Vol. 46 No. 1 Journal of the Communications Research Laboratory March 1999
Printed in Tokyo, Japan pp. 213−218

8.5 CENTER-OF-MASS CORRECTION OF THE SATELLITE AJISAI

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ABSTRACT

The center-of-mass correction of the Japanese geodetic satellite Ajisai is studied through simulation. The optical response is precisely modeled simulating the material and the shape of the satellite's corner cube reflectors. Due to the large size of the satellite, the retro-reflected pulse becomes broadened and our model predicts a 28 mm difference in the center-of-mass correction between a typical multi-photon system and a typical single-photon system. The Keystone laser ranging system uses a photomultiplier and an avalanche diode, both of which can be operated simultaneously, so the system can potentially detect the difference.
Keywords: Laser ranging, Satellite signature, Center-of-mass correction, Ajisai

1. Introduction

The size of geodetic satellites has become one of the limiting factors in laser ranging precision, and this factor is called the "satellite signature" effect. The center-of-mass of the satellite is the ideal position to locate a single corner cube reflector (CCR) to simply represent the satellite motion. However, many CCRs need to be attached to the surface to keep the sufficient intensity of the return signals. As a result, what we can measure is the range to the CCRs and it should be corrected to the range to the satellite's center-of-mass. In this paper, we focus on the satellite signature of the Japanese geodetic satellite Ajisai and its center-of-mass correction values. Ajisai was launched in 1986 and is still one of the most frequently tracked satellites.

The value of 101 cm for a 200 ps pulse width laser derived in the pre-launch analysis[1] has been the only standard for its center-of-mass correction, even though various laser ranging systems are currently in operation and their performance has improved considerably since the time of the Ajisai launch. According to Sinclair[2] and Neubert[3], the Lageos' center-of-mass correction a the single-photon system differs by several millimeters from its standard value. The larger Ajisai is likely to be more dependent on laser ranging systems. In this paper, the return pulse shape from the Ajisai is simulated and its center-of-mass correction values are determined for several system configurations.

Table 1 Specification of Ajisai satellite.

Launch	August 12, 1986 by NASDA
COSPER ID	8606101
Diameter	2.15 m
Mass	685 km
Number of CCRs	1436 (120 sets)
Optical index of CCR	1.46 (fused silica)
Number of mirrors	318
Orbital altitude	1485 km
Orbital inclination	50.01 deg.

2. Simulation of the Return Pulse Shape

The specifications of the geodetic satellite Ajisai are listed in Table 1 and its external appearance is shown in Fig. 1. Most of its surface is covered by mirrors to reflect sunlight, and the sets of CCRs are sparsely distributed between the mirrors. Therefore, the return pulse shape varies significantly depending on the laser incident angle to Ajisai.

We can evaluate the satellite signature effect of Ajisai only by computer simulation because the satellite is already orbiting in space. We simulated the return pulse from Ajisai for each incident angle, but when we started the simulation using a detailed specification, two critical problems were found: one is that all CCRs are installed so that their front faces are located at 1.053 m from the center-of-mass with a tolerance of 5 mm; the other is that the angles between the CCR faces have an error of about 2 arcseconds. It is difficult to discuss the signature effect at 1 mm or better because of the first limitation, and modeling the far field diffraction pattern would be meaningless because of the second problem. However, even if each simulated return pulse does not model the real one due to these limitations, we believe the statistical behavior will follow that of our simulation. In this study, we therefore assumed that the installation was done with no error and that the far field diffraction pattern is simple.

The CCR installed on Ajisai is shown in Fig. 2. Consider the strength of the return pulse reflected by the CCR. The back face is not coated, and the CCR's reflectance as a product of double refraction at the front face and triple reflection at the back face depends on the azimuth angle, especially when the incident angle is wide (Fig. 3). In the pre-launch analysis, the reflectance was uniformly treated as zero when the incident angle exceeded 17 degrees, which is corrected in this study. Each vertex of the front face is cut as long as 8.5 mm, which makes the calculation of the effective reflection area complex (Fig. 4). Although we could not model the far field diffraction pattern, the diffracted area is in inversely proportional to the effective reflection area of a CCR. Hence, the return strength is proportional to the effective

Fig. 1 Outlook of Ajisai satellite.

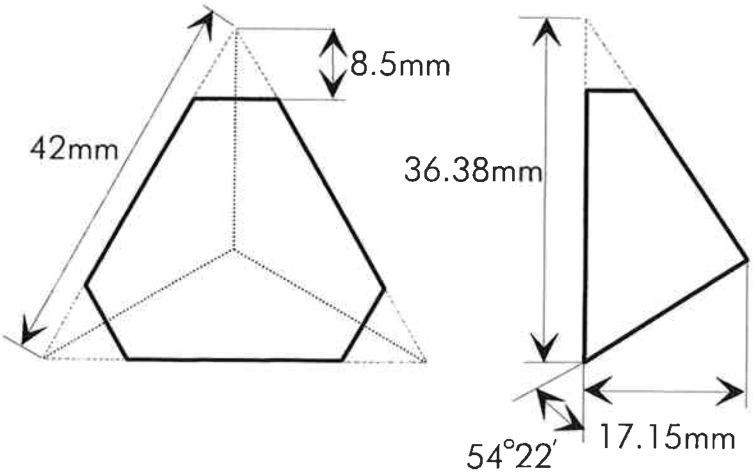

Fig. 2 Corner cube reflector of Ajisai.

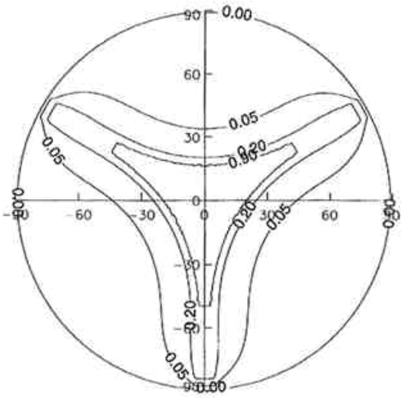

Fig. 3 Reflectance of Ajisai CCR calculated from the double refraction at the front face and the triple reflection at the back face. The azimuthal direction is common to that of Fig. 2.

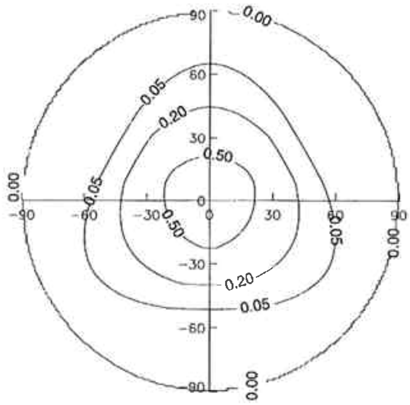

Fig. 4 Effective reflection area of Ajisai CCR. Area of the front face without vertex cut is 1. The azimuthal direction is common to that of Fig. 2.

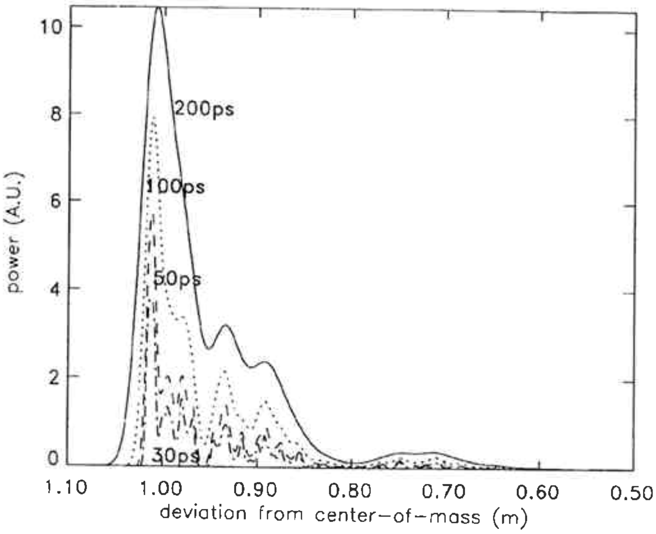

Fig. 5 A sample of the return pulse shape from Ajisai.

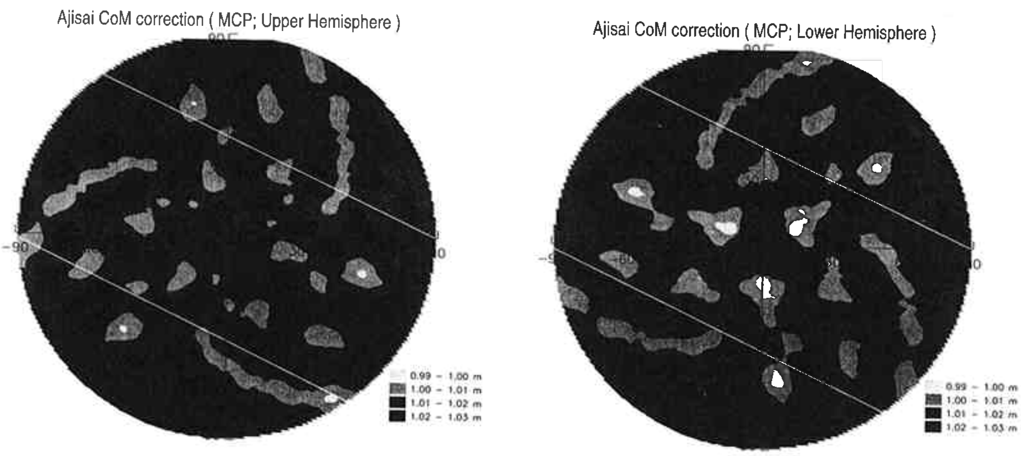

Fig. 6 Ajisai's center-of-mass correction for a multi-photon system with respect to the incident angle.

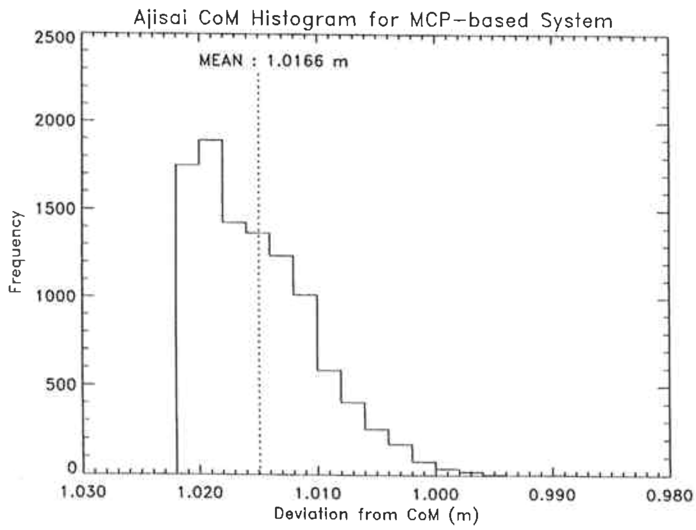

Fig. 7 A histogram of Ajisai's center-of-mass correction for a multi-photon system and a laser of 100 ps pulse width.

reflection area for the diffraction effect. The relative return pulse strength for a CCR is thus given as[3]:

$(strength) \propto (effective\ reflection\ area)^2 \times (reflectance)$.

We assumed a return pulse shape from Ajisai is a simple incoherent sum of the returns from all of the CCRs because the complex diffraction pattern is ignored here. For each incident angle, the delay and the return intensity for each CCR were calculated and the contribution of each was totaled.

We simulated return pulse shapes for 10,267 incident angles about 2 degrees apart and equally distributed around Ajisai. The incident laser pulses were assumed to be Gaussian with pulse widths (FWHM) of 200 ps, 100 ps, 50 ps and 30 ps. A sample is shown in Fig. 5. The return pulse was more than 40 cm wide in one way. The deformation of the pulse is simple with a 200 ps laser, but complex with a 50 ps and 30 ps lasers in that there are many peaks.

3. Center-of-mass Correction

3.1 Multi-photon system

Most laser ranging stations now detect the return echo as a pulse, i.e., at a multi-photon level, and generally use a combination of a micro-channel plate photomultiplier (MCP) and a constant fraction type discriminator (CFD). In our study, both the MCP and the CFD were assumed to work ideally.

The calculated center-of-mass correction for this multi-photon system and its dependence on the incident angle is shown in Fig. 6 for a laser pulse width of 100 ps. The center-of-mass correction varies by about 3 cm from peak to peak. The vague pattern of the 120-degree azimuth interval in Fig. 6 was caused by the arrangement of the sunlight reflection mirrors; that is, three mirrors in each row are identical.

Table 2 Center-of-mass correction of Ajisai for a multi-photon system with respect to the laser pulse width.

Laser pulse width (FWHM)	Center-of-mass correction and rms (m)
200 ps	1.0103 (0.0060)
100 ps	1.0166 (0.0054)
50 ps	1.0199 (0.0049)
30 ps	1.0211 (0.0047)

A histogram of the center-of-mass correction values for 10,267 incident angles is plotted in Fig. 7 for a 100 ps laser. It represents the distribution of full-rate data residuals under the condition that Ajisai is shot adequately and uniformly from every direction, and that the tracking operation is done with no systematic error. In other words, the rms of the full-rate data residuals cannot be better than that of Fig. 7; 5.4 mm for a 100 ps laser. The results for 200 ps - 30 ps pulse widths are listed in Table 2. The pre-launch value, 1.01 m, which was derived for a 200 ps laser, agrees well with our result for a 200 ps laser, 1.0103 m, although the effective digit of the pre-launch value is not clear. The shorter the laser pulse width is, the longer the center-of-mass correction becomes. This dependence on the laser pulse width might

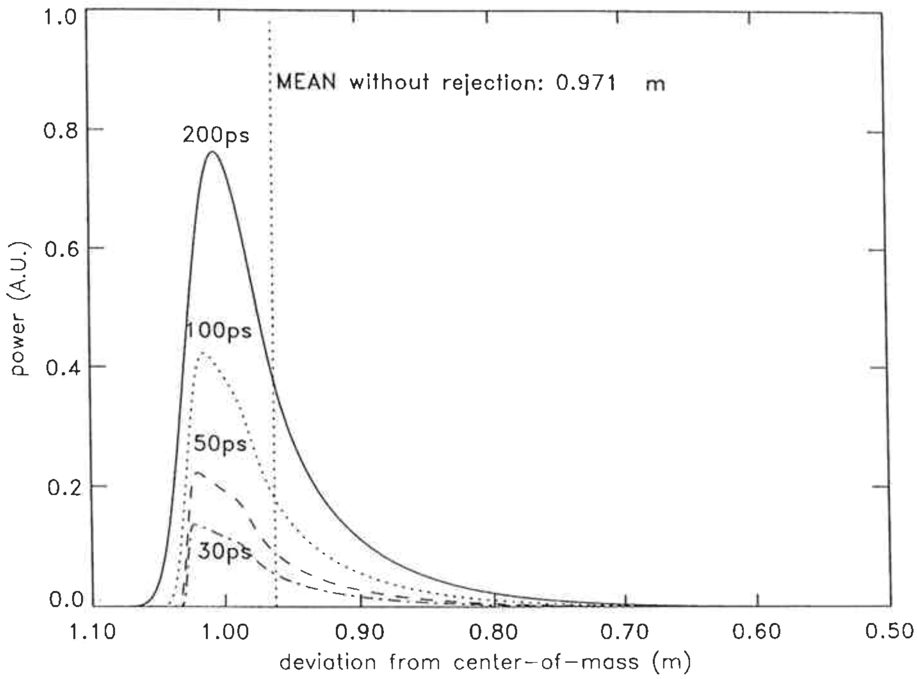

Fig. 8 Residual distribution of Ajisai ranging for an ideal single-photon system.

cause centimeter-level bias because of the system configuration.

The MCP response time or jitter from any of the devices also limit the laser ranging precision, and the response time behavior in the leading edge becomes important if the laser pulse width is significantly shorter than it. Hence, the value for the 30 ps laser in Table 2 might not be realistic for current stations even if such a short pulse laser was available.

3.2 Single-photon system

Several laser ranging stations began using a single-photon avalanche diode (SPAD) recently (e.g. the Herstmonceux, Graz, Wettzell, Orroral, Riyadh and Keystone stations), but Herstmonceux seems to be the only station that now regularly uses a SPAD system for Ajisai ranging at the single-photon level[4][5].

The return epoch cannot be determined for each shot, but its statistical behavior can be estimated. A return pulse shape like that of Fig. 5 is the probability distribution for the SPAD system, as long as the signal strength is kept at a single-photon level. It is of no use to examine each return pulse shape, but the residual distribution will follow the "average" pulse shape (Fig. 8) if the data amount is sufficient. Fig. 8 is the sum of the 10,267 simulated pulse shapes for incident laser pulses, at 200 ps to 30 ps. Note that the mean is almost constant at 0.9712 m, independent of the laser pulse width.

Because the distribution in Fig. 8 is apparently larger than the current system noise and because it is skewed, the pre-processing procedure will reject a certain part of the distribution tail. The data-clipping method currently differs from station to station but most of stations use Gaussian fitting with 2 to 3 x rms clipping criteria. We repeated 2.0, 2.5 and 3.0 x rms clipping and determined the convergence value (Fig. 9). A difference of about 2 cm would appear between a 2.0 x rms clipping and 3.0 x rms according to Fig. 9. Ajisai's center-of-mass correction for single-photon detection is robust with respect to the incident laser pulse width, but sensitive to the noise rejection procedure.

3.3 Application in the Keystone system

In the Keystone laser ranging system, both the MCP and the SPAD systems will be installed[6] and operated simultaneously. Thus, the range can be measured by using the two detectors for a real-time comparison. The main reason to install the two detectors is to ensure the accuracy of the range measurement, but we will also look into the small difference that comes from the characteristics.

Because the center-of-mass correction of Ajisai varies significantly with respect to the detection systems, the simultaneous two-detector ranging would be a direct solution to the problem of detecting the Ajisai variable center-of-mass correction. In that case, we must also control the signal strength in the calibration ranging since the range comes from the subtraction of the calibration result from the raw range value.

4. Conclusion

Ajisai's center-of-mass correction should be treated as variable, not constant. To determine the value accurately, we must take into account the laser pulse width

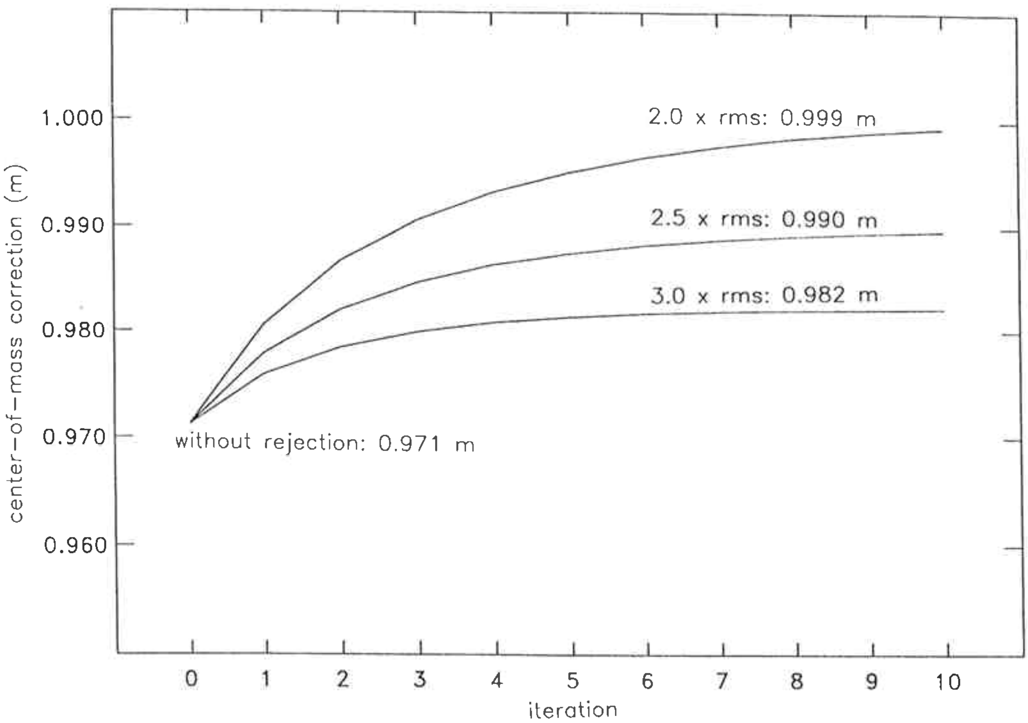

Fig. 9 Shift of Ajisai's center-of-mass correction for a single-photon system with respect to the rejection criteria.

and the timing response of the detector for a multi-photon system, and the data-clipping criteria for a single-photon system for each laser ranging station. The correction values need to be derived using the following new factors: the azimuth angle dependence of each CCR's reflectance, the narrowing of the laser pulse width as little as 30 ps, and the modeling of a single-photon system.

In the future, we plan to study the relationship between the center-of-mass correction and Ajisai's spin motion. The simultaneous detection by the MCP and SPAD systems will facilitate this research. The study reported here can also be applied to smaller satellites.

Acknowledgment

We thank Mr. H. Hashimoto, National Space Development Agency of Japan, and Dr. A. Sengoku, Hydrographic Department of Japan, for providing the Ajisai specification data and a many stimulating discussions. We also thank Dr. G. M. Appleby, Institute of Terrestrial Ecology, UK, and Dr. Georg Kirchner, Institut fuer Weltraumforshung Austria and Mr. A. Willing, AUSLIG, Australia for the information on the SPAD ranging configuration at Herstmonceux, Graz and Orroral.

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