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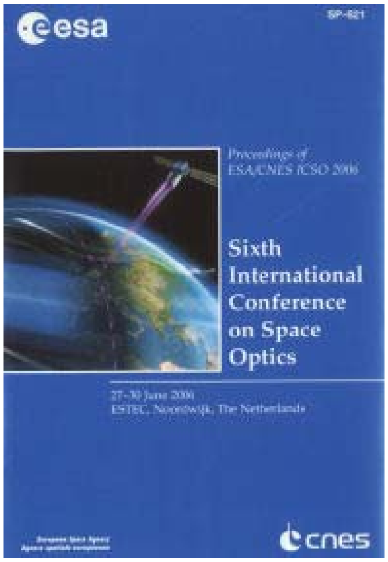
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LIDAR ON BOARD ASTEROID EXPLORER HAYABUSA

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ABSTRACT

HAYABUSA, launched May 2003, is the first Japanese spacecraft to explore the small asteroid Itokawa. HAYABUSA had rendezvous Itokawa in three month in 2005 and touched down it twice to sample the material from it. LIDAR is a one of important navigation sensor to measure the distance between HAYABUSA and Itokawa from 50km to 50m. LIDAR operated in the three months and was estimated to have shot more than 4 million laser pulses and had supplied the ranging data to spacecraft navigation system to approach Itokawa down to 30 m.

1. INTRODUCTION

In recent years, many planetary exploration missions have been carried out. For example NEAR performed many asteroid flyby observations and ROSETTA will rendezvous with Comet 67P/Churyumov-Gerasimenko, many Mars observations are in progress and Mercury and Venus exploration programs follows.

MUSES-C was launched on May 9 2003. It was given the name of 'Hayabusa' (falcon) after it. Hayabusa is a technology demonstration spacecraft focusing on key technologies that are required for future large-scale sample and return mission, yet is also making new scientific observations and discoveries. The technology demonstration component of the mission consists of five goals,

(1) Interplanetary cruise via ion engines as primary propulsion system.
(2) Combination of lo thrust ad gravity assist.
(3) Autonomous navigation and guidance using on board optical observation data
(4) Sample collection from asteroid surface under micro gravity environment.
(5) Direct Reentry for sample recovery from interplanetary orbit.

HAYABUSA project has accomplished these demonstrations up through the third goal. Specifically at the time of arrival at Itokawa, HAYABUSA had driven its proprietary new ion engines for 25,800 hours, including their operation during an Earth flyby. It has also perfectly completed a period of optical hybrid navigation followed by precise guidance and navigation of the spacecraft during its station keeping period around Itokawa. These engineering achievements are the primary mission of HAYABUSA and their successful completion is a great achievement for interplanetary exploration.

HAYABUSA employs three laser sensors, LIght Detection And Ranging (LIDAR), Laser Range Finder[2] (LRF) and Fan Beam Sensor[2] (FBS), for rendezvous and touchdown phase and their data are combined with optical navigation[1]. These three sensors cover the range from 50km to a few meters. LIDAR detects the distance from the target and provide accurate range with a few meters and range rate information at the initial encounter to Itokawa, since the optical imagery information may have relatively large ambiguity to brake to rendezvous LIDAR covers the range form 50km to 50m. LRF covers short range from 100 to 5 meters. LRF has 4 laser beams to measure four slant range and provides relative attitude to the local vertical of the Itokawa surface al well as altitude of the spacecraft. LRF has fifth measurement beam to detect the touchdown of the spacecraft onto the Itokawa. FBS is a unique laser sensor to detect obstacles under the solar array panels at touchdown not to be damaged by the unwanted obstacles.

LIDAR is one of the most important sensors to get to Itokawa and to initiate various observation on it.

2. HAYABUSA EXPLORER AND LIDAR REQUIREMENTS

Fig. 1 shows the bottom view of the HAYABUSA spacecraft. The spacecraft is three-axis stabilized with fixed two solar array panel, and its attitude control and navigation subsystem has many functions during long

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voyage from launch to return to the Earth, it cruise with and without ion engine thruster, flyby the earth, acquire the Itokawa, rendezvous, scientific observation form many direction, approach, touchdown for sampling, long cruise again and inject the reentry capsule into the earth atmosphere to return the collected material of Itoakwa. So, the spacecraft have many sensors and other components to perform the long voyage to Itokawa and return on the spacecraft with dry weight of 374kg. Total mass of the attitude and navigation control subsystem have designed to be 44kg for 40 components. So every components and sensors have been required to have smaller mass.

HAYABUSA is required to be the high performance and extremely light weight spacecraft with highly intelligent and autonomous system. On the other hand, the spacecraft has relatively large solar array panel to supply sufficient power to operate ion thruster on its way back to the earth. When spacecraft use ion thruster without full power operation or it is on the way to Itokawa, there is some margin in the generated power.

Thermal system design requires great restriction on LIDAR, since the surface temperature of Itokawa has large uncertainty and maximum temperature may be 300 degrees Celsius. The equilibrium temperature of the component near the surface of Itokawa will be a few hundred degrees. Therefore, LIDAR employs independent thermal control and maximum temperature at touchdown will be maintained by the balance between heat capacity and external heat input from Itokawa surface. The maximum temperature may be characterized by the ratio of heat capacity and input heat, i.e. external input heat and power consumption. Though heavier mass is preferred from the point view of thermal design, the system resource of the spacecraft system is limited and to minimize its power consumption is very important issue..

According to the study of the navigation requirements, LIDAR shall be able to acquire the range information from 50 km far from Itokawa not to overrun Itokawa. The minimum allowable range of 50m is require to smooth data joining with short range LRF data with accuracy better than 1m. The requirements and specifications are summarized on Table 1.

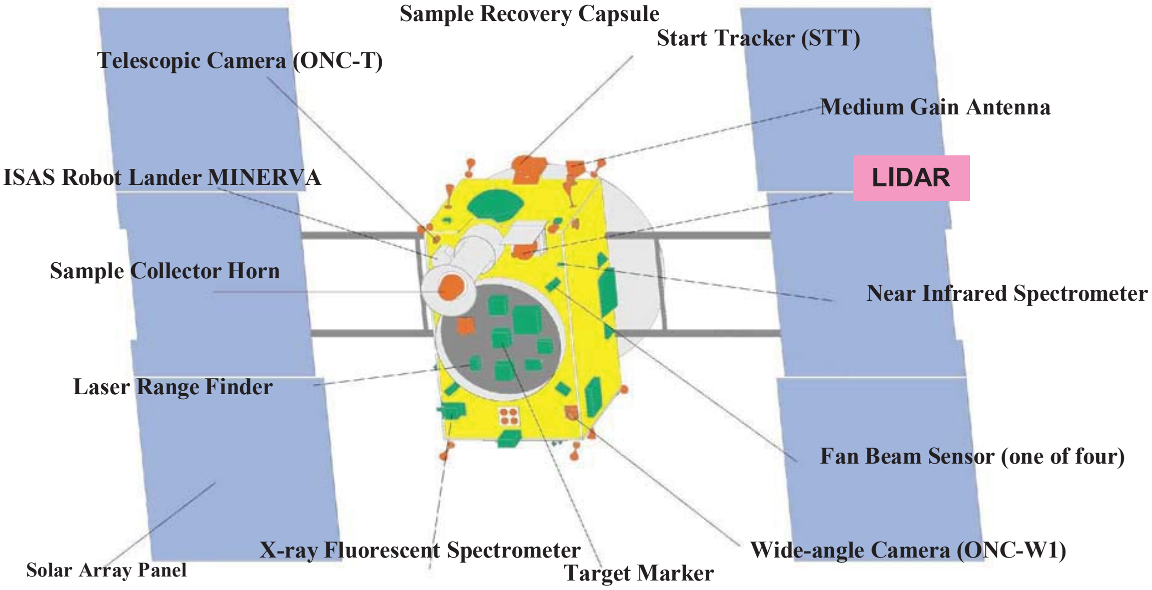

Fig. 1 Bottom Panel View and Instruments of HAYABUSA

Table 1 LIDAR Specifications

Item	Specifications
Range	50m ~ 50km
Accuracy	±1m at 10m, ±10m at 50km
Repetition Rate	1pps
Wave Length	1064 nm(Nd:YAG)
Pulse Power	10 mJ
Pulse Width	14nm
TX Beam	ϕ0.5mrad(1/e^2)
RX FOV	ϕ1mrad
Target Reflectance	0.05~0.2 (Lambert Surface)
Weight	3.65kg (Include Primary Bus I/F and Thermal Radiator)
Power Consumption	17.0W (exclude LD heater with 5W max)
Size	240mm×228mm×350mm (Exclude radiator 240mm×300mm)

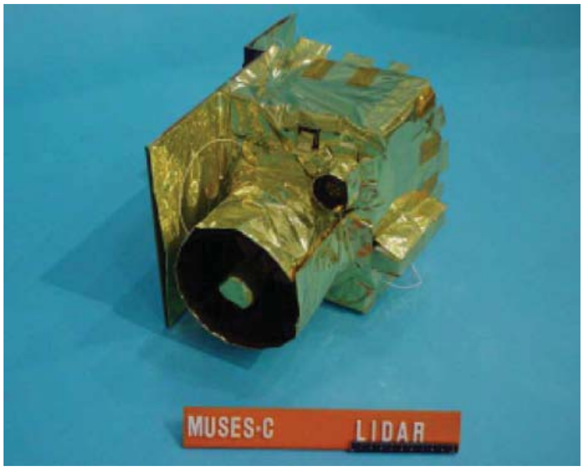

Fig. 2 LIDAR FLIGHT MODEL

3. LIDAR SYSTEM DESIGN

Fig. 2 shows the flight model of LIDAR. To fulfil the various requirements LIDAR is designed according to the following concepts.

(1) LIDAR has integrated design to minimize the structure and harness weight.
(2) Minimize the telemetry, command and functions.
(3) Simple optics, classical Cassegrain telescope with relay optics, with silicon carbide (SiC) mirror is employed.
(4) Develop the low power signal processing electronics.

The functional block diagram is shown in Fig. 3, which has typical laser radar with Nd:YAG diode pumped laser. No autonomous function except for receiver AGC (Automatic Gain Control) has installed in LIDAR. Attitude and Orbit Control Unit (AOCU) has so much autonomous capability that the function is concentrated to AOCU to reduce total system mass. LIDAR has simple telemetry and command, on, off, observation start, observation stop and Gain setting commands and one serial telemetry chunk of data including detected range, signal monitor level and other status. The telemetry data are transmitted to AOCU for every second. AOCU edits and feed the data as house keeping data and navigation sensors packet data. The house keeping data provides low time resolution data in most operation modes. The navigation sensor packet has high time resolution to monitor navigation status at the spacecraft navigation.

The single mode Q-switched diode pumped laser employs the side pumped configuration with four three-bar quasi CW laser diode and $LiNbO_3$ Pockels cell[2]. The laser used two miniature DC/DC converters, capacitor bank charger and high voltage supply for Pockels cell driver to reduce mass of laser. The range is obtained the time difference between laser transmission signal and return signal by counting the internal clock time base with frequency of 75 MHz. Since the scaler of the processing electronics counts both leading and trailing edge, the system has the range resolution of the system of 1m.

The 1mm diameter laser pulse is transmitted through the transmitting optics, i.e. beam expander with magnification of three. In the transmission optics small signal, attenuated by much order of magnitude, is picked up to generate start timing and to monitor the output power.

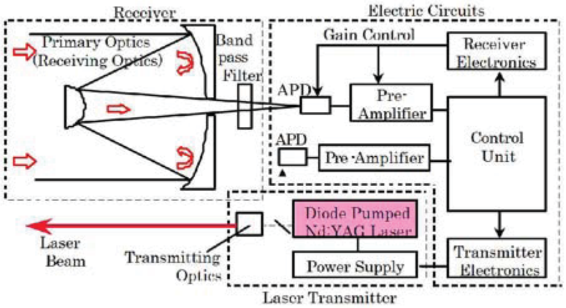

Fig. 3 Functional Block Diagram

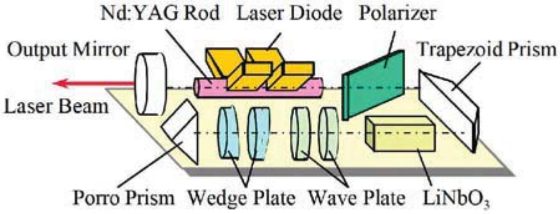

Fig. 4 Diode Pumped YAG Laser

The light weight SiC ceramics receiver primary optics is developed. The silicon carbide is most suitable material for the light weight optics by the high stiffness and thermal stability. LIDAR Cassegtrain telescope with effective diameter of 126mm employs CVD SiC with porous SiC core to reduce mass (**Fig. 5**). Next CVD SiC telescope launched February 2006, which is a 68.5cm aperture cryogenic optics of Japanese infrared astronomical satellite AKARI (formerly ASTRO-F).

Fig. 5 CVD SiC Light Weight Telescope

The receiver optics and transmitter optics with laser are mounted on simple optical bench to maintain the alignment between these optics.

Because LIDAR has very wide range coverage from 50m to 50km, the dynamic range of the receiving signal may be expected to 10^6. The output signal of the detector is proportional to the input photon number, i.e. receiving energy. Dynamic range of the processing electronics system should have 10^6(120dB). Normal processing electronics with wide frequency range compatible to the 14 ns pulse have poor signal to noise ratio and less dynamic range than requirements. We accept following processing design.

1. The gain of the processing amplifier is fixed not to change frequency response and pulse response
2. The processing chain with charge sensitive amplifier, pulse shaping amplifier[3][4] and zero-crossing timing detection is adopted to maximize the signal to noise ratio (SNR).
3. The processing gain is controlled by charge conversion gain and avalanche photo-diode (APD) multiplication gain.
4. The overlap of FOV between the receiver and the transmitter optics come loose in the near region and received signal is decreased and dynamic range is suppressed about factor 10. The offset distance and the alignment angle between them is properly designed.

The APD gain is controlled by high voltage bias. Higher value is limited by break down and lower voltage is limited by slow response time. The gain ratio is about 16. The charge gain is controlled by selecting the feedback capacitor. The selecting circuit is carefully designed not to change response time. The gain ratio is designed about 900. Processing electronics has its dynamic range larger than 500 and the receiving system has very large dynamic range about 10^7 with small response time dependence.

The detection gain can automatically controlled by AGC. The APD and charge sensitive preamplifier gain have three gain levels respectively and controlled by the average of the 100 shot receiving signal before. Eight levels of nine, 3 times 3, are carefully chosen to control the signal level between 0.6 and 3Volts in signal monitor. The gain levels are called from Gain 1 (maximum) to Gain 8 (minimum).

4. PRE-FLIGHT TEST

Since LIDAR is an instrument to measure the range from 50m to 50km, the instrument shall fully operate in wide range, from 300ns to 300 μs in time of flight with 7ns resolution and large signal dynamic range over 10^6. We verified the performance from the point of view of the range and the signal respectively and combined. The range measurement performance is verified by the direct, optical fiber and electrical delay method. Direct measurement is the method to measure directly using LIDAR and targets. This method is limited by the size of open space in the clean room and we can test 30m to 100m in satellite integration area. Optical fiber method, small fraction of the transmission laser is injected into fiber and return to the receiving optics, is limited by the loss of the fiber transmission. This method applied up to a few km. This system has so stable time delay as to apply in thermal vacuum test. The last method is that transmitted laser is detected by the photodiode and that the signal trigger the YAG laser with electrical delay to simulate return signal. In this method the electrical delay is easily controlled by the electrical time base or time delay, though the time delay between the trigger timing and actual laser oscillation is somewhat ambiguous. So the time difference between two laser signals is monitored by the interval analyser. This method is used for range calibration as well as long range verification.

The signal level verification is simply performed noise and dynamic range verification. However we need to confirm to correlate the absolute return signal level. The direct measurement data supply the reference to value. Since the flight model cannot operate outside of the clean aria, it was measured within 100m range and medium range field measurement was conducted using the prototype model. The field measurement was performed at Uchinoura Space Center, the launch site of ISAS. The 20m satellite tracking antenna is selected to be target. The prototype LIDAR was placed 3.3km from the antenna and measured the edge of main reflector and sub reflector, 10m range difference. The LIDAR operated maximum gain and provided useful information of received signal level and range resolution.

Q-switch instability problem appeared at the thermal vacuum test of the flight model. At the low temperature, laser oscillation mode had change unexpectedly and some small spurious pulse had sometimes generated. The intensive test and various designs had been tried and the $LiNbO_3$ crystal of the Pockels is identified as the cause. The temperature change of $LiNbO_3$ with mechanical holder generates unexpected extinction ratio of the Pockels cell degradation. Because it was not removed form our design, the laser required storage temperature maintenance of 35±5degrrees Celsius.

5. IN ORBIT RESULT

HAYABUSA was launched at May 9 2003. After launch the temperature has been maintained storage condition of 35 degrees Celsius to avoid instability of Q-switch. Initial checkout was performed successfully, when the spacecraft had earth flyby at May 2004. After the initial checkout LIDAR was turned off and hold storage condition again.

At the beginning of September 2005, LIDAR was turned on to encounter Itokawa and had good health.

On the approach to Itokawa, first detection signal was received form it at the distance of 48.69km. Though only eleven shot hit Itokawa further than 40km, it was no doubt that the signals were returned from Itokawa according to the range rate. Because from 50km distance Itokawa subtends only 10 mrad (0.58 degree) and there are some ambiguity in the direction from HAYABUSA to Itokawa, very few shot could hit on it.

Fig. 6 shows the history of LIDAR observation, the range and the magnitude of return signal. After two week stay at “Gate Position”, which had distance of about 20km, HAYABUSA moved to “Home Position” at about 7km distance and detailed observation had been conducted. On the basis of the detailed observation image at the “Home Position”, five close approaches have tried including rehearsal, and HAYABUSA landed on and lifted off Itokawa on the last two try at November 19 and 25[1]. In three month operation from acquisition to final touchdown, LIDAR shot about 4.1 million laser.

The data at the final phase of the touchdown of last one is shown in Fig. 7. According to the touchdown scenario, FOV of the LIDAR was off the surface of Itokawa near 12:00 and the data was missed and LIDAR acquired Itokawa again. This data clearly show that it is useful at the shorter range than 50m. The hand over from LIDAR to LRF was successfully achieved. LIDAR provided range data from 48km to 30m to navigation system in tree months. Fig. 8 shows the correlation between the range and return signal. The data include five approaching data with high time resolution data as well as initial acquisition, the gate position, home position observation with low time resolution. The signal at longer range than 300m is proportional to $(range)^{-2}$, and controlled by stepwise AGC. In the five approaches, HAYABUSA travelled the region near 3km six times and all data show the good coincidence in a month. In the long range region also show the good correlation and consistent to the near range. The data show that the condition of LIDAR, for example output power, receiver responsivity and so on, did not change in the three months rendezvous.

The signal seems to be change ±10% at the constant range. The variations are correlated to temperature variation cycle due to the heater control. The heater is attached on the base structure which support the optical bench, the optical bench may slightly deformed to change alignment between telescopes.

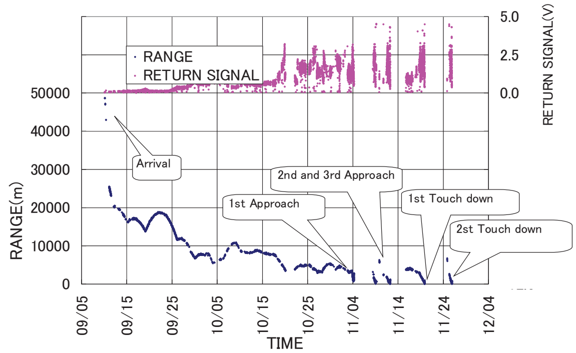

Fig. 6 LIDAR observation History of Itokawa

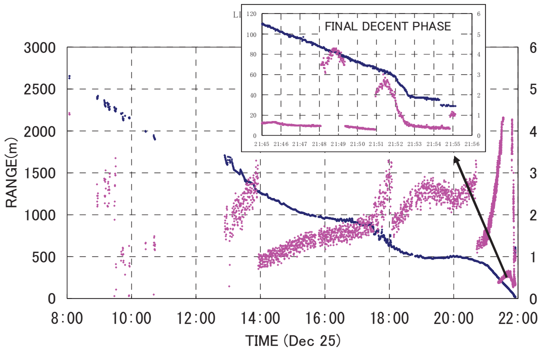

Fig. 7 LIDAR Data at Touchdown Dec. 25

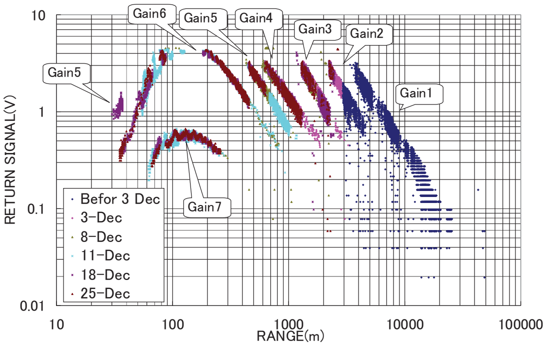

Fig. 8 The Relation between Range and Return Signal

6. CONCLUSION

LIDAR on board HAYABUSA has very simple and light weight design and suitable for the deep space applications. The wide range useful distance of 50m to 50km is especially applicable to the short range rendezvous and landing in the interplanetary exploration. LIDAR has proved its capabilities and contributed to touchdown and scientific measurements of Itokawa.

LIDAR had shot about 4.1 million laser pulses in three month and no significant change or degradation have been observed.

HAYABUSA suffered from serious accident to loose its chemical propulsion capability after 2ndtouchdown. Many people have work to rescue HAYABUSA to return to the earth and we hope the success of the efforts and we acquire the sample of Itokawa.

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8. REFERENCES

1. Takashi Kominato et al. Optical Hybrid Navigation in HAYABUSA-Approach, Station Keeping & Hovering, Proceeding of 2006 AAS/AIAA Space Flight Mechanics Meeting, AAS-06-209. January 2006,
2. Michio Nakayama, Spaceborn Diode-Pumped Nd :YAG Laser for Asteroid Sample return Misson, TOSHIBA Review, Vol. 56 No.6, 66-69, 2001.
3. C.H. Nowlin, IEEE Trans. Nucl. Sci. NS-17(1), 226-241 (1970)
4. C.H. Nowlin, IEEE Trans. Nucl. Sci. NS-18(6), 456 (1971)