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Hayabusa, Summary of Guidance, Navigation and Control Achievement in its Proximity Phase

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Hayabusa performed five descents last November, among which two touching-down flights were included. Actually Hayabusa made three touching-downs and one long landing on the surface of Itokawa during those two flights. This paper summarizes how series of descents were planned and operated. The contents focus their attention on the correction maneuvers planning as well as what kind of terminals with what kind of software tools were actually built and used. The project team had distilled and accumulated their experiences through the rehearsal flights and accomplished the this difficult mission. This paper presents the entire story about it.

I. INTRODUCTION

The Hayabusa spacecraft launched in May of 2003 arrived at the target asteroid Itokawa in September 12th of 2005, having been propelled via its proprietary ion engines and through the Earth gravity assist in May of 2004. After the arrival, the spacecraft jockeyed its position from the Gate Position (around 20 km from the asteroid) to the Home Position (around 7 km from the asteroid) to perform the in-situ scientific observation in September and October of 2005. This scientific observation was highly successfully done and the results will be presented in LPSC meeting this March and also in the COSPAR meeting this July. This paper provides neither those remote sensing phase operation nor the scientific results, but the guidance and navigation operation in the descents and touch-downs and landing for sample collection of the Itokawa. Those who are interested in shall refer to the past papers on the guidance and navigation and the papers on the science results that appear in near future.

The major purpose of the paper is in how accurately the spacecraft was navigated and guided at the distance of 2 AU from the Earth. The Itokawa surface exposed was completely different from any surface condition of the asteroids that ever have been glimpsed. The surface is full of big boulders and there is little space for the spacecraft to touch down and to land. Even with the very small speed of 1 centimeter, the dispersion during an hour exceeds the dispersion specification of 30 meters that is almost the similar size of the candidate area for touching down.

The Hayabusa project team devised and developed its new and unique navigation way while the actual operation was conducted. This paper summarizes the contents of the operation and the related papers at this meeting will describe the detailed strategies.

II. PRACTICE DESCENT (REHEARSAL-1) ON NOVEMBER 4TH, 2005

For the first rehearsal descent, Hayabusa commenced its descent at 19:17 GMT on November 3rd at the altitude of about 3.5 km. It took an aim at calibrating its proximity laser range finders, the visibility calibration and the image processing of a target marker as well as at deploying a hopping robot MINERVA. Down to about 700 meters in attitude, the onboard navigation computer detected an anomalous information (LIDAR reflection was lost), and the abort command was issued and sent at 03:30 GMT on November 4th. Despite the interruption, the project team acquired a very important information through this practice descent flight, and that this practice does make the strategy stiffer. This means the Laser range Finder (LRF) calibration and Nav&Guid experience.

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III. NAVIGATION AND GUIDANCE TEST ON NOVEMBER 9TH, 2005

About the first rehearsal flight, through the investigation, owing to a lot of spots identified on the successive image processing caused the onboard navigator at a loss what the right descent path should be. And this problem was found corrected by appropriate parameters set to the processor.

The spacecraft lost two reaction wheels aboard and it was found at this test that the persistent thrusting for attitude control gave fluctuated disturbance force and the perturbation that amounted to a significant level for the precise guidance to the landing site. A new support tool on the ground was concluded required. In addition, in view of the high resolution images taken aboard during the first rehearsal presented that the second landing site candidate 'Woomera Desert' area may not be suitable for the sampling site any more, since the area is covered with much more boulders than anticipated. At the Navigation & Guidance Test Descent, two descents were performed. (left), and LRF measurements were correctly obtained. (right)

This test descent on November 9th aimed at verifying the items above and if those were appropriately fixed, verifying both its proximity laser range finder (LRF) and the target marker tracking function with illumination via flash lamps aboard. Hayabusa lowered the altitude twice down to 70 meters and 500 meters respectively.

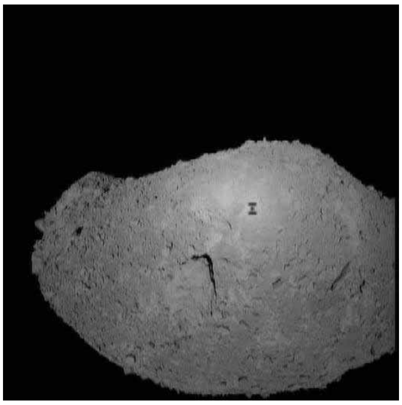

Fig. 1 Close-up Image taken on Nov. 9th.
Opposition and Hayabusa Shadow. (up)

IV. 2ND REHEARSAL DESCENT ON NOVEMBER 12TH, 2005

As for the 2nd Rehearsal descent, on November 12th, at around 03:00 JST (GMT+9hours), Hayabusa started the descent at the altitude of 1.4 km. This aimed at verifying the Nav&Guid skills and deploying the MINERVA lander on the Itokawa surface.

Descent operation took one hour more and the project decided to shift the closest approach to occur during the DSN pass switched from the JAXA's UDSC antenna. The lowest altitude reached was about 55 meters. The MINERVA was released at the altitude of about 200 meters. However, it failed to be placed on the surface with a little ascent velocity of about 15 cm/second, which slightly exceeded the escape velocity. The verification of LRF sensors was correctly performed successful.

At the second closest approach, Hayabusa separated a target marker to make sure if the separation, detection, flash lamp function and the extraction of navigation information all functioned properly. The test was successful.

V. FIRST TOUCH-DOWN ATTEMPT FOR SAMPLING ON NOVEMBER 20TH

As a fourth descent, the Hayabusa performed the first touching-down attempt for sampling on November 20th (JST). Hayabusa started descent at the distance of about 1 kilometer from Itokawa, at 21:00 JST (12:00 UTC) on November 19th. Approaching, descending and the guidance and navigation were all performed in order as planned. And having been directed from the ground at 04:33 JST on November 20th (19:33 UTC on November 19th) for the final vertical descent, Hayabusa succeeded in making it descend precisely close to the intended area. Current analysis concluded the guidance accuracy was within 30 meters in terms of the hovering point.

The landmark tracking / position estimation technique performed and the ground support have less accuracy while Hayabusa is in a distance. However, as this plot shows, the accuracy was well assured when the distance becomes close within 1 kilometer. What this plot shows is how precisely the approaching guidance & navigation were accomplished in the approach phase. When the final vertical descent commenced, the speed was about 12 cm/second. Hayabusa flight computer commanded the target marker to be released at the altitude of 54 meters at 05:28 JST (20:28 UTC), followed by the spacecraft deceleration of 9 cm/second at 40m at 05:30 JST (20:30 UTC) forcing the marker depart from the spacecraft. It was confirmed that the marker was actually positioned and placed properly through both the camera images and the telemetry information, which indicate the descent speed of the spacecraft. (See Fig. 2) Latest estimation says the marker landed in South-West (Upper-Right in the image) area of the MUSES-Sea. Hayabusa then switched the Laser altimeter to Laser Range Finder (LRF) mode at the altitude of about 35 meters and started hovering at the altitude of about 25 meters by canceling the residual descent velocity.

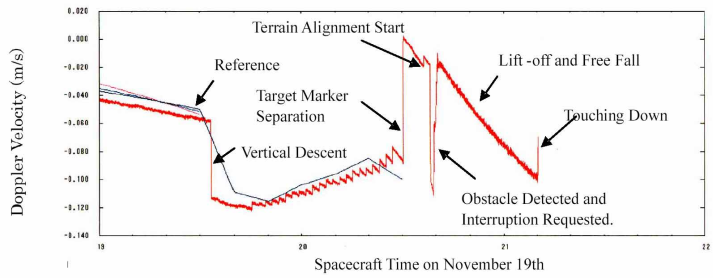

Fig. 2 Doppler Velocity History :Descent Velocity

The Doppler information obtained as in Fig. 2 shows every delta-V applied autonomously and well agreed with the plan commanded.

The Laser Altimeter (LIDAR) measurement obtained together with the integrated Doppler measurement history associated with this first touching-down flight was obtained. Note once the terrain alignment started, the LIDAR information transmission terminated as scheduled. And as the integrated Doppler information said, the spacecraft position moved even inside the equatorial surface distance. This shows the spacecraft moved to the polar gained latitude toward the polar direction. As the subsequent paper describes, the Hayabusa spacecraft was estimated to have moved to south, where the spacecraft started landing for half an hour.

The spacecraft succeeded in deploying the target marker with the 880,000 signatures onboard at the area specified. The target marker was photographed and the images are shown in Fig. 3 below. This does show how accurately the guidance and navigation were accomplished as planned.

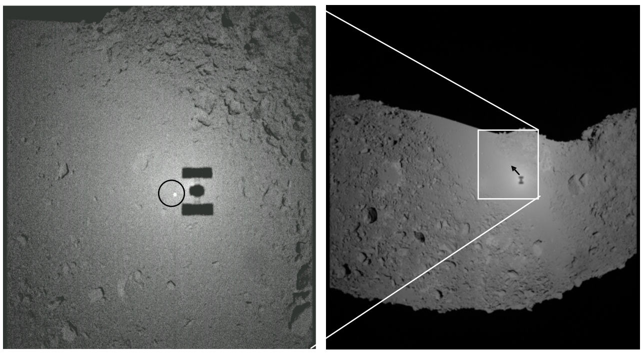

Fig. 3 Target Marker (at 05:33 JST at 32m)

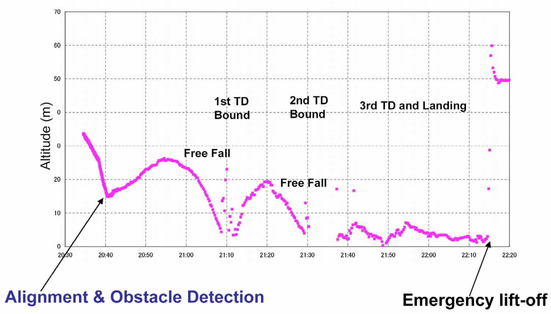

Fig. 4 LRF data at Touch-Downs and Landing (D-beam, m)

As scheduled, the spacecraft made a free fall until it reached the 17 meters altitude at 05:40 JST (20:40 UTC), and the Terrain Alignment Control mode commenced, when the telemetry transmission was terminated and it was taken over by the beacon-only radio configuration via a wide angle Low Gain Antenna (LGA). Since then, neither instruments information nor house keeping information were obtained in real time on the ground.

However, according to the data reproduced so far, Hayabusa-carried Fan Beam Sensor (FBS), an obstacle detector, seemed to have received the laser reflection signal from something around and an emergency ascent command was requested issued from the Data Handling Unit (DHU), the primary flight computer aboard. But at that instance, the attitude deviation was large and did not meet the emergency ascent burn requirement and the ascent was cancelled by the DHU. As a result, the spacecraft decided to continue the descent as long as no interruption was directed from the ground. As a matter of fact, nothing was commanded from the ground, while the touching-down trigger including take-off sequence was cancelled beyond it.

The height became almost zero at 06:10 JST (21:10 UTC) as shown in Fig. 4. And then another bouncing was observed later at 06:30 JST (21:30 UTC) also as in Fig. 4. This resulted in very soft landing on the surface and the spacecraft continued to sit on the surface for half an hour, before the emergency take-off command was sent to the spacecraft at 07:14 JST (22:14 UTC). During the period from 06:40 JST (21:40 UTC) to 07:10 JST (22:10), the same engines had been commanded fired at almost 100% duty, with the LRF read-out of almost zero.

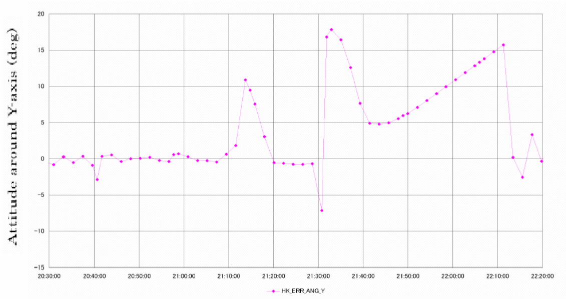

Fig. 5 Attitude Error Angle (Y-axis, degree)

Fig. 5 indicates the error angle (Y) to the target orientation that was specified at the terrain alignment. As the total magnitude of the error angle including X and Z direction equals to the Itokawa's rotation angular velocity and this shows the angular motion of both Hayabusa and Itokawa was identical to each other. Besides the thruster firing accumulation monotonously increases with no corresponding angular motion. This indicates the attitude was fixed regardless of the thruster firings and the Hayabusa was caught in the Itokawa. This in turn indicates the Hayabusa kept sitting on the surface until commanded to lift-off it.

The data reproduced said that Hayabusa made slow speed bouncing (touching-downs) twice, followed by the complete landing & staying still for 30 minutes long. This was confirmed by the LRF read-out and attitude history. The touching-down speed at both bouncing, was about 10 cm/second. As of today, no serious damage was found and reported as for the instruments.

Hayabusa continued this landing status stably before the emergency take-off was directed from the ground at 06:58 JST (21:58 UTC). No projectile was shot, since the FBS detection disabled the triggering sequence as stated above. Landing attitude seems that sitting on the sampler horn sustained by two corners of the spacecraft bottom plate or by the tip-ends of the solar array panels.

Hayabusa now became the first spacecraft that has taken off from the extra-terrestrial body's surface. The spacecraft after lift-off fell into the Safe-Hold Mode, since the ground based operation directed extraordinary attitude maneuvers during a short period. It took a few hours for the spacecraft to resume the communication by directing the RF configuration resumed. It was found that the spacecraft functioned very normally.

VI. THE 2ND TOUCHING-DOWN ATTEMPT

With the practices and first touching-down plus landing experience, the Hayabusa attempted to have another touching-down for sampling on November 25th (UTC).

Hayabusa started the descent at 22:00 JST on November 25th. The descent path taken was almost same as that at the 1st touching-down attempt, toward the west part of the MUSES-Sea. Approach information with altitude and descent rate are shown below. As already one target marker was in the MUSES-Sea, to avoid the confusion, the project decided not to release a new marker, this time. And also the obstacle detection sensor was set not to be referred to, since it reported inappropriate or too-sensitive signal. The traps that the sequence of events should not pass are reduced this time. Once the terrain alignment sequence starts, the SOE was set so that the lift off must be only if the sampler horn deformation is detected.

The touching-down operation was planned originally during the DSN pass preceded by the UDSC (JAXA) pass. However, based on the experience by that time, the project decided to switch antenna relatively ,early so that the sophisticated operation can be performed only during the Goldstone pass, which is immediately passed to the UDSC pass after the touching-down.

VII. Approach and Descent Path Planning (2nd Flight)

In Fig. 6, Approach and Descent Trajectory are shown The target trajectory is successively updated during the descent and not vigorously identical to the planned path. The right figure shows the trajectory in Itokawa-fixed coordinate. Both show the path was built correctly and guidance was successful.

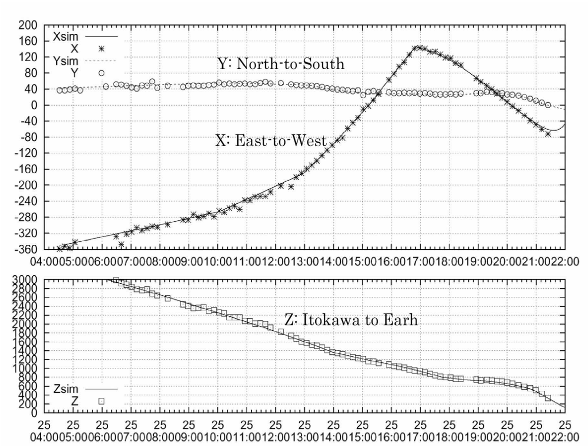

Fig. 7 Navigation (Semi-Inertial Coord)

The landmark tracking navigation was not primarily assumed for the descent before launch, since it does not seem to fit for the real-time operation. The primary guidance was assumed by the onboard software that detects the center of illumination that is assumed to coincide with the center of mass.

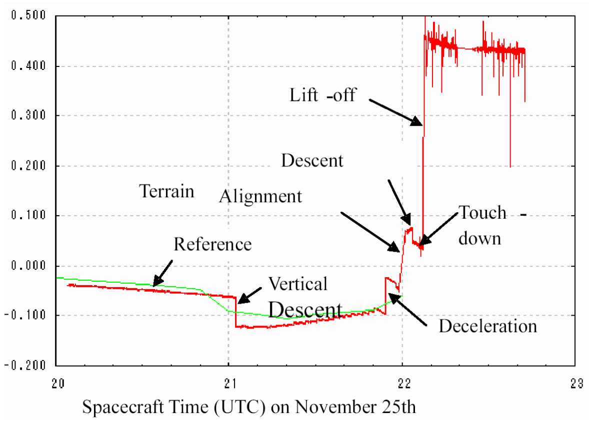

Fig. 8 Descent Rate in 2nd Touch-down

Fundamentally this assumption is true, however, even a small amount of inconsistency was found to cause the dispersion over the expected dispersion area. During the flight data evaluation process, very efficient and quick landmark tracking method was exploited on the ground. (Fig. 7) And with the trajectory prediction was found useful with the attitude control derived acceleration compensated and also with the path predicted in feed-forward manner. Both, in other words, constitutes a real time Extended Kalman Filter plus Feed-Forward control scheme. The flight results obtained showed the guidance accuracy was almost within 5 mm/second before the final automated final vertical descent started. This satisfied the guidance and navigation requirements.

Fig. 8 shows the descent speed history measured at the DSN station. Fig. 9 shows the altitude history integrating Doppler measurement. It is observed that the hovering took place at the low altitude and started ascent.

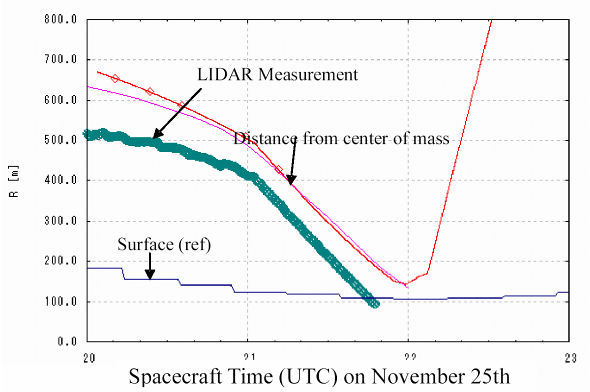

Fig. 9 Distance/Altitude in 2nd Touch-down

IIX. Hovering and Attitude behavior at Touch-down

It is observed that the hovering, a part of terrain alignment was performed at the altitude of 7 meters in Fig. 10. The attitude fluctuation was stable within well small width until the touch-down at 0707 JST (2207 UTC), which shows no contact of the spacecraft with the surface took place before it.

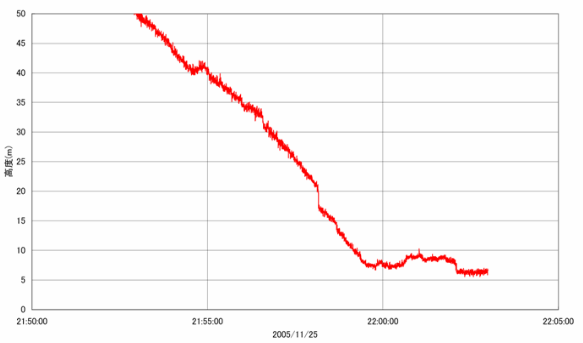

Fig. 10 LRF history (Unit: m) in 2nd Touch-down

Later, the data will show how the Reaction Control System (RCS) jets were fired at the touching-down. Everything was smoothly done and the project team was confident in having a safe touch-down to the surface. The lift-off occurred very normally and ascent direction was due the Sun direction, which was expected assuming the touch-down area should be perpendicular to the Sun direction. The spacecraft lifted off the surface with 0.5 meters per second.

The operation station was switched from the Goldstone DSN site to the JAXA's UDSC site as scheduled. No data gap occurred and the operation was almost complete, until the unexpected fuel leak took place after the three axis stabilization was reestablished. The details will be described later in the paper.

Hayabusa is now the first spacecraft that could land for sampling at the extra-terrestrial objects. In view of the robotic exploration, Hayabusa could demonstrate its unique and new methodology in the planetary exploration. At the same time, this success made Japan to be at the front position in deep space exploration. The project thinks this Hayabusa success does contribute to the not only domestic but also the world-wide space activities.

IX. STATUS OF HAYABUSA AFTER 2ND TOUCING-DOWN FOR SAMPLING

Hayabusa finished its second touching-down for sample collection and took off from the asteroid surface on November 26th. And it successfully decelerated its ascent speed four hours later.

When the stop maneuver ended, thruster-2 temperature went down very quickly and it showed the leak occurred there. Shutting-off commands were kept sent for both A and B systems to stop the leak and those worked before the LOS from the UDSC.

On December 8th, Usuda station observed a sudden shift of the range-rate measurement at 04:13 UTC with the corresponding gradual decrease of signal intensity AGC (Automated Gain Controller) read. But the control capability of it was not enough strong for the spacecraft to withstand the disturbance on December 8th. Estimation says the spacecraft may be in a large coning motion and that is why the spacecraft has not responded to the commands sent from the ground station.

Hayabusa was recaptured on January 23rd of 2006, when the attitude was significantly drifted 70 deg offset. Since then the attitude control with Xe gas thrusters were performed to resume the operation. Since March, the spacecraft has been operated normally.

And it is concluded that the commencement of the return cruise during December is found difficult. The project has determined that the return cruise should start from 2007 so that the spacecraft can return to the Earth in June of 2010, three years later than the original plan, as long as no immediate resumption takes place very soon. New trajectory (red line) leaving Itokawa vicinity in spring of 2007, returning to Earth in June of 2010 is shown here in Fig. 11. The Xenon gas consumption meets the current amount that remains. There will be some strategy needed and left for the operational discussion on how the attitude is protected against unexpected disturbance

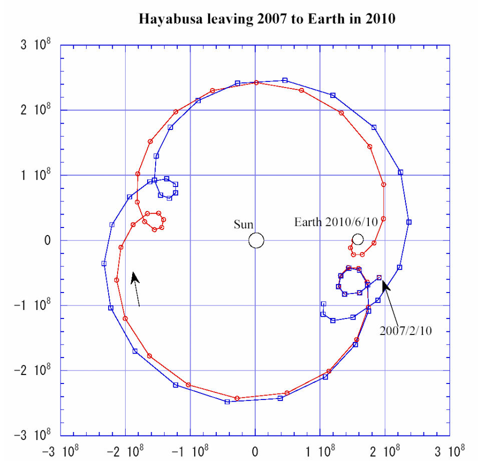

Fig. 11 Return Trajectory Postponed to 2010

X. CONCLUDING REMARKS

The summary of Descents, Touching-downs and Landing of the Hayabusa to the Itokawa surface was presented. Hayabusa is the first spacecraft that landed on the surface and lifted off again. The major output in terms of the Guidance and Navigation is in the fact that the spacecraft succeeded in the pin-point landing at an extra-terrestrial object. The guidance accuracy accomplished was down to several millimeters per second and the final dispersion well satisfied the expected condition of within 30 meters.

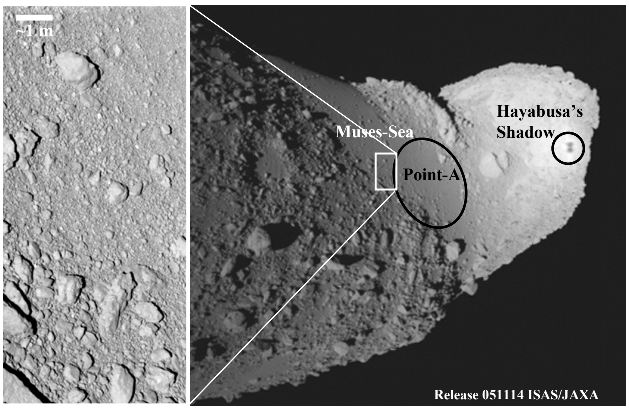

Fig. 12 World's Best Resolution Asteroid Image.

Figure 12 is an image example taken for the science purpose. A number of images were taken during the proximity period and they are presently under detailed analysis and will be reported in the papers soon.
For all fuel leak accidents, the spacecraft was fortunately restored and has been operated normally now. Every output from the Hayabusa will be highly utilized for the next mission such as 'Hayabusa-2' in near future.

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