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Alignment measurement with optical transponder system of Hayabusa-2 LIDAR

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Abstract. *The laser altimeter named "LIDAR" aboard Hayabusa-2 asteroid mission is a ranging instrument which measures the distance between spacecraft and the target asteroid now called 1999 JU_3. It is also equipped with a function of "optical transponder", in which LIDAR receives the laser from a ground SLR station and sends back to the same ground station. The experiment will be carried out when the satellite is near the Earth for gravity assist. It will be not only the first full-operation of LIDAR, but also it will provide an opportunity of in-flight measurement of the alignment of LIDAR boresight after the launch. The SLR telescope of 1.5m aperture in NICT Koganei will be used as a ground station. A 1-micron laser with power of 1.2J and repetition rate of 10Hz will be installed for this purpose. The spacecraft will scan the Earth at a certain rate so that each of footprint of LIDAR (1 mrad) can overlap each other. Taking into account the attitude determination error of 0.5 mrad, the boresight of LIDAR to the spacecraft body will be determined within accuracy of 1.5 mrad. The opportunity of the experiment is restricted according to the position of Sun, spacecraft, and Earth due to thermal condition of spacecraft.*

Introduction

The Japanese first asteroid sample return mission, called Hayabusa, reached an asteroid Itokawa in September 2005. Though it had many challenges in touchdown and returning journey to the Earth, it successfully brought back the surface materials of the asteroid Itokawa in 2010. In this mission, the asteroid was revealed to be a rubble-pile structure (Fujiwara et al. 2006) which was long predicted but there was no observational evidence before Hayabusa reached at Itokawa and did remote sensing surveys.

As a successor of the Hayabusa mission, JAXA and collaborating scientists are now developing the next asteroid sample-return mission named Hayabusa-2. The launch is scheduled in winter 2014, and it will arrive at the asteroid in 2018. After one and half year of the stay near the asteroid and several touchdowns onto the surface for material sampling, it will leave the asteroid in 2019 and will come back to the Earth in 2020. The first Hayabusa went to one of the S-type (stony) asteroids, which is typical in the near asteroid belt, mainly due to the easiness of the mission, and because it was an engineering test satellite mission. From the scientific point of view, one of the main targets for exploring asteroids is to know the origin of the solar system. Asteroids, especially ones located in the more distant position from the Sun, are expected to have primitive materials on their surface because they are expected not to have experienced any global melting like the planets and Earth's Moon. The target asteroid 1999 JU_3 is a C-type (carbonaceous), which consists of carbonaceous materials, which is more primitive than the samples returned by Hayabusa. Before the touchdown, global mapping of the asteroid will be carried out by various remote sensing instruments for determination of the landing sites. Among such instruments, LIDAR (Light Detection and Ranging; Figure 1) measures the distance between the spacecraft and the asteroid surface by detecting the time of flight of 1064 nm laser light. LIDAR is one of the navigation instruments of AOCS (Attitude and Orbit Control Subsystems), however, the data will also play an important role as a scientific instrument (Namiki et al, submitted).

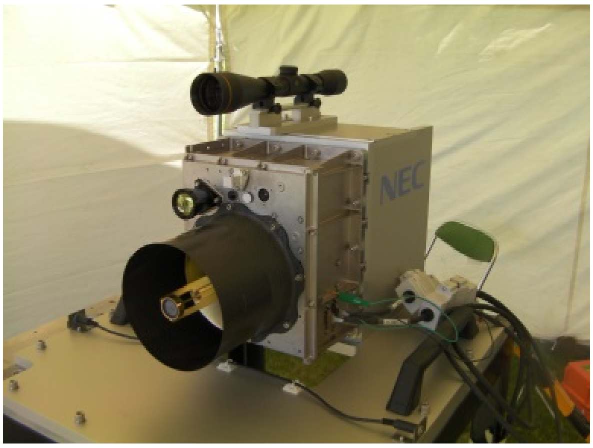

Figure 1. The appearance of LIDAR as ground ranging test set.

Hayabusa-2 LIDAR and scientific requirement for alignment

There are three operation mode and five scientific applications for LIDAR.

i) Topographic mapping and scaling of images: the most important role of the LIDAR is to develop a shape model of the asteroid. Range data can be converted to the topography once we know the spacecraft position. Range data are also used to determine the scale of images taken by the Optical Navigation Camera (ONC). The images can be converted to the true scale by LIDAR data, and they will be used for developing the shape model of the asteroid.

ii) Mass determination: several free-fall experiments toward the asteroid will give us the data of gravity field of the asteroid. In this experiment, range data will be used to calculate the gravity acceleration by the asteroid, which yields the GM value of the asteroid. And depending on the number of free-fall experiments, the low degree gravity field may be determined which may reflect the variation of the internal structure of the asteroid.

iii) Albedo measurement: LIDAR is equipped with energy monitors of both transmitting and receiving laser light. Corrected received laser energy with distance, surface slope and transmitting power will give a measure of surface albedo at laser wavelength. Albedo determined with LIDAR does not need any phase-angle correction, because both the incident and emitting angle are zero degree. Albedo measurement is always available on ranging mode.

iv) Dust detection: the fourth application and the second mode of LIDAR is prepared for detection of the levitating dust which may exist above the asteroid surface. Because small meteorites and dusts always fall onto any solar system bodies, it is easily expected that 1999 JU_3 also has fine dust particles which are ejected by such interplanetary bodies. For this purpose, LIDAR is equipped with the dust detection mode, in which one bit status (0 or 1) will be returned along each bin of the line of sight direction of LIDAR until the laser light hits the hard surface. If it is detected, it will be the first observational evidence of the dust above the asteroid.

v) Optical transponder: the fifth application and the third mode of the LIDAR is optical transponder. When the LIDAR is on this mode, it will wait for the laser light from the SLR (Satellite Laser Ranging) station on the Earth. Once LIDAR detects the laser signals from the Earth station, it will emit laser light with nominal energy immediately. The main purpose of this mode is an experiment of time transfer from the ground to the spacecraft. Because the asteroid is very far from the Earth, such operation is possible when the spacecraft is much near the Earth.

Asteroids are often regarded as the “Rosetta Stone of the early solar system”. Small planetesimals which could not be evolved as planets remained in the solar system. Some big ones, like Vesta, grew by absorbing small pieces of bodies and differentiated. Other rather big ones survived collisions and become almost monolithic asteroids. On the other hands, smaller ones repeat collision, fragmentation, and accumulation to form porous asteroids. Therefore, the value of porosity is a key measure to group asteroids as “fractured or monolithic” or “rubble pile” groups. To identify which category the target asteroid falls on, the required accuracy of the porosity measurement is almost 10 %.

The range accuracy of LIDAR directly influences the determination of the total volume. The bulk density of the target asteroid can be estimated from the shape model and GM value from the observation. From the spectral analysis of the surface materials and also detailed studies of returned samples, the material can be estimated. Assuming the average density from these information, one can derive the porosity. For this purpose, we must determine the volume of the asteroid as accurate as possible.

From the requirement mentioned above, the volume must be determined within 5 %, and as a result, the accuracy of the radius measurement must be within 2 %. As the radius of the asteroid is nearly 500 m, “statistical” range accuracy must be almost 10 m.

If the boresight direction of the transmitting telescope with respect to the spacecraft body is shifted from the expected value, the resulting asteroid volume estimation might also be degraded. Suppose there is a slope of 30 degrees as the worst case. Then, if we observe it from the 20 km distance and the boresight direction has errors of 1.5 mrad, the range error becomes almost 15 m per shot, and it is still larger than 10 m ranging accuracy. However, taking the slope angle distribution and number of laser shots into account, we consider the requirement of volume estimation will be nearly satisfied statistically.

Laser link experiment

The spacecraft needs gravity assist by the Earth for departure to the deep space. This operation is scheduled in winter 2015, and taking this opportunity, the optical transponder experiment will be carried out. It will also be the first full operation of LIDAR including laser transmission and receiving. In this opportunity, by using the ground SLR station as a reference, the boresight directions of the receiving and transmitting telescope of LIDAR can be determined, and it will be the confirmation of the boresight direction after the launch.

In the first Hayabusa mission, the near infrared spectrometer (NIRS) covered the LIDAR wavelength at 1064 nm, and the footprint of the LIDAR on the asteroid surface was detected by NIRS. From such observation, the relative boresight direction between NIRS and LIDAR was determined within the field of view angle of 1.7 mrad. NIRS and the visible camera (ONC) were co-aligned and the boresight direction of the ONC could be determined with respect to the spacecraft body (Abe et al 2006). Combining all these information, LIDAR boresight direction was also determined with respect to the spacecraft body. In Hayabusa-2, however, the near infrared spectrometer only covers wavelength of near 3 micrometers, therefore this method is not applicable. The laser link experiment offers an opportunity to confirm the boresight direction of LIDAR. As the attitude error of the spacecraft is assumed as 0.5 mrad (0.03 degrees) and the field of view of the transmitting telescope is 1 mrad, the boresight direction of transmitting telescope with respect to the spacecraft body will be confined to 1.5 mrad.

In this experiment, the SLR telescope of 1.5m aperture in NICT Koganei will be used as a ground station. The parameters of the ground and LIDAR telescopes are summarized in Table 1. Based on the standard laser link equations shown as follows, we calculated the link budget:

$$P_s = P_t \cdot \eta_t \cdot G_t \cdot \eta_r \cdot L_p \cdot L_s(r) \cdot G_r \cdot L_0 \quad \text{(uplink)}$$

$$N_{pe} = \eta_q \cdot (E/h\nu) \cdot \eta_t \cdot G_t \cdot \eta_r \cdot L_p \cdot L_s(r) \cdot G_r \cdot L_0 \quad \text{(downlink)},$$

where Ps and Npe show the received power by LIDAR and the number of photoelectron at ground station respectively, and other parameters are listed in Table 2. For uplink case, namely from ground SLR station to LIDAR, the power of the laser light is calculated in per-pulse basis, because the detector of LIDAR is APD (Avalanche Photo Diode) which is used as multiphoton detector. For downlink case, the APD of the ground station is used as single photon detector (Geiger mode), therefore the calculation is carried out on a photon basis.

Table 1. Parameters of ground and onboard telescopes

parameter	NICT 1.5m	LIDAR
Transmitter		
wavelength, nm	1064	1064
Laser pulse energy, mJ	1200	10
Repetition frequency, Hz	10	1
Pulse width, ns	10	<10
Beam divergence, mrad	0.01	1
Receiver		
Telescope diameter, m	1.5	0.11
Detector FOV, mrad	0.1	1.5
Pointing		
Pointing accuracy, mrad	~ 0.01 (~2 arcsec)	0.5 (attitude stability)

Table 2. Parameters for link calculation

symbol	meaning	Value (uplink)	Value (downlink)
P_t	Transmitter power	1.20 E6 W (/pulse)	--
E_t	Transmitter energy	--	0.01 J
η_q	Quantum efficiency	--	0.2
η_t	Transmitter efficiency	0.8	0.8
G_t	Transmitter gain	1.6E11	1.6E7
η_r	Receiver efficiency	0.5	0.5
L_p	Pointing loss	0.487	0.487
$L_s(r)$	Space loss	1.2E-34 @ 0.05 AU	
G_r	Receiver gain	1.05E11	1.96E13
L_0	Other losses	0.5	0.5

Figure 2 shows the expected output voltage of APD of LIDAR and number of photoelections at Koganei station. Because high powered laser is emitted from the ground station, even if the detection is done as multiphoton on the LIDAR, the output voltage of the detector is well above the detection limit of 9 mV up to distance of 0.5 AU. For the downlink, the distance where number of photoelectrons becomes one is much shorter than the uplink case, mainly because of the small laser energy of 10 mJ from the LIDAR. It is because it is optimized to the observation near the asteroid up to 25 km distance from the surface. Even though, the distance which meets the detection limit is more than 0.3 AU (= 4.5 x 10^7 km), which is much further distance than the distance one month before the Earth swing-by operation.

In terms of the spacecraft operation, there is one limitation which may reduce the chance of experiment. Because Hayabusa-2 is solar-powered spacecraft and the solar panels are almost fixed to the spacecraft body, they must face toward the Sun within certain range due to power and thermal conditions. With this constraint, the Sun – Spacecraft – Earth (SPE) phase angle must be within 120 degrees. By using a predicted orbit, SPE angle is larger than 120 degrees for most of the time before the Earth Swing-by operation (Figure 3), therefore we do not need to take this limitation into account. However, if 130 degrees is required as the SPE angle, the experiment will not be permitted. Purple squares in Figure 4 show the chances of experiment at Koganei station, taking the following conditions into account:

1) the spacecraft is visible from the Koganei station
2) after the sunset at Koganei
3) SPE angle limitation stated above.

On average, we have chances of almost four hours a day before the Earth swing-by operation. However, after the Earth swing-by, there is no chance of experiment, mainly because the spacecraft will fly above the southern hemisphere of the Earth and is not visible from the northern hemisphere.

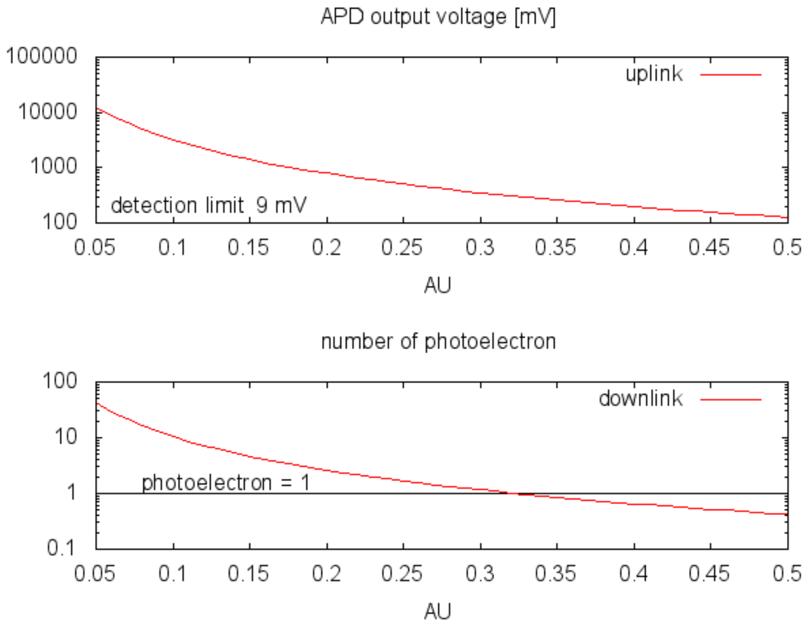

Figure 2. Calculation of uplink and downlink budget.

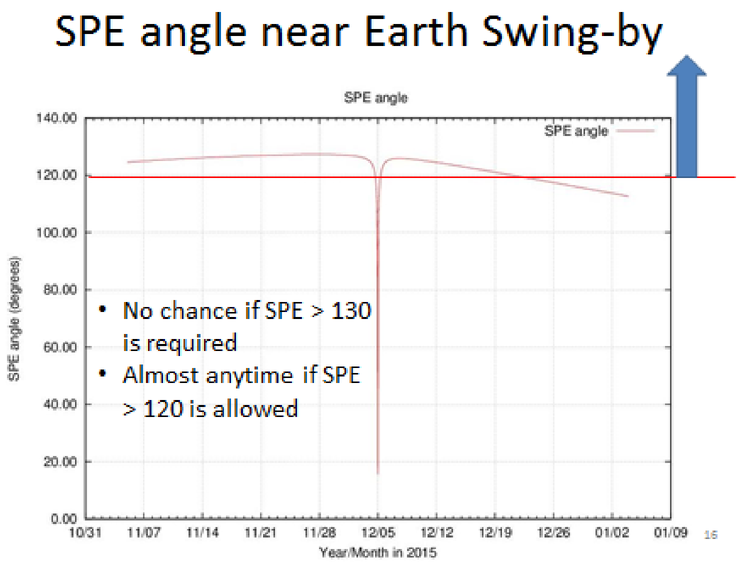

Figure 3. Calculation of SPE angle before and after the Earth swing-by on December 2015.

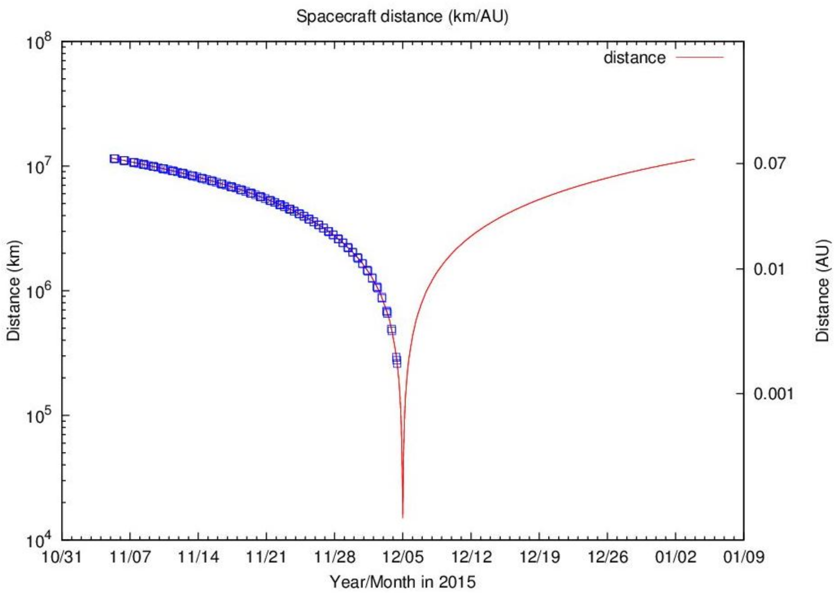

Figure 4. Chances of experiment before and after the Earth swing-by on December 2015 at Koganei SLR station. Curves shows the distance of the spacecraft from the Earth, and boxes on the curve show periods where the experiment can be carried out.

Summary

Hayabusa-2 is the second asteroid sample return mission of Japan which will be launched in winter 2014. The target asteroid, 1999 JU_3 has spectral type of C-type, and it is considered as the carbonaceous asteroid. C-type asteroids are considered as older ones than S-type asteroids, one of which the first Hayabusa spacecraft visited. The estimation of bulk density of the asteroid by using the shape model and GM value measured with LIDAR and ONC camera is crucial for the estimation of porosity, which is used for the categorization of asteroids. For this purpose, the accuracy assessment of LIDAR ranging is important, and the determining the boresight direction of laser transmitting telescope directly links to the estimation error of the volume. From the laser link experiment, the boresight direction of transmitting telescope can be decided within 1.5 mrad accuracy, which yields the ranging accuracy about 15 m at 20 km distance. Taking statistical treatment, the aiming accuracy of volume estimation with 10 % error may be achievable. From the link calculation, laser powers of both ground and onboard segments are enough for this experiment at less than 0.1 AU distance between the Earth and spacecraft, and the experiment will be done during one month before the Earth gravity assist operation in winter 2015. The visibility from the ground station and SPE angle limitation determines the chances of experiment, and almost four hours after the sunset will be suitable for experiment.

References

Abe, S. et al, Science 312, 1344-1347, 2006.

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