kHz Single Photon Ranging:
A Precise Tool to Retrieve Optical Response of Satellites

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Abstract

Single-photon laser ranging has been proven to be useful for retrieval of optical pulse shapes of satellite returns. kHz single-photon ranging with a 10-ps-pulse laser currently realised at Herstmonceux is much more powerful than 10-Hz laser ranging to precisely retrieve a optical pulse shape, with just one passes. A new "deconvolution" approach is examined for quick and precise retrieval of satellite optical responses.

1. Introduction: Single photon laser ranging

Single photon detection policy, originated at Herstmonceux, UK, in early 1990's, has demonstrated to be a precise satellite-laser-ranging method to relate a post-fit residual profile and a centroid of residuals with the modeled optical response. It results in less ambiguous determination of satellite centre-of-mass corrections, compared with high- or variable-energy detection policy. For instance, Otsubo and Appleby (2003) numerically simulated the optical responses from spherical satellites such as LAGEOS, AJISAI and ETALON, and presented single (=stable) centre-of-mass corrections for single-photon stations and variable centre-of-mass corrections for multiple-photon stations.

Meanwhile, following successful development of 2-kHz laser ranging systems in Graz, Austria, and also in Greenbelt, USA, the 10-Hz laser ranging system at Herstmonceux is being upgraded to a 2-kHz system (Gibbs, et al., 2008). Herstmonceux station continues its single photon detection policy with the 2-kHz system, which means that it will be the first "kHz and single photon" station in the world. This paper deals with the early 2-kHz observation data obtained at Herstmonceux and some numerical test results.

2. Residual histogram: 10Hz vs 2 kHz

The post-fit full-rate residuals of single photon observations enable us to retrieve the whole optical response from a retroreflector array.

Fig. 1 shows a typical full-rate residual profile when tracking AJISAI satellite with a 10-Hz (strictly speaking, up to 14-Hz) laser ranging system at Herstmonceux. This station always controls return rate low, less than 15% per pulse, so that the number of detected photoelectrons is zero or one, which is known as single photon ranging. This results in

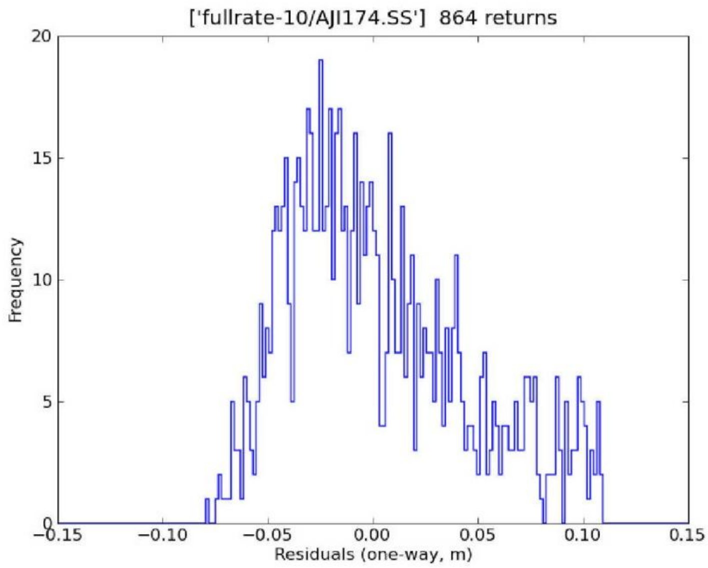

Figure 1. Full-rate residual histogram of an AJISAI pass observed by the 10-Hz system at Herstmonceux, around 21 h UT, 19 June 2000.

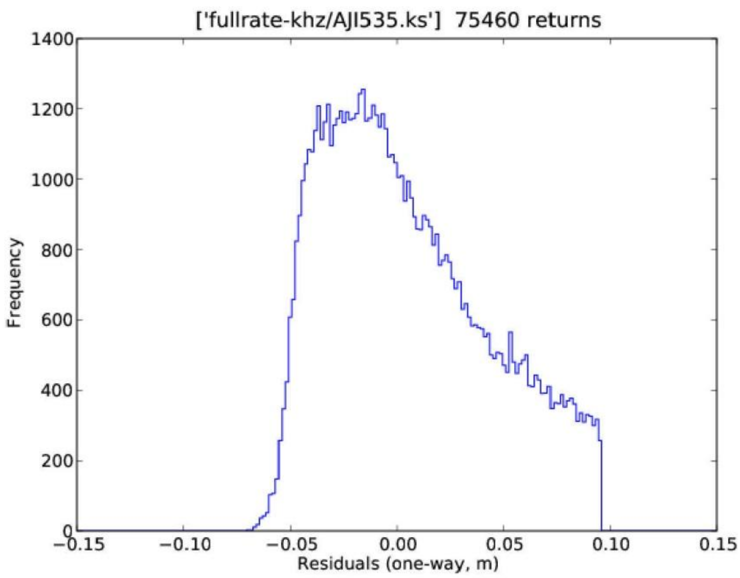

Figure 2. Full-rate residual histogram of an AJISAI pass observed by the 2-kHz system at Herstmonceux, around 7h UT, 18 February 2008.

a significantly reduced number of returns especially for low satellites that produce strong signals, compared with multiple-photon systems. The number of full-rate returns per AJISAI pass (10 to 15 minutes) is usually less than 1000, although it transmits much more laser shots to the satellite. As Fig. 1 indicates, the shape of a residual histogram is not very stable and it is not realistic to use such one-pass data for the studies of satellite optical response. Otsubo and Appleby (2003) had to accumulate a hundred of passes to generate a residual histogram, but it was not ideal to mix months of observations as the system characteristics would change.

kHz laser ranging provides a new solution to this situation. The number of laser shots becomes more than 100 times and, in the case of strong-return satellites like AJISAI, the return rate does not change so much. As a result, the number of full-rate returns potentially gets 100 times higher, and the histogram profile is much smoother as seen in Fig. 2.

In addition to the number of returns, it should be noted that the narrower laser pulse width (~ 10 ps in comparison to ~ 100 ps of 10-Hz laser) and the better timing precision of a new event timer (7 ps; in comparison to 35 ps of old time interval counter) of the kHz laser system and the consequent small observation noise are also useful for the histogram analysis.

3. "Deconvolution" approach

Let us assume these three functions:

- f: a residual profile oflaser ranging to a single-reflector target
- g: a residual profile of laser ranging to a target to be studied
- p: an average optical response function of a target to be studied

where it is clear that g is expressed as a convolution of f and p. In the extreme case of ultimate 0-ps of system noise (f), the observed residual profile g would completely agree with the optical function p.

Preceding studies such as Otsubo and Appleby (2003) adopted a convolution approach where a satellite-ranging residual scatter is assumed to be equal to the system noise convolved with the optical response of the onboard retroreflector array. Various p_{model}'s have to be generated in advance based on the various assumption on the optical response, and the function f_{obs} is then convolved with each p_{model}, which yields various g_{model}'s. The best p_{model} is chosen when a convolved function g_{model} agrees best with the observed g_{obs}. Note that the subscript *"model"* indicates that the function is created by numerical simulation and the subscript *"obs"* indicates that the function is based on observations.

With 2-kHz data, it could be also a realistic way to apply a deconvolution approach. Deconvolution numerical computation requires frequency domains of functions f, g and p, whereas the convolution numerical computation is easier and more straightforward. From the observed residual histograms f_{obs} and g_{obs}, their frequency domains F_{obs} and G_{obs} can be obtained. Then the frequency domain of p is simply given as:

$$P_{obs} = F_{obs} / G_{obs},$$

Then a low-pass (high-cut) filter needs to be applied for P_{obs} . Finally, the time domain p_{obs} can be obtained and that is the retrieved response function.

This algorithm does not require any modeled p functions, and makes it possible to obtain the 'observed' response function of p_{obs}. Fig. 3 shows an example of deconvolution test, using an ERS-2 residual profile for f_{obs} and an AJISAI residual profile for g_{obs} both of which are formed by just one pass observed on the same day and processed without chopping the tail. The numerically deconvolved function p_{obs} is also shown in the bottom graph of Fig. 3. Its full-width half-maximum (FWHM) width is 71 mm which is close to 66 mm obtained in our preliminary optical simulation of AJISAI's retroreflector array.

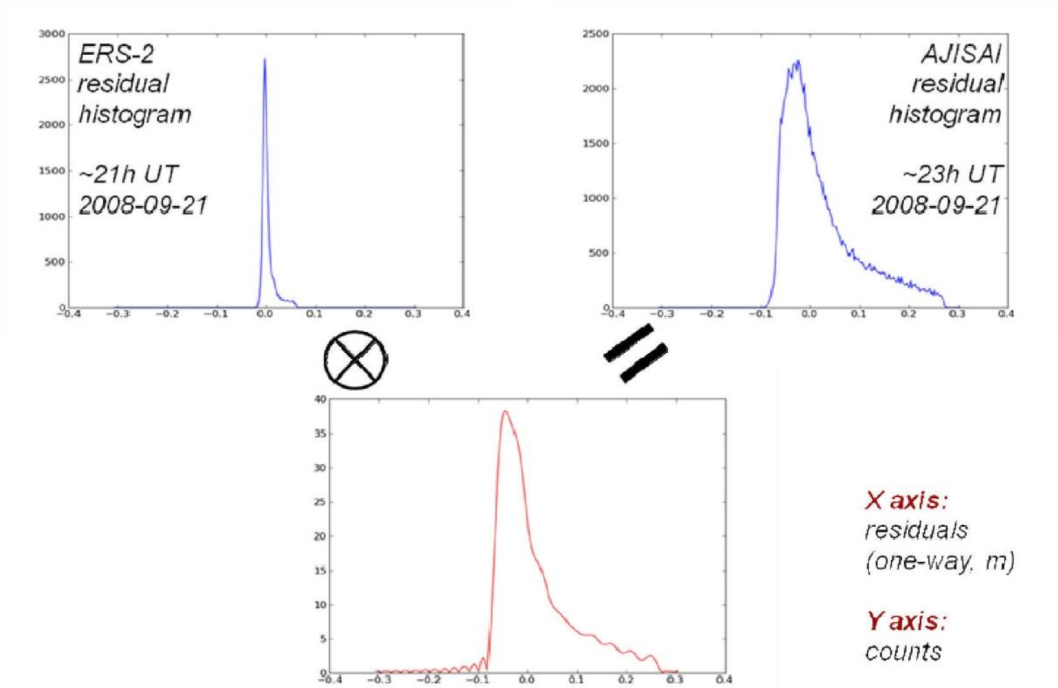

Figure 3. Deconvolution test of AJISAI satellite. Top left: ERS-2 residual histogram for f_{obs}. Top right: AJISAI residual histogram for g_{obs}. Bottom: "deconvolved" response function p_{obs}, FWHM = 71 mm.

4. Conclusions and future studies

Single photon laser ranging data are becoming a more powerful tool for retrieving the satellite optical response function with kHz laser ranging. As demonstrated by recent 2-kHz single-photon laser-ranging data from Herstmonceux, one hundred times more data with kHz observations nicely covers up for the longstanding issue-fewer amount of returns.

A new 'deconvolution' approach has been tested for retrieving the satellite optical response function. It worked reasonably well with AJISAI data.

However, there are two issues remaining before fully utilize this approach. First, this method is very sensitive to leading or tailing noise points and the choice of low-pass filter criteria. The bottom graph of Fig 3 shows many small wobbles before the leading edge. It is not easy to reduce these due to this problem. The other issue is that this approach cannot be so powerful for the small-signature satellites as for AJISAI. When the function g_{obs} is not very different from f_{obs} like LAGEOS or STARLETTE, the deconvolved method does not precisely produce the retrieved response function. It will be useful in the future work to accumulate a large number of passes to overcome these problems and fully utilize the deconvolution approach.

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References

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