Optical Response Simulation for ASTRO-G Laser Reflector Array

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Abstract

Optical response of retroreflectors is studied for the precise laser range measurement to ASTRO-G, to be launched in 2012. Geometric variation on incidence angle and velocity aberration is modeled assuming the orbit and attitude of this satellite. Due to its highly elliptic orbit unfamiliar to the satellite laser ranging community, the reflector configuration has to be designed with a number of new concepts. Optical response of each retroreflector is then precisely simulated as a four-dimensional function, which is to be used for simulating the response from its whole reflector array.

1. Introduction: highly elliptic orbit of ASTRO-G

A next-generation satellite mission ASTRO-G (Fig. 1) is being developed at Japanese Aerospace Exploration Agency (JAXA). This satellite is for radio astronomical studies utilising the space VLBI technique, and is scheduled to be launched in the fiscal year of 2012.

This ASTRO-G satellite, with a 9.6-metre mesh antenna, will receive high frequency radio signals up to 43 GHz and enhance the resolution of images by approximately 10 times than the former Japanese mission known as HALCA. It is expected to provide high-resolution imaging of active galactic nuclei, motion in galactic star forming regions, observations of extragalactic water masers, etc.

Figure 1. ASTRO-G satellite.

This satellite requires centimeter-level precision of orbit to obtain precise images of these radio-astronomical targets. Laser ranging retroreflctor array is onboard as well as a GNSS receiver. The orbit determination simulation is ongoing for this satellite (Otsubo, et al., 2006).

It adopts a highly elliptic orbit.
With an eccentricity of 0.62, its altitude varies from 1000 km (perigee) to 25000 km (apogee). The orbital period is about 7.5 hours and the inclination is set to 31 degrees. Unlike existing SLR targets orbiting almost circularly around the Earth, the station-to-satellite distance varies nearly 30 times through the orbit, which means its SLR link budget changes by as much as 30^4 (~ 10^6) between the perigee and the apogee.

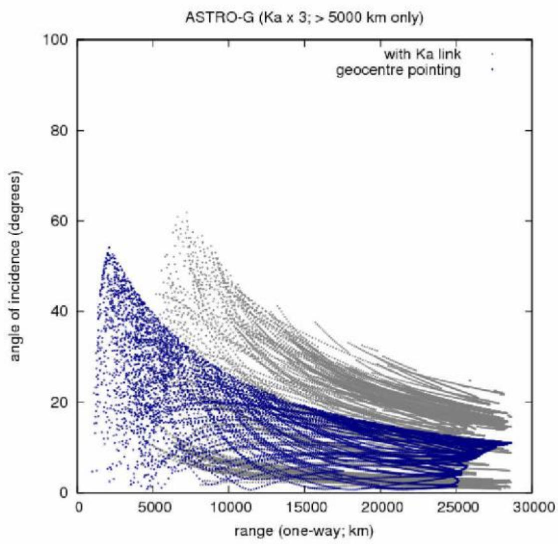

Figure 2. Angle of incidence toward ASTRO-G retroreflector array.

The angle of incidence toward the reflector array varies up to nearly 60 degrees at low altitude (Fig. 2) due to this type of orbit. In this calculation, the reflector array is modeled to point one of three Ka-band antennas or the geocentre. Ten existing SLR stations are assumed to track it every minute. The result is far different from 20000-km. GNSS satellites in which the angle of incidence does not exceed 14 degrees.

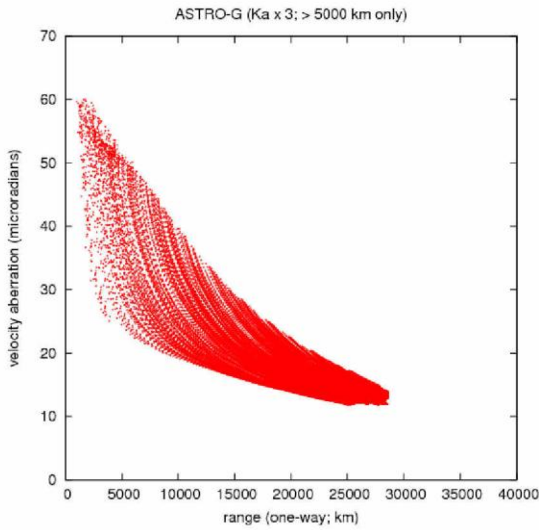

Figure 3. Velocity aberration of ASTRO-G seen from existing SLR stations.

This type of orbit also brings a new challenge in terms of velocity aberration. In the case of circular-orbit satellites, the velocity aberration stays in a certain small range throughout the orbit. However, as indicated in Fig. 3, the velocity aberration of ASTRO-G varies from 12 microseconds around the apogee to 60 microseconds around the perigee. None of existing or past satellites have experienced such a huge variation of velocity aberration.

We have to tackle these unprecedented problems when designing its reflector array.
This paper deals with a preliminary part of optimisation studies of a reflector array to be carried on the ASTRO-G satellite.

2. Basic concept of ASTRO-G reflector array

A planar array is common for GNSS satellites around 20000 km of altitude, and a compact pyramid-style array is common for low-earth remote sensing satellites at or below 1500 km of altitude. In order to cope with the wide range of angles of incidence shown in Fig. 2, we have devised a basic concept of a reflector array for ASTRO-G as seen in Fig. 4. It is basically the combination of the GNSS-type array in the surrounding area and the low-earth-orbiter-type array in the central area.

Three types of circular-faced reflectors are currently assumed. The central six reflectors are 28 mm in diameter, all slanted by 30 degrees, and coated on backfaces. The surrounding 14 reflectors (called 'inner ring') are also 28 mm in diameter, not slanted, and uncoated on backfaces. Finally, the outer 14 reflectors ('outer ring') are the same as the inner ring except for its size of 38-mm diameter.

The slanted and coated six reflectors are placed at the centre, so that the centre-of-mass correction changes smoothly with respect to the angle of incidence and also so that most of the area on the array panel can be spent for the non-slanted reflectors whose amount is the key to succeed long-distance laser ranging.

Figure 4. Basic design of ASTRO-G retroreflector array.

3. Numerical simulation of four-dimensional reflector response

It is necessary to numerically simulate the precise response pattern of each reflector in order to find the optimised combination of the components. Hitotsubashi University has embarked software development required for this study as we had only constructed two dimensional models (Otsubo and Appleby, 2003). The new program is written in C#.

The optical response is described as a four-dimensional function, i.e., two dimensions for angle of incidence including azimuthal angle, and two dimensions for velocity aberration that is a two-dimentional relative velocity vector perpendicular to the line of sight.

The software firstly set every parameter of a retroreflector, such as optical index, shape of front face, backface coating, dihedral angle. It then calculates the actual path length inside the reflector taking a small (0.2 mm) grid size of ray tracing, for a given angle of incidence. It finally generates a far-field diffraction pattern of 2 microradians' mesh size based on the phase difference of outgoing rays. This sequence is repeated for every angle of incidence separated by 2 degrees.

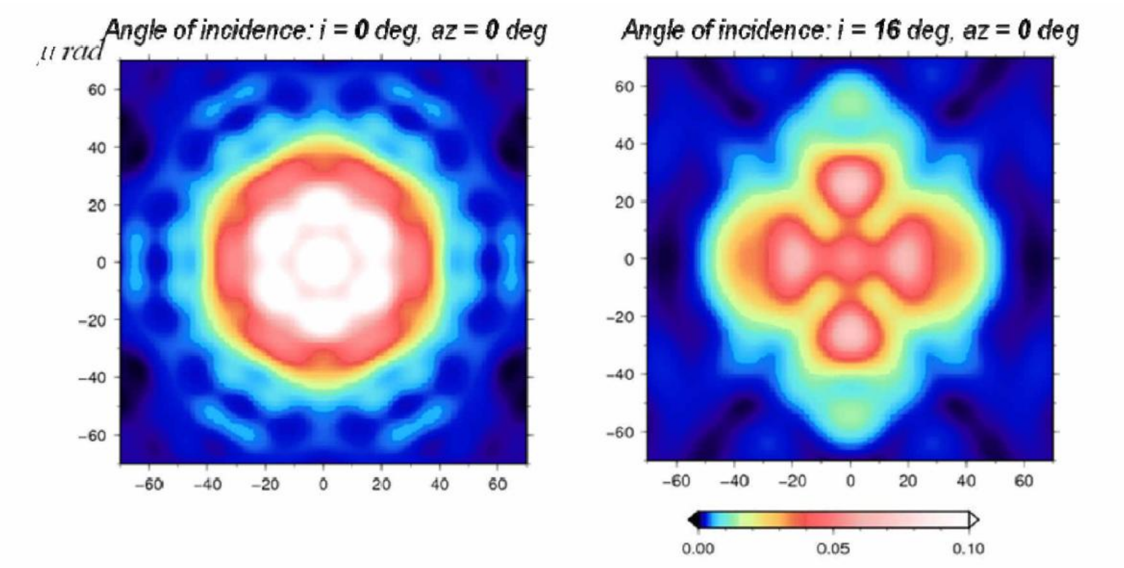

Figure 5. Far-field diffraction patterns of a 38-mm-diameter circular-face reflector with backface uncoated and 0.75-arcsecond dihedral angle.
Left: angle of incidence = 0, right: angle of incidence = 16 degrees.

Two examples of far-field diffraction patterns are shown in Fig. 5 for the outer ring reflector. Dihedral angle is set to 0.75 arcseconds. The left graph is the zero angle of incidence and it shows a diffraction pattern with azimuthal symmetry every 60 degrees. In the right graph, the angle of incidence is set to 16 degrees upward with respect to the plane of this paper, and the diffraction pattern is broadened along the up-down axis since the effective aperture is horizontally long. These patterns are calculated every two degrees of two-dimensional angle of incidence.
It should be noted that this software is still being developed and these are still preliminary results.

4. Link budget estimation for ASTRO-G reflector array

Based upon simulated orbits of ASTRO-G and the existing laser ranging stations, the link budget of laser ranging observations is estimated. This work is very important for the feasibility analysis of the laser reflector array.

As the Asian and Australian stations have recently succeeded in laser ranging to the geostationary satellite ETS-VIII (Uchimura, et al., 2004), simulated observations to ETS-VIII assuming JAXA Tanegashima station (30.5-deg N) are used as a baseline in the following analysis. Although the optimisation of dihedral angle should be made, we set the dihedral angles at 0.75 arcseconds for central reflectors, and 2.0 arcseconds for inner and outer ring reflectors. The other parameters are the same as given in Section 2.

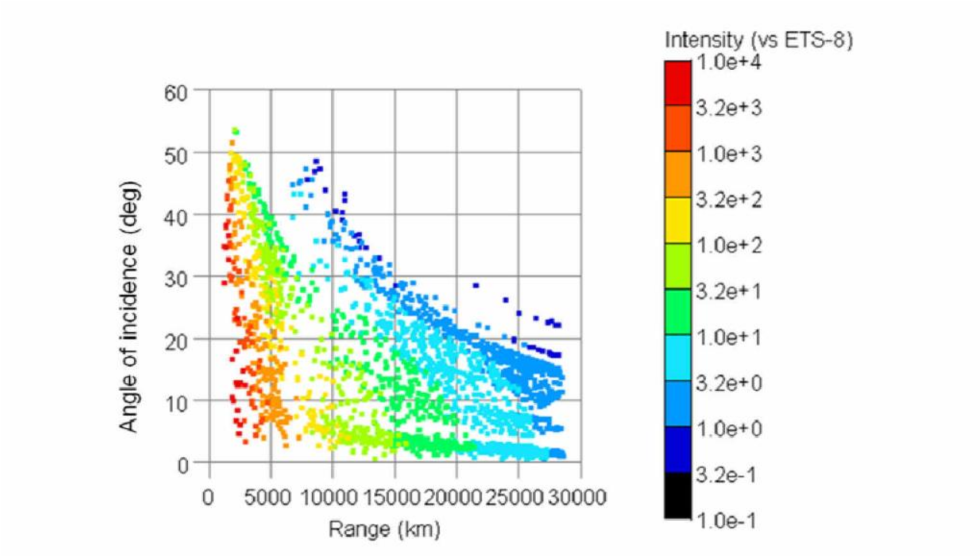

Figure 6. Intensity of estimated returns from ASTRO-G satellite, in comparison with ETS-VIII.

The result is shown in Fig. 6. The intensity is estimated to be stronger than ETS-VIII in almost 98% of the time. The remaining 2% is plotted as dark blue dots that are scattered both in [1] > 25000 km range with ~20 degrees of angle of incidence and in [2] 7000-15000 km range with ~40 degrees of angle of incidence. The intensity is expected to be just 1 to 10 times stronger than ETS-VIII for 76 % of the time (light blue and medium blue dots) as the satellite flies slowly around the apogee. Nevertheless, it is clear that ASTRO-G will be observable as long as a station can track ETS-VIII.

5. Conclusions and future studies

Laser ranging to highly elliptic orbits is challenging. A basic design of ASTRO-G laser reflector array is almost finished. It is a combined structure of a GNSS-type array and a low-earth-orbiter-type array. Using newly developed software for four-dimensional optical response, the link budget to ASTRO-G is estimated. This satellite will give stronger returns than ETS- VIII for most of the time.

There are still remaining studies for optimising the details of reflector configuration, such as dihedral angles, slant angle of central reflectors, and target signature effects. We plan to continue further numerical simulations to find the best combination of a number of configuration parameters.

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