Systematic Range Bias Related to GLONASS Reflector Array

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1. Introduction

The global laser ranging network has made a great effort to track the satellites of the Russian navigation system GLONASS. Especially since the IGEX-98 campaign (Oct 1998 to Apr 1999), we obtained much more laser ranging data than initial expectations, roughly triple that of GPS. The large data volume enabled us to determine orbits of the GLONASS satellites from laser ranging data alone [1].

Laser ranging had been expected to independently evaluate the GLONASS-borne microwave-based orbits simply by comparing the range data with the microwave orbits. For instance, it has been reported that laser range measurements are on average shorter by about 4 cm than ranges derived from the microwave-based precise orbits [2]. Another method is now possible using the SLR-based orbit, that is, the comparison between the two independent orbits. We found the agreement was 20 cm rms in the radial component and 1 m rms in the along-track component [1].

It was the large array of corner cube reflector (CCR) on the GLONASS satellites that made it possible to obtain a fairly large amount of range data. On the other hand, the very size of the array causes a severe target signature effect [3-4] which plays an important role in this case when we consider centimetric accuracy.

2. Reflector Array of GLONASS Satellites

396 CCRs are placed on 1.2 m x 1.2 m flat array whose normal vector always points towards the geocentre. According to the data provided by Russian Institute of Space Device Engineering, the reflector array has several gaps filled by antennae as shown in Fig. 1. No CCRs are obscured as seen from a tracking station by any of the antennae. The pattern repeats every 90 degrees in azimuthal direction. The

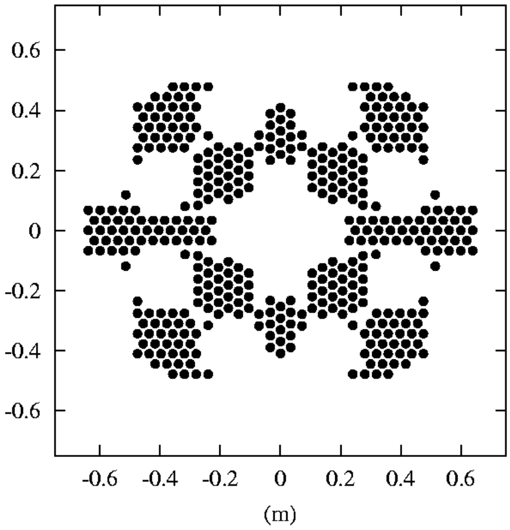

Fig.1: Arrangement of CCRs on the GLONASS satellites.

reflector is made of fused quartz whose optical index is 1.4607 for 0.532 nm wavelength. The front face is hexagonal with a diameter of 31 mm and the depth is 19.1 mm.

The optical reflection point of the array centre is located at a distance of 1.51 m from the satellite centre-of-mass toward the geocentre direction.

The flat array of GLONASS is new to our satellite signature study because all the reflectors evenly contribute to the retro-reflection. This is very different from the spherical satellites whose response function always shows a steep leading edge [3-4].

The pulse shape of an incident beam will not be distorted when the angle of incidence is normal to the array, that is, when the satellite is in the direction of a station's zenith. However, the angle of incidence reaches 13.7 degrees to the normal when a station observes a satellite at 20 degrees of elevation. In such an event, the retro-reflected pulse is spread by as much as 28 cm = array size (1.2 m) multiplied by sin 13.7 degrees.

We can use single-photon laser ranging data to trace the profile of the retro-reflected pulse [4]. Since each detected photon can have originated from any one of the reflectors, over the course of many detections, the spatial distribution of the array is mapped such that the scatter of full-rate range residuals during a pass actually varies with respect to the elevation angle. A sample shown in Fig. 2 is a set of full-rate residuals from a single pass obtained at Herstmonceux, UK, and has five segments. The observation started at 35 degrees of elevation, peaked at 76 degrees and ended at 40 degrees. The plot clearly shows that the scatter is smaller at high elevation and larger at low elevation.

The distribution of the retro-reflected pulse is likely also to vary with respect to the azimuthal angle of incidence. To investigate this we modeled the response of the reflector array and varied the azimuth

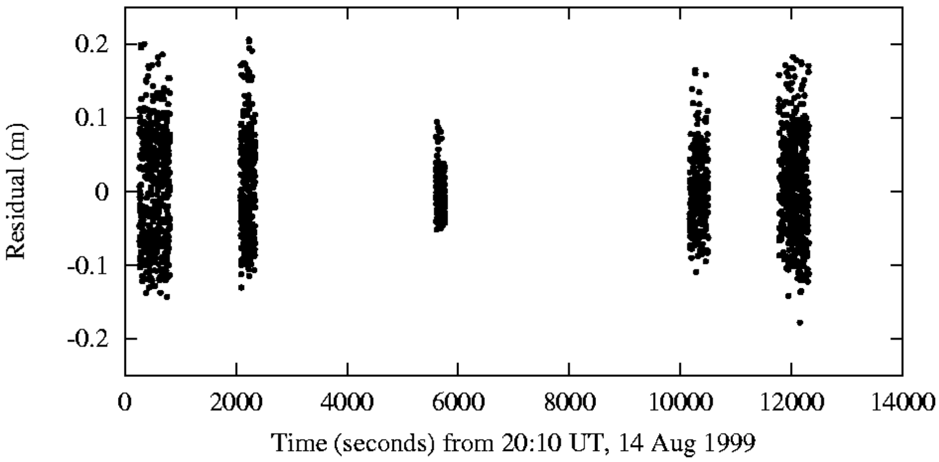

Fig. 2: Full-rate post-fit residuals of GLONASS-79 data obtained at Herstmonceux.

from 0 degrees (horizontal direction in Fig 1) to 90 degrees (vertical) in 10-degree step. Fig. 3 shows the modeled variation of the pulse shape for a Gaussian incident laser pulse of 100 ps FWHM. The angle of incidence is set in the model to 12.5 degrees, which is the case for observations made at 30 degrees of elevation.

Single-photon data can be used again to verify such modeled pulse shapes. Full-rate residual data of 9 GLONASS satellites from Oct 1998 to December 1999 were taken from Herstmonceux. Only data obtained at elevations of between 30 and 40 degrees were used here with an adjustment of scattering scale according to the actual elevation. The azimuth direction towards the reflector array can be calculated from the geometry between the satellite, the station, the Sun and the Earth, so we were able to sort the residual data to match Fig. 3. Fig. 4 shows the histograms of the post-fit range residuals. Although the data amount is not sufficient in some cases, the general shapes of the profiles agree with the model.

For single-photon systems, the average reflection point is coincident with the array centre because it corresponds to the centroid of the residual histogram. Therefore, the centre-of-mass correction to be applied to each observation is computed from a point 1.51 m from the satellite centre-of-mass, along the satellite-geocentre vector. On the other hand, the behaviour of a multi-photon station is hard to model. It is likely that the multi-photon systems measure shorter than single-photon systems in low elevation but there is an ambiguity of the detection timing during the long leading edge which can amount to 0.14 m in one-way range. This problem is caused by the large flat array and creates a new challenge for laser

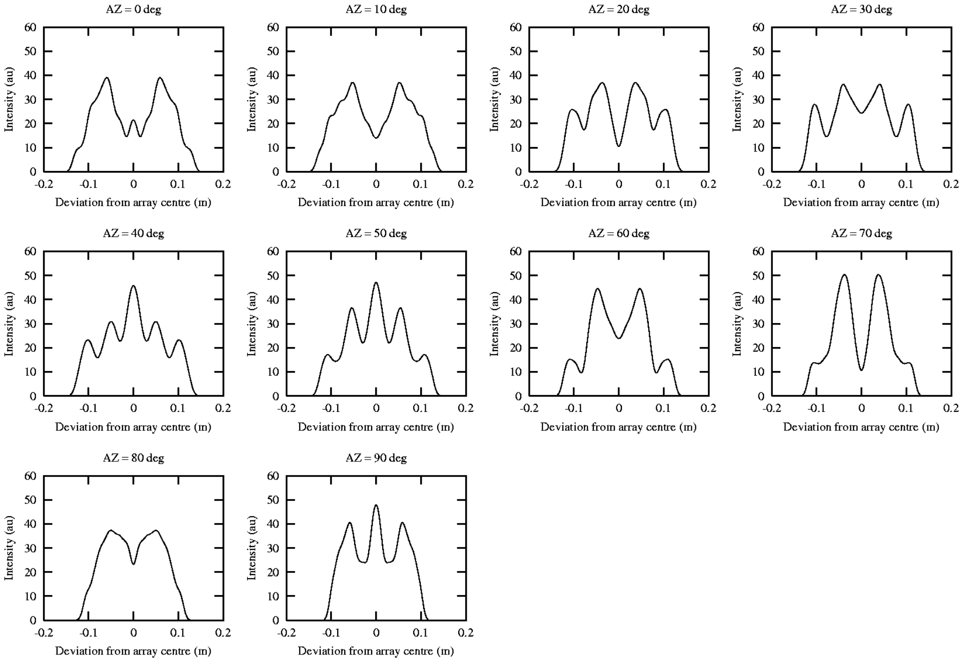

Fig. 3: Azimuthal variation of the retro-reflected pulse assuming 100 ps FWHM of incident pulse and 30 degrees of elevation angle.

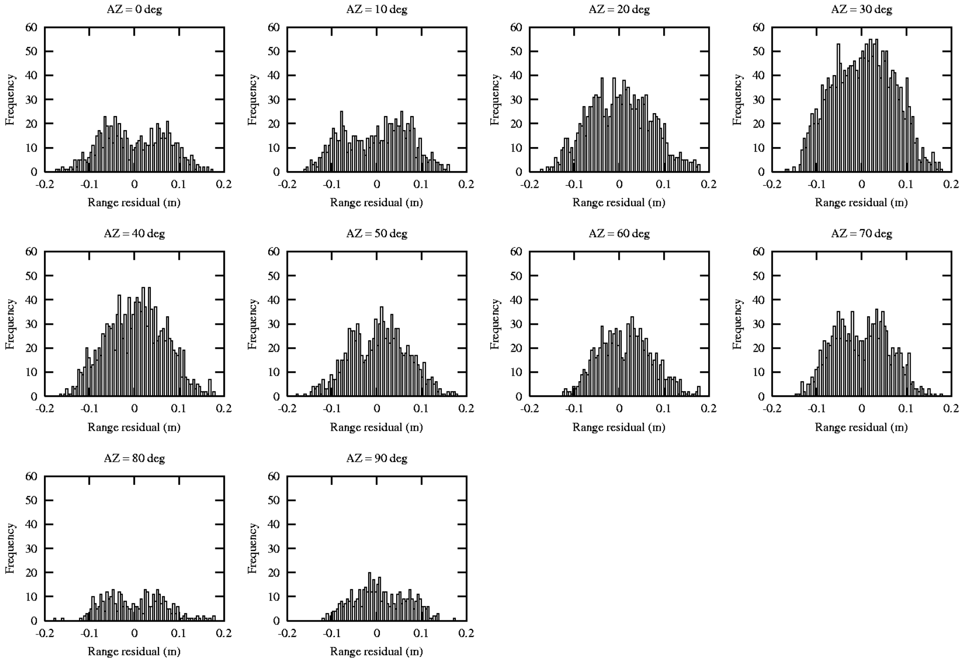

Fig. 4: Azimuthal variation of the range residuals of GLONASS full-rate data obtained at Herstmonceux with a scattering scale mapped to a case of 30 degrees of elevation angle.

ranging because we do not experience such a long leading edge in ranging to spherical satellites. The magnitude of the effect is considered to be dependent on the configuration of each system, but it is almost impossible to predict the exact point of the detection timing for every station.

3. Estimation of Effective Array Size

We introduced a new parameter in our orbit analysis software CONCERTO. The change of one-way range $\delta\rho$ is modeled as a function of the angle of incidence i:

$$\delta\rho = -a \sin i$$

The parameter a indicates the distance between the array centre and the effective reflection point, in other words, half of the effective array size. This is to be treated as an adjustable parameter for every station. If the detection timing were always of the first photon in a sufficiently strong signal, this parameter would be 0.5 or 0.6 m, which is half of the actual array size. A single-photon detection system is expected to give on average a zero value.

The normal-point data for three satellites, GLONASS-72, 79 (both Oct 1998 to May 2000) and 80 (Oct 1999 to May 2000), observed at 14 high-quality stations, were used in the orbit analysis. The orbits were estimated every 10 days by adjusting the along-track constant acceleration and the along-track once-per-revolution acceleration. Station coordinates were fixed to ITRF97 but range bias was solved for as a common parameter through all the stations. We found the estimation of the once-per-revolution acceleration significantly effective to absorb the unmodeled forces. The post-fit weighted-rms was about 2.5 cm.

The new parameter was adjusted for every satellite and for every station and the results are summarised in Fig. 5. All the NASA stations, plus Grasse LLR and Wettzell are multi-photon stations

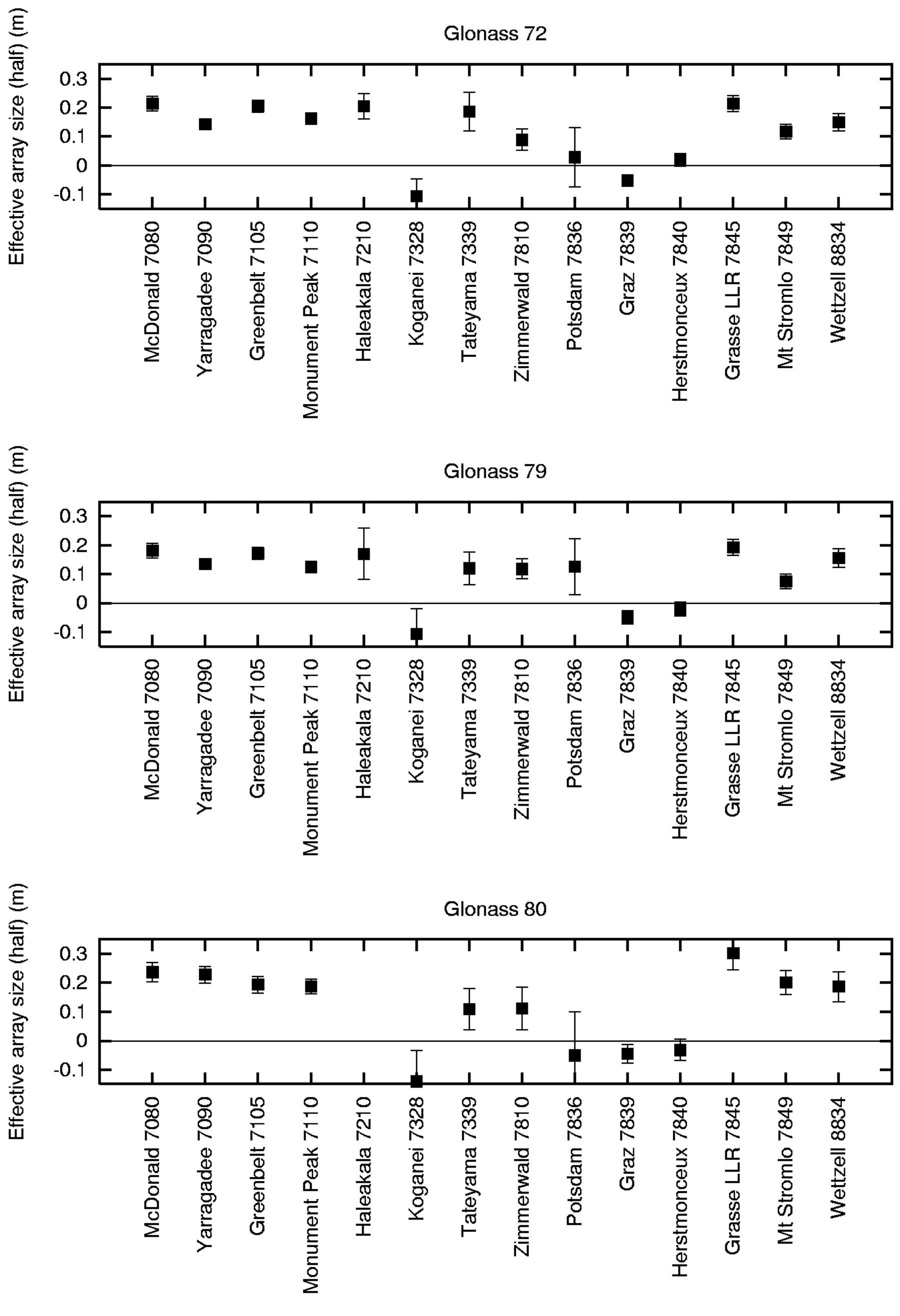

Fig. 5: Estimated effective array size (half) for 14 global laser stations.

with a high detection level. The estimated value of a for these stations fell into the range 0.1 to 0.3 m. Herstmonceux is the only station that always operates at a single-photon level, but we found that Graz was using single-photon detectors at low return rate for GLONASS ranging. For these two stations the solutions for a were close to zero.

The averaged effective array size (half) was 0.145 m. Multiplying this by the average $\sin i$ of 0.151 and reversing the sign, we obtain –22 mm as the offset bias averaged over the whole laser ranging network. This seems to explain half of the known discrepancy between the microwave orbit and laser range measurements.

However, at the same time, we estimated the range bias as a common parameter, and obtained –48 mm for GLONASS-72, –41 mm for GLONASS-79 and –37 mm for GLONASS-80. These values themselves are close to the reported 4 cm offset between the microwave orbit and the laser data, which value would of course include the above-mentioned target signature effect (–22 mm). Because such a large offset bias is very unlikely to be due to ranging system problems, the result suggests the existence of an unknown force or an error in the assumed centre-of-mass correction.

4. Conclusions and future studies

The satellite signature effect should be taken into consideration when we analyse the precise orbit of the GLONASS satellites from laser ranging data. If this is ignored, an error of about 20 mm in radial distance will result. We recommend that such an effect be investigated at the design stage of future satellite missions if high precision tracking is required.

It was reported for the first time at the workshop that the centre-of-mass correction of 1.51 m seems to be wrong [5]. We would like to continue this study with the correct value of this parameter so as to improve the accuracy of laser ranging technology.

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