ESTABLISHMENT OF LASER LINK BETWEEN GROUND STATION AND HAYABUSA2 LIDAR. H. Noda[1], T. Mizuno[2], H. Kunimori[3], H. Takeuchi[2], H. Senshu[4], N. Ogawa[2], T. Saiki[2], T. Yamaguchi[2], A. Pollard[5], C. Moore[5], N. Namiki[1], Y. Tsuda[2], [1]National Astronomical Observatory of Japan (2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan, hirotomo.noda@nao.ac.jp), [2]Japan Aerospace Exploration Agency (3-1-1 Yoshinodai, Chuo-Ku, Sagamihara, Kanagawa 252-5210, Japan), [3]National Institute of Information and Communications Technology (4-2-1 Nukui-Kita-machi, Koganei, Tokyo 184-8795, Japan), [4]Chiba Institute of Technology (2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan), [5]Space Environment Research Centre (AITC2 Mt. Stromlo Observatory, Cotter Road, Weston Creek, ACT 2611, Australia).

Introduction: The Hayabusa2 asteroid explorer, launched on 3rd December 2014 from Tanegashima Space Center, has finished its EDVEGA (Electric Delta-V Earth Gravity Assist) phase in winter 2015 and was inserted into the transfer orbit toward 162173 Ryugu (formally known as 1999 JU_3). Before and after the closest approach to the Earth on 3rd December 2015, we conducted laser link experiments between ground-based Satellite Laser Ranging stations and the laser altimeter named LIDAR aboard Hayabusa2. The main purposes of the experiment are engineering demonstrations of optical ranging and the time transfer from the ground to the spacecraft, and the laser communication in deep space. The experiment also offers us the first opportunity for performance check such as in-flight alignment of the transmitting and receiving telescopes of LIDAR and the evaluation of laser link budget [1]. In terms of the scientific use of LIDAR data, malalignment of the telescopes may lead to the worse estimation of shape and gravity field of the asteroid, therefore the in-flight calibration is crucial.

So far, deep space laser link experiments, farther than the lunar distance, have been realized with MLA aboard MESSENGER at 23.9 Gm [2] and MOLA aboard MGS at 80 Gm [3]. Experiments with LIDAR of Hayabusa2 have been conducted for three periods of time, October, November and December. Among these periods, the experiment was successful on December thanks to the weather condition. Here the results of experiments in December will be reported. The spacecraft distance ranged 3 to 6.5 Gm in this period.

Experimental setup: *Flight segment.* LIDAR emits 1 micron pulse laser of 15 mJ with repetition rate of 1 Hz. The field of view size of the receiving telescope is 1.5 mrad. Other detailed specification of the LIDAR hardware is described in [4]. In addition to the normal ranging mode, the instrument is equipped with “optical transponder mode” for the dedicated laser link experiment. In this mode, LIDAR waits for a laser pulse for one second, and once it receives the laser pulse, it emits back a laser pulse. LIDAR also detects second successive laser pulse within the waiting time gate, and returns the time of the first pulse reception and the period of time between two pulses measured with the time interval counter. Also the time of the laser excitation is stored as another timing data. As a results, instrumental internal delay as a transponder is available as telemetry data. Flags indicating two laser receptions and emission are also downlinked, however, received laser energies are not available as telemetry data due to the limitation of data amount.

On the other hand, in the normal ranging mode, transmitting and received laser energies are recorded as telemetry data in every second, which enables us to evaluate the link budget. Naturally, only first pulse can be detected with one APD detector in the range gate. There is one negative point in this mode: the chance of detection of the uplink laser from the ground is limited in time. The range gate opens only for 437 micro seconds after LIDAR emits the laser pulse. Considering the rate of the master clock of the spacecraft to UTC and the spacecraft velocity in the line of sight direction (~4.5 km/s), the chance of detection comes every three minutes in December experiment.

LIDAR emits and receives single laser pulse in every one second in ranging mode, while in the transponder mode it is reduced to every two seconds due to the limitation of the command sequence to set this mode.

The orientation of the spacecraft was changed with step size of 1 mrad (0.057 degrees) spirally, and almost square area of 1 degree by 1 degree was covered so that the boresight of LIDAR hit the ground station direction. This operation was conducted until the alignment of the LIDAR to the spacecraft body frame was confirmed. Then the attitude of the spacecraft was fixed so that the boresight continued to track the ground station direction.

Ground segment. Two ground-based Satellite Laser Ranging facilities emit same 1 micron pulse laser toward LIDAR and receive the laser from LIDAR individually in time share basis. A 1.5 m reflecting telescope at Koganei Station of NICT in Tokyo, Japan for October and November experiments, and 2 m reflecting telescope at Mt. Stromlo Observatory of SERC in Canberra, Australia for November and December. The time sharing is mainly due to the visibility of the spacecraft from the ground before and after the closest approach to the Earth. Other specifications of the telescopes are listed in the Table. The telescope pointing is confirmed via star calibration prior to the experiment and the orbit determination error is small enough compared to the pointing accuracy, therefore basically no scanning was done except for one experiment session.

Results: *Alignment of LIDAR.* Fig. 1 shows the number of first pulse detection flag in the transponder mode with respect to the attitude scan of the spacecraft. This scan session was done on 11, 13, 14 Dec. and data are summarized in one figure. The spacecraft distance between the Earth was about 3.3, 4, 4.5 Gm for each day. Color shows the number of detection flags. One tile corresponds to 1 mrad of scanning step size. Spacecraft kept one attitude position for 35 seconds, so 17 was the maximum number. Horizontal and vertical axis corresponds to right ascension and declination direction respectively. The origin is the best estimated location of the boresight direction in pre-flight alignment measurement by using alignment cubes attached on the spacecraft body and the body of LIDAR. Apparently several tiles show the enhancement of the number, and the boresight direction of the LIDAR receiving telescope is located among these points. Note that the field of view of receiving telescope is wider than the scanning step size. The same operation was done on 15 December, and concluded that the shift of the detected boresight direction from the pre-flight position was 3 mrad in right ascension and 2 mrad in declination direction. The cause of the shift might be due to the error of ground calibration, difference between the boresight of the telescope and alignment cube, and possibly, the shock of launch.

Laser power in ranging mode. Fig. 2 shows the received laser energy by LIDAR in ranging mode measurement in 19th Dec. from Mt. Stromlo station. The unit of the vertical axis is millivolt. As is stated above, the signals appear every three minutes when the range gate is open for 437 microseconds. The reason of the intensity change in each time slot might be due to the atmospheric attenuation, small attitude changes, small amount of mispointing of the ground-based telescope, or other unknown reasons. The intensity was lower than the previous estimation which must be explained.

The search for the downlink laser from LIDAR to the ground station is still ongoing, due to background photons and slow repetition rate of LIDAR.

References: [1] Noda H. et al. (2013) *proceedings of 18th International Workshop on Laser Ranging,* 13-Po-06. [2] Smith D. et al. (2006) *Science,* p53, vol. 311. [3]Abshire J. et al (2006) *proceedings of the Conference on Lasers and Electro-Optics (CLEO)* [4] Mizuno H. et al (2016) accepted in *Space Sci. Rev.*

Table. Specification of ground segment

parameter	NICT	Mt. Stromlo
transmitter	Q-SW Nd:YAG	Q-SW Nd:YAG
laser wavelength, nm	1064	1064
pulse energy, J	1	2.2
pulse width, ns	10	15
beam divergence, arcsec	10	12
repetition rate, Hz	10	170
receiver	InGaAs APD-array	IR enhanced Si-APD
telescope diameter, m	1.5	1.8

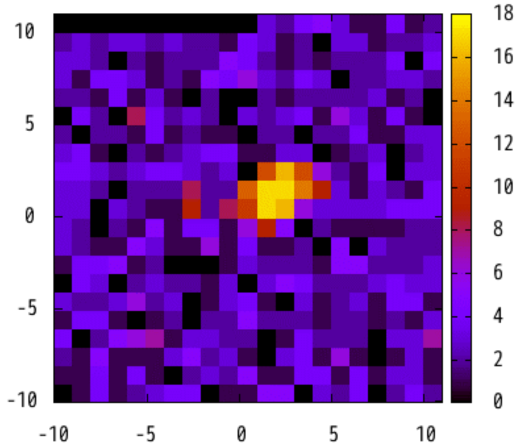

Fig. 1 The number of first pulse detection flag in the transponder mode with respect to the spacecraft scan. Horizontal / vertical axis corresponds to the right ascension / declination direction of the spacecraft attitude. Color shows the number of detection flag. Origin of this figure is the best estimated location of boresight direction before launch. The size of a tile is 1 mrad by 1 mrad.

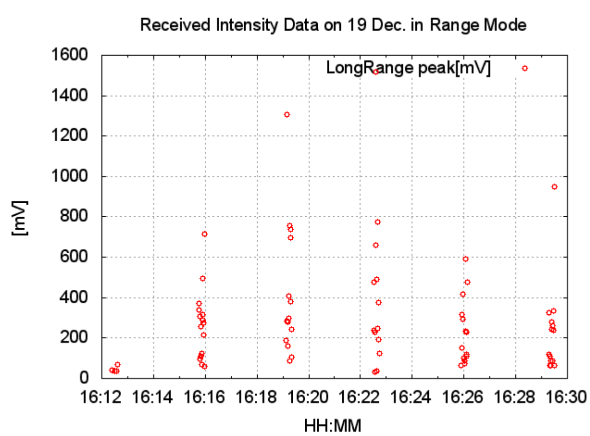

Fig. 2 The laser power equivalent received with LIDAR. The unit of the vertical axis is millivolts, which is the raw telemetry data of peak hold circuit of the received signal strength. Signals are detected in every 3 minutes, because of the range gate, rate of the onboard clock, and the spacecraft motion.