Poster #3021

Submillimeter SLR: Ajisai as the zero-signature satellite

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Abstract

The high repetition-rate Satellite Laser Ranging (SLR) data allows to distinguish between the range measurements to the single corner cube reflector panels of Ajisai. We utilize the complete attitude model of Ajisai during the post-processing of the Graz SLR data in order to remove the satellite signature from the distribution of the post-fit range residuals and improve the single-shot RMS per normal point from 15.44 mm to 3.05 mm. The normal point RMS per pass is reduced from 2.97 mm to 0.06 mm - a value expected for a zero-signature satellite.

Background

Experimental Geodetic Satellite - Ajisai

The Experimental Geodetic Satellite Ajisai was launched on August 12, 1986 by the National Space Development Agency of Japan (NASDA), currently reorganized as Japan Aerospace Exploration Agency (JAXA). Objective of the mission is the accurate position determination of fiducial points on the Japanese Islands. The satellite is equipped with 120 corner cube reflector (CCR) panels for satellite laser ranging (SLR), arranged in the form of 15 rings around the symmetry axis. Each panel contains 12 CCRs except for the one mounted on the central ring - with 8 CCRs only. The satellite is placed in a quasi-circular orbit of altitude 1490 km and inclination of 50º.

Satellite Laser Ranging

The on-site produced normal points (NP) are the principal SLR data product and express the one-way optical distance between the reference point of the SLR station and the mean reflection point of the satellite (Fig. 1-A).

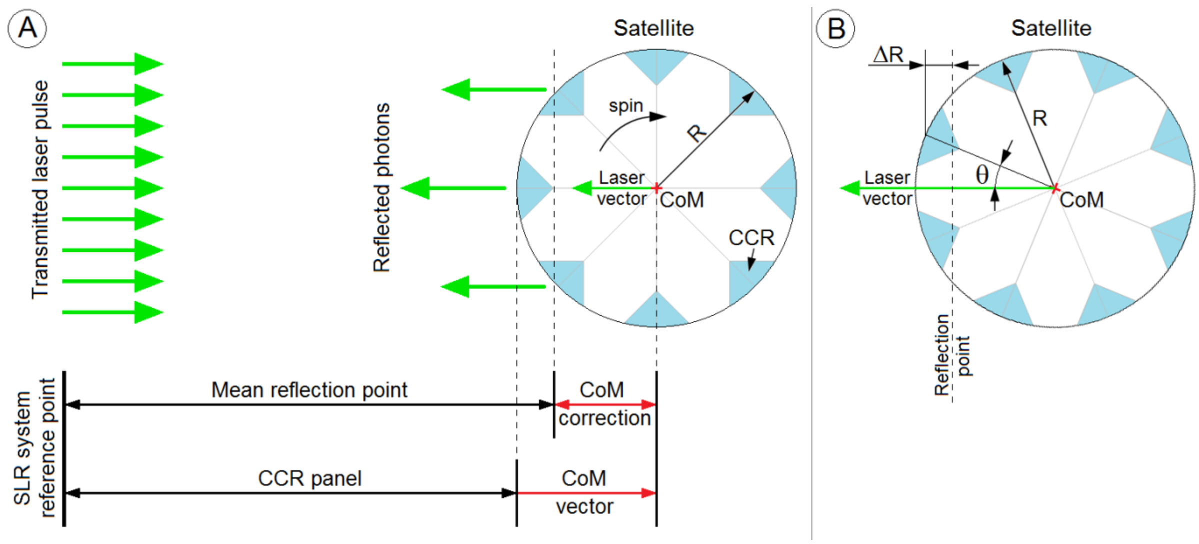

Fig. 1. Satellite reference points for the post-processing methods. A) The mean reflection point and the position of the CCR panel are used as the reference points for the normal points formation. Laser vector indicates direction from the satellite's center-of-mass (CoM) to the ground SLR system, R is the satellite's radius. B) The range correction ΔR is a distance from the center of the front face of a retroreflector to the optical reflection point. The θ represents an incident angle between the laser vector and the symmetry axis of a CCR.

In order to deliver an effective distance between the ground SLR system and the satellite the center-of-mass correction is added to the normal points.
The optical range measured by SLR is longer from the physical value due to the delay of a laser pulse passing through the glassy corner cube reflectors. The optical distance to a CCR refers to the optical reflection point and can be corrected by the range correction ΔR in order to represent the physical distance to the center of the CCR's external surface. The range correction ΔR is defined as $\Delta R = L\sqrt{n^2 - sin^2\theta}$, where L is the height of CCR (17.15 mm for Ajisai), n is the refractive index of the material (1.46 for fused silica and 532 nm wavelength) and θ is an incident angle between the laser vector (vector from the satellite's center directed towards the ground SLR system) and the optical axis of a retroreflector (Fig. 1-B).

SLR measurements to Ajisai at Graz Observatory

Fig. 2-A presents a 5 seconds part of the Ajisai pass measured by Graz on January 17, 2006. The observed mm-scale modulation of the range residuals (amplitude of ~25 mm) is caused by the rotation of the satellite (spin period of 1.995 s).

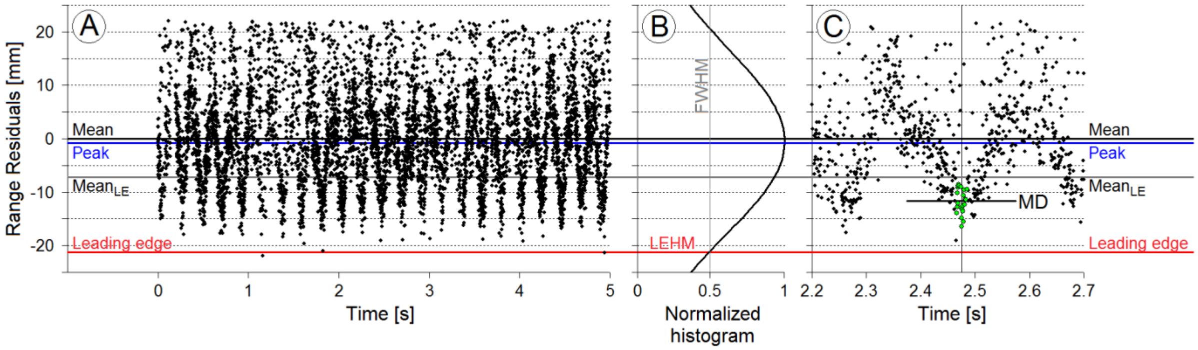

Fig. 2. Range residuals of a kHz SLR pass. A) 5 seconds part of Ajisai pass measured by Graz on January 17, 2006: 6337 data points, RMS = 8.81 mm. B) Histogram of the range residuals distribution (obtained with a 15 mm smoothing coefficient). C) V-shape data peak represents change of the distance to the single CCR panel due to the spin of the satellite; the minimum deviation MD of the panel is indicated. The significant levels of the data distribution are marked: mean of the range residuals after 2.5 sigma clipping, peak (-0.78 mm), mean of the leading edge points (Mean$_{LE}$), leading edge at half maximum LEHM (-21.2 mm). The full width at half maximum FWHM is 41.7mm.

Due to the fast spin of Ajisai the distance between the nearest CCR panel and the satellite's front face is quickly changing - this effect is represented as the V-shape distribution of the laser echoes on Fig. 2-C. The situation when the incident angle θ between the laser vector and the central axis of the panel (Fig. 1-B) is the smallest defines the minimum deviation of the observed CCR panel (MD). The range coordinate of the minimum deviation (MD) can be calculated as an arithmetic mean of the range residuals located around the MD epoch (data bin width of 20 ms) and clipped by an iterative 2.2 sigma filter. In the example case (Fig. 2-C) the range coordinate of the MD event is calculated as the mean of 23 selected points (return rate of 57.5%), and is equal to -11.7 mm, RMS = 2.29 mm.

Normal Point formation with Reflector Filter

The use of the complete attitude model of Ajisai (Kucharski et al., 2010a, b) allows to predict the epochs of the minimum deviation MD events throughout the analyzed pass. The range residuals around each predicted MD epoch (within ±10 ms) are selected and clipped by an iterative 2.2 sigma filter. If the amount of the remaining data points is ≥10 (return rate of 25%) and the RMS is ≤ 5 mm, then the selected range residuals are considered to be given by a single CCR panel and their mean represents the optical distance to the given panel (Fig. 2-C: minimum deviation MD level). In order to determine the physical distance to the identified panel the selected range residuals and the corresponding range measurements are corrected by the range correction ΔR (Fig. 1-B). The corrected data points refer to the external surface of the identified CCR panel which is placed on the radial distance of R=1053 mm from the satellite's center of geometry (coincides with the center of mass). As the final step the center-of-mass vector (vector length along the laser range direction = R·cos(θ); Fig. 1-A) is added to each of the selected data points and the mean of the resulting range residuals indicates position of the satellite's center of mass. Identification of the laser echoes given by the single CCR panels allows to refer the particular range measurements to the satellite's center of mass and eliminates the satellite signature effect from the normal points.

The zero-signature SLR data of Ajisai can be compared with the range residuals of the zero-signature satellite BLITS (Vasiliev et al. 2007, Kucharski et al. 2011). Fig. 3 presents the zero-signature range residuals of Ajisai (Fig.3-A) and BLITS (Fig.3-D) measured by Graz SLR system on March 13, 2014 and January 24, 2012 respectively.

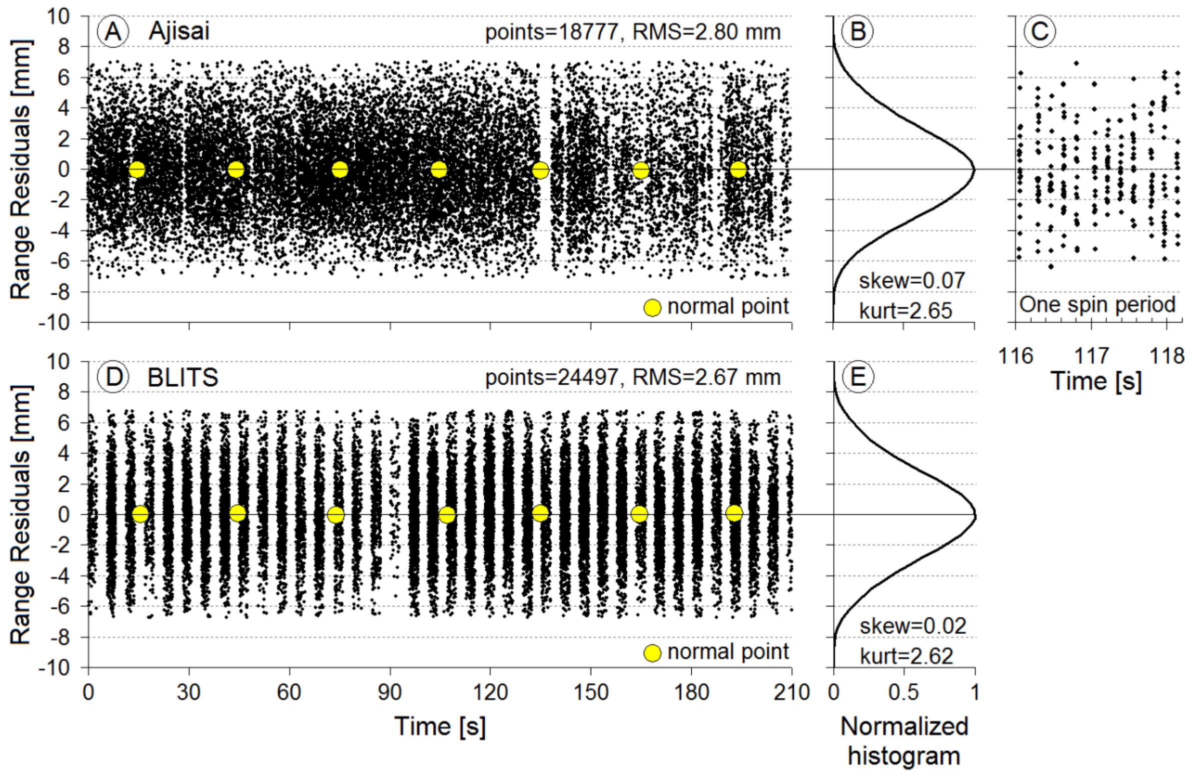

Fig. 3. Range residuals and normal points of Ajisai and BLITS. A) Ajisai, pass measured by Graz on March 13, 2014, and D) BLITS, pass measured by Graz on January 24, 2012. B, E) distribution of the range residuals obtained with a 1 mm smoothing coefficient. C) range residuals of Ajisai during one rotation of the satellite (~2.2 s). Zero level is the mean of the range residuals.

Table 1 presents the statistical parameters of the results obtained from the analysis of Graz kHz SLR data (2731 passes of Ajisai October 2003 - September 2014, 450 passes of BLITS September 2009 - June 2012).

Table 1. The mean values of the parameters calculated from 2731 passes of Ajisai and 450 passes of BLITS

	unit	Ajisai	BLITS
Pass RMS of range residuals (after 2.5 sigma filtering)	mm	3.04 ±0.29	3.17 ±0.31
Normal point RMS per pass	mm	0.06 ±0.02	0.09 ±0.05
Single-shot RMS per normal point	mm	3.05 ±0.36	3.21 ±0.32
Measurements per normal point	points	960	3480

The mean pass RMS of the range residuals of Ajisai and BLITS is at the level of 3 mm and coincides with the RMS of the SLR system calibration to the ground target of 2.25 mm. The symmetrical distribution of the range residuals around the 0 level (Fig. 3-A, D) gives a very low normal point RMS per pass: 0.06 mm for Ajisai, and 0.09 mm for BLITS.

Results

The normal points calculated with the range measurements to the single CCR panels NP_{CCR} refer to the physical position of the satellite's center of mass while the standard normal points NP - to the optical mean reflection point (Fig. 1-A). The obtained single-shot RMS values per normal point are presented on Fig. 4.

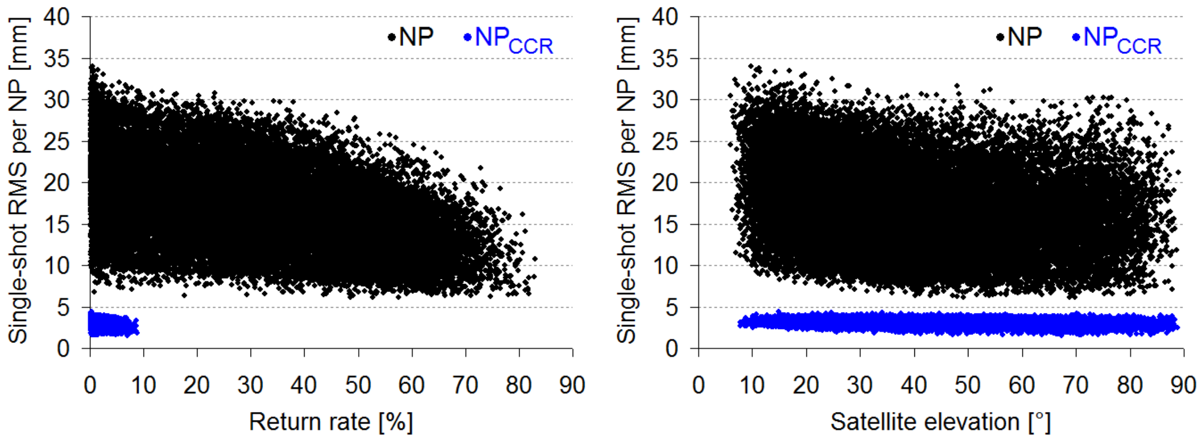

Fig. 4. Single-shot RMS per normal point. Data obtained by the standard 2.5 sigma clipping (NP) and the compression of the minimum deviation points NP_{CCR}.

The mean single-shot RMS per NP is 15.44 ±5.23 mm and for NP_{CCR}: 3.05 ±0.36 mm. Average NP RMS per pass is 2.97 ±0.9 mm and for NP_{CCR}: 0.06 ±0.02 mm.
The minimum deviation level (MD on Fig. 2-C) indicates the position of the specific CCR panel, thus it can be used as the reference to calculate the distance between the satellite's center of mass and the significant levels of the range residuals distribution: Peak, LEHM, NP (refers to Mean on Fig. 2) and $Mean_{LE}$ - Table 2.

Table 2. Distance between the significant levels of the range residuals distribution (Fig. 2) and Ajisai center of mass. The physical distance between the outer surface of the CCRs and the satellite's center of mass is 1053 ±5 mm.

	Physical distance to CoM [mm]	Optical distance to CoM [mm]	RMS [mm]
Minimum deviation MD	1052	1027	0.4
$Mean_{LE}$	1048	1023	1.7
Peak	1041	1016	2.6
NP (after 2.5 sigma clipping) (Mean level on Fig. 2)	1037	1012	4.7

The optical distance to the satellite's center of mass presented in Table 2 is shorter from the physical distance by the range correction value ($\Delta R = 25.04$ mm) calculated for the incident angle $\theta = 0°$ (Fig. 1-B). The optical distance between the Mean (reference level for NP) and CoM is 1012 mm and coincides with the standard center of mass correction of 1010 mm (Otsubo and Appleby 2003).

Conclusions

The attitude model of Ajisai applied during the post-processing allows to select the range measurements to the single CCR panels and to form normal points which indicate the physical distance between the ground station and the satellite's center of mass. This process eliminates the satellite signature effect from the distribution of the post-fit range residuals and improves the average single-shot RMS per normal point from 15.44 mm to 3.05 mm (Fig. 4). The normal point RMS per pass is reduced from 2.97 mm to 0.06 mm - a value expected for the zero-signature satellite.

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