hybrid orbit determination technique can be described as below. First set up the pseudo-station network as a set of evenly distributed grid points on sphere. Then acquire target TLE from public source, and compute the initial orbit of target. Pseudo-observations are computed from the initial orbit with the pseudo-station network. The pseudo-observations alone fulfill the requirement of a solution, and the real observation data join in to improve orbit accuracy. Weight should be assigned as reciprocal of measurement precision for both types of observations, which we assume 0.6 km for TLE pseudo-observation, and 1 m for real laser tracking data.

Perturbation model of the target is similar to those of sun-synchronous orbits. We used EGM96 as earth gravitation model, truncated to degree and order 70. Lunisolar gravitation effects are computed with DE403 planetary ephemeris. Atmospheric density is modeled with Drag Temperature Model 94.

Follow-up tracking with improved orbits promoted the efficiency and ease of operation, and produced more data. However, assessment based on prediction error is required to quantify the

effect of orbit improvement.

3. Orbit prediction results

3.1 Criterion of assessment

Assessment of the effect of orbit improvement is done with prediction error comparison between TLE orbit and improved orbit. Prediction error is computed as below. For a given observation record, we first interpolate the target ephemeris table to observation epoch, then compute the station-target distance with corrections, and compare with real observation range value on that epoch. Root-mean-square (RMS) value of the differences is calculated for each pass. The RMS value represents the general range prediction error of a pass, so that to form a valid criterion of prediction error.

3.2 Prediction error of TLE and improved orbits

Prediction error was calculated as described above for both TLE orbit and improved orbit. Statistic results are shown in Table 1.

Table 1. Statistics for TLE and HOD prediction errors

Stats	TLE prediction error / km	HOD prediction error / km
Mean	0.31	0.33
Median	0.32	0.16

The two error distributions have similar mean values, but median values are different. The distributions are shown in Figure 2. The dotted histogram shows TLE prediction error while the crossed histogram shows HOD improved orbit prediction error. The TLE distribution bulges around 0.3 km, while the HOD distribution peaks at bottom and decline with larger error values. The distribution bulge of TLE is caused by its nature as mean orbital element, which leads to stable performance in range prediction. The HOD distribution peaks at low error values because it adopted more precise orbit model, but the lack of observation data causes the long tail in high error values.
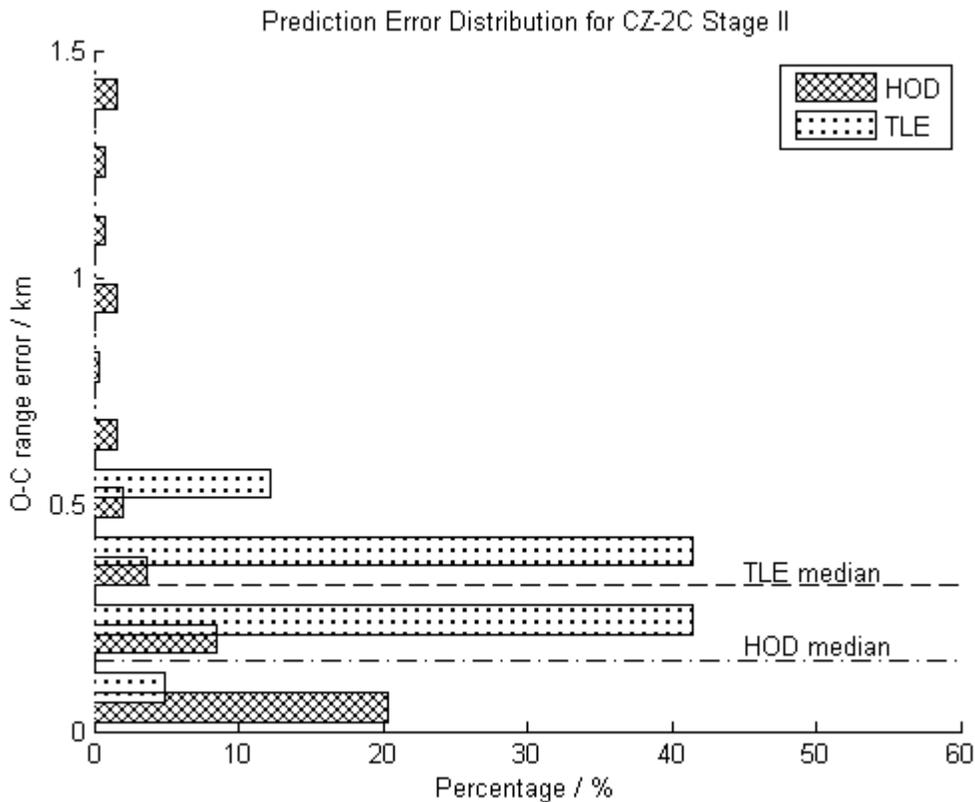
Figure 2. Comparison of bias distribution histogram of CZ-2 rocket stage. The TLE prediction error is represented by dotted patches, while the HOD counterpart is represented by crossed patches.

4. Target reflectivity and rotation analysis

While examined with KHz SLR data, the CZ-2C rocket stage exhibits multiple reflecting points and rotational feature. A sample data plot is shown in Figure 3. Three data curves exist in the plot, which implies three reflectors or reflecting points exist on the target. The curves have minor structures themselves, caused by the station's laser pulse train. The curves intersect at different epochs, that means the reflectors are not in a line, because reflectors in a line should produce curves intersecting at one point in the data plot. Echo strength of the reflectors vary with time, that exhibits 'phase in / phase out' behavior, due to apparent rotation of the rocket stage observed from the ground station.

Origin of the reflectors is unknown, nor their size, shape or array configuration. One possibility is that they are near-distance positioning instruments during rocket manufacture, especially prelaunch transportation, when the rocket is erected and requires attitude monitor during translation to the launch pad. If the above is true, the reflectors are then NOT purported for on-orbit laser ranging and should cost less.
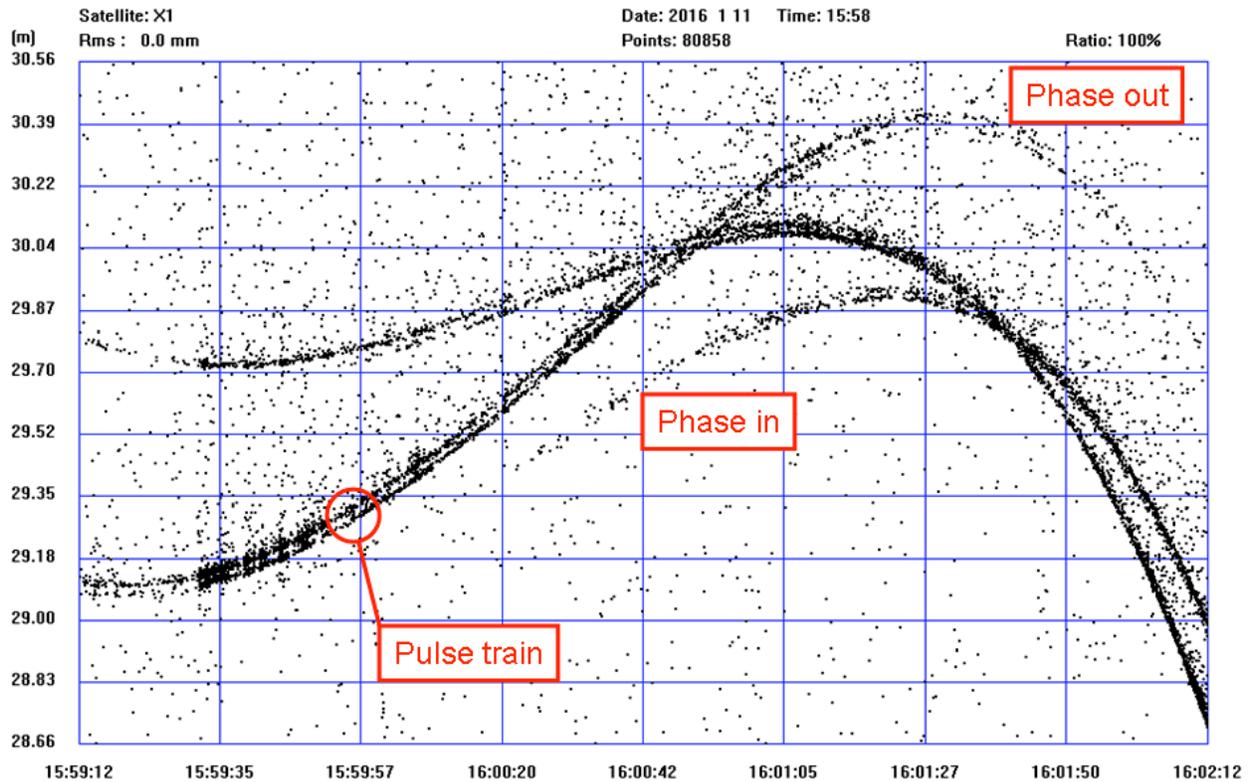
Figure 3.   KHz SLR data plot showing rotation of rocket stage with multiple reflecting points. Text boxes indicate phenomena in the data.

5. Conclusion and discussion

The results imply that HOD improved orbits are statistically better than TLE. The improved orbit accuracy even enabled laser tracking of the target in earth shadow and full daylight conditions. This is the first known success in daylight laser tracking to orbiting rocket stage in China.

Type of device on the rocket stage that caused retro-reflection is still unknown, not to mention its original purpose. However, the presence of such device enables the rocket stage to be easily tracked by laser, leading to more accurate orbit. We suggest all future rocket stages to equip with retro-reflectors, so that improved orbit accuracy could promote the reliability and efficiency of space debris applications.

REFERENCES
[1] Gong, Z.Z., Xu,K.B., Mou,Y.Q., "The space debris environment and the active removal techniques", Spacecraft Environment Engineering(in Chinese) 31(2), 129-135 (2014).

[2] Wei, D., Zhao, C.Y., "An Accuracy Analysis of the SGP4/SDP4 Model", Chinese Astronomy and Astrophysics 34(1), 69-76 (2010).

[3] SASTIND Space Debris Committee, "Introduction to the 27th IADC conference and the 5th European Conference on Space Debris", Spacecraft Environment Engineering(in Chinese) 26(5), 401-406 (2009).

[4] Greene, B., Gao, Y., Moore, C., "Laser tracking of space debris", 13th Intl. Laser Ranging Workshop Proceedings, 198-202 (2002).

[5] Sang, J.Z., Bennett, J.C., Smith, C., "Experimental results of debris orbit predictions using sparse tracking data from Mt. Stromlo", Acta Astronautica 102(1), 258-268 (2014).

[6] Sang, J.Z., Bennett, J.C., "Achievable debris orbit prediction accuracy using laser ranging data from a single station", Adv. Space Res. 54(1), 119-124 (2014)

[7] Kirchner, G., Koidl, F., "Laser Ranging to Space Debris from Graz Laser Station", Vermessung & Geoinformation 2(3), 151-155 (2015).

[8] Kirchner, G., Koidl, F., Friederich, F., Buske, I., Volker, U., Riede, W., "Laser measurements to space debris from Graz SLR station", Adv. Space Res. 51(1), 21-24 (2013).

[9] Zhang, Z.P., Tang, K., Wu, Z.B., "Laser measurement to space debris based on high repetition rate laser and its application", Space Debris Research and Application 14(1), 1-5 (2014).

[10] Zhang, Z.P., Zhang, H.F., Deng, H.R., "Experiment of laser ranging to space debris by using two receiving telescopes", Infrared and Laser Engineering(in Chinese) 45(1), 1-7 (2016).

[11] Li, Y.Q., Li, R.W., Li, Z.L., "Application research on space debris laser ranging", Infrared and Laser Engineering(in Chinese) 44(11), 3324-3329 (2015).

[12] Yu, H.H., Gao, P.Q., Shen, M., "Detection Capability Analysis of Space Debris Laser Ranging", Astron. Res. & Tech. (in Chinese), (2016).

[13] Li, M., Xue, L., Huang, C., "Estimation of detection range for space debris laser ranging system based on efficient echo probability", Optics and Precision Engineering(in Chinese) 24(2), 260-267 (2016)

[14] Di, N.Y., Zhu, W.Z., Wu, R.H., "Introduction to Long March series launch vehicles: the CZ-2 series (Part II)", Aerospace China(in Chinese) 97(9), 12-16 (1997)

[15] Liang Z.P., Liu C.Z., Fan C.B., "TLE-Aided Orbit Determination Using Single-station SLR Data", Chinese Astronomy and Astrophysics 36(1), 417-425 (2012).

[16] Pearlman, M.R., Degnan. J.J., and Bosworth, J.M., "The International Laser Ranging Service", Adv. Space Res. 30(2): 135-143 (2002)