Guidance and Navigation Scheme for Hayabusa Asteroid Exploration and Sample Return Mission

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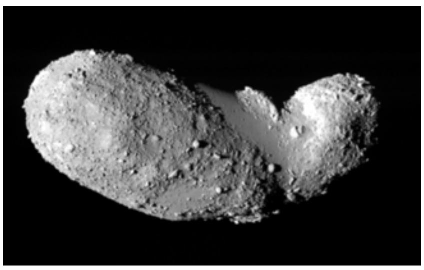
Hayabusa Mission

JAXA launched Hayabusa spacecraft, which is an engineering test spacecraft for sample and return technologies, *aiming at demonstrating key technologies*

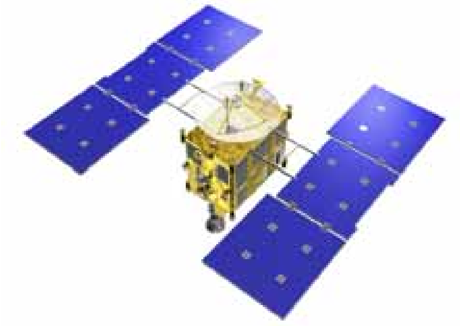
- Electric Propulsion for Interplanetary Cruise
- Autonomous Optical Navigation and Guidance
- Automated Sampling Mechanism
- Direct Reentry of Recovery Capsule

Hayabusa arrived at Itokawa on September 12th in 2005, and performed touchdown in November and will return back to Earth in 2010.

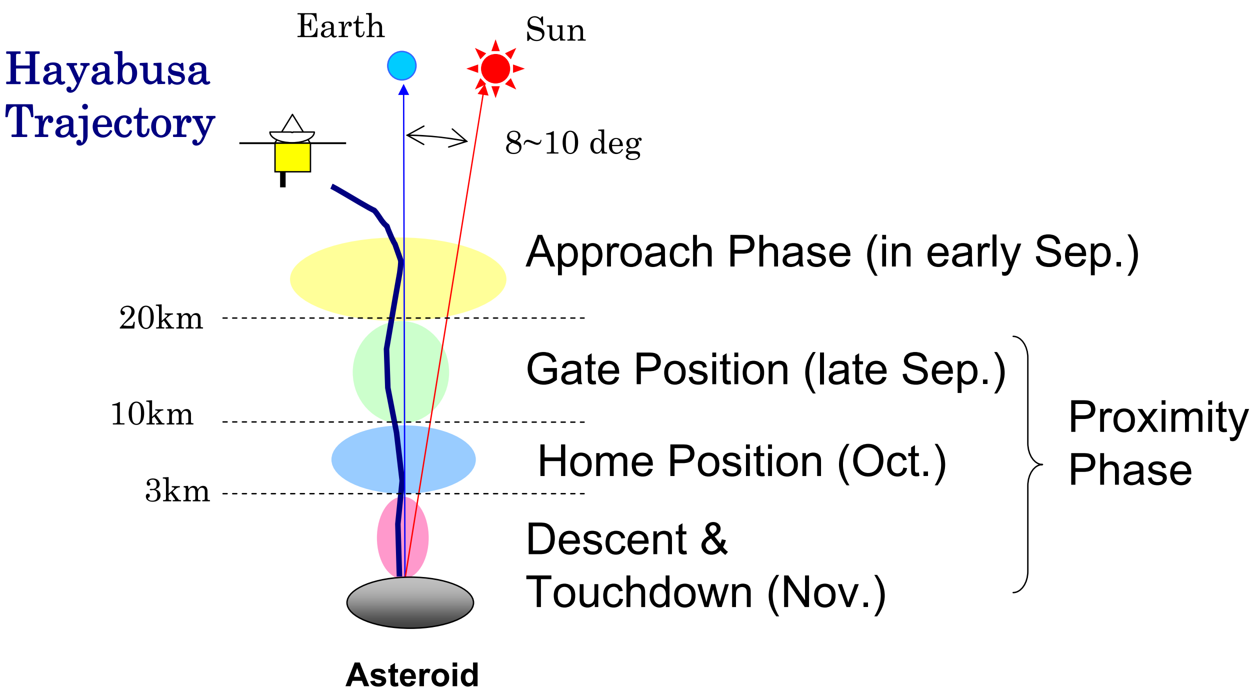


MUSES-C Spacecraft

- Launch weight : 510kg
  - Chemical Fuel : 67kg
  - Xenon propellant : 66kg
- Attitude Control : three-axis stabilize
- Communication : Xband (max:8kbps)
- Solar Cell Paddle : 2.6 kW at 1 AU
- Chemical propellant : 12 RCS (Isp:290sec)
- Electric propellant : 4 IES (Isp:3200sec)
- Payloads
  Telescope cameras, Near Infra-red Spectrometer,
  X-ray Spectrometer, Sampling Mechanism,
  Laser Altitude-meter, Reentry Capsule, Small Rover



Outline of Proximity Operation



Hayabusa Descent and Touchdown

- Ground based operation is limited due to the communication delay (32minutes) and low bit-rate (8kbps).
- Information on Sampling Point, the detailed terrain and the condition of the surface are not known in advance

Intelligent NGC technology are required for the spacecraft to descend and touchdown safely.

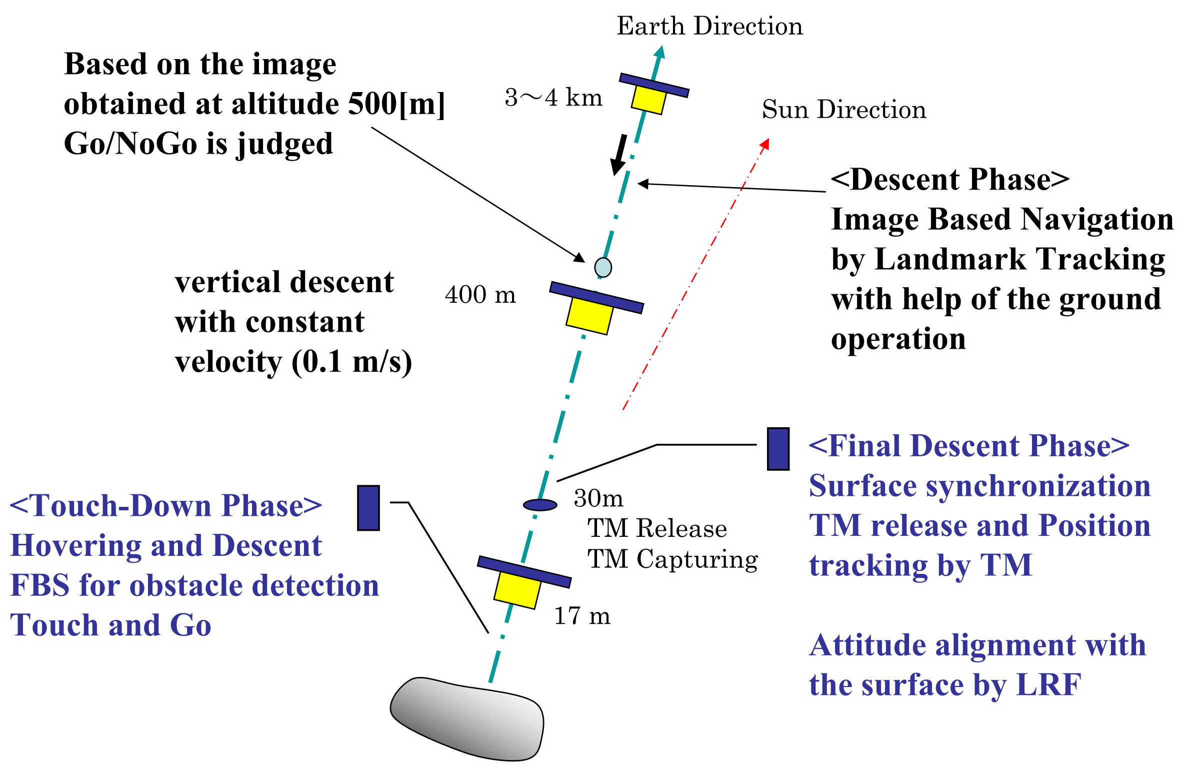
In Final Descent Phase (50 [m] to 17[m])

- Cancellation of the relative horizontal speed is essential
- Attitude alignment w.r.t. the surface is also needed

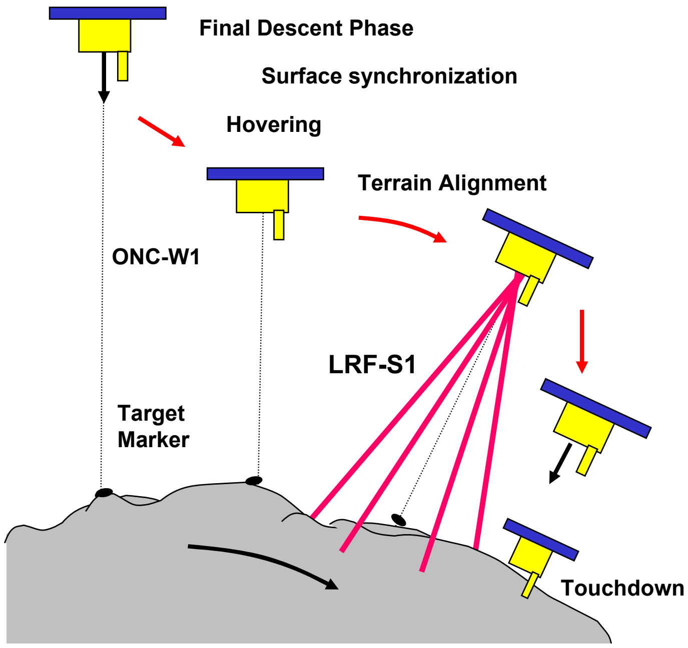
In Touch-down Phase (10 [m] to touch-down)

- Obstacle avoidance such as rocks is needed

Hayabusa Descent and Touchdown



Summary of Final Descent and Touchdown



1. Surface synchronization
2. S/C hovering
3. Terrain Alignment
4. S/C starts descent
5. S/C touch down
6. Touch-down detection
7. Projectile is ejected
8. Samples collection
9. S/C lift-off
10. S/C attitude control by off-modulation of RCS

NAV sensors

LIDAR
for altitude measurement
ONC-W1
for Target Marker tracking
LRF
for attitude and altitude
FBS
for unexpected obstacle detection

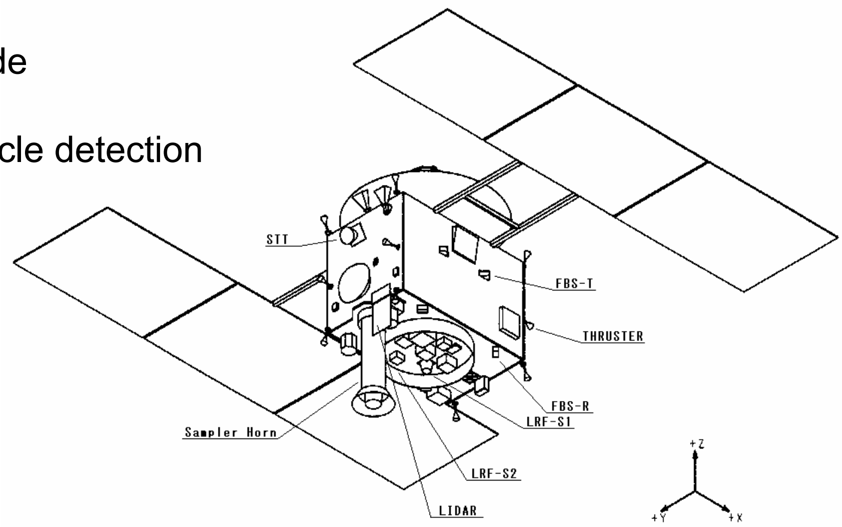
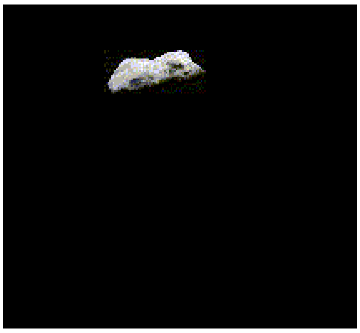


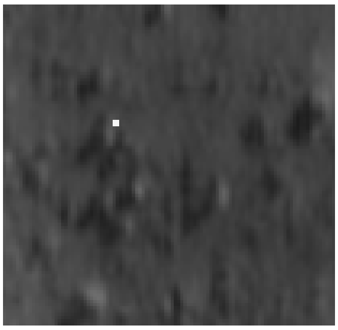
Image Based Navigation

- Tracking functions
  - Whole image Center Tracking (WCT)
  - Target Marker Tracking (TMT)
  - Fixed Window Correlation Tracking (FWC)
  - Auto Window Tracking (AWT)

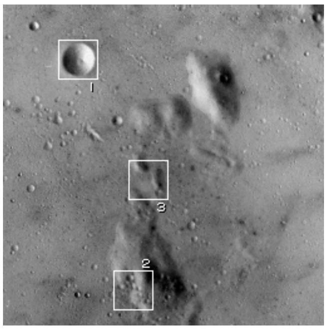
WCT



TMT



AWT



Hayabusa Descent and Touchdown

Highlight Event

•Cancellation of the relative horizontal speed by asteroid rotation is essential for successful descent and touchdown for sampling.

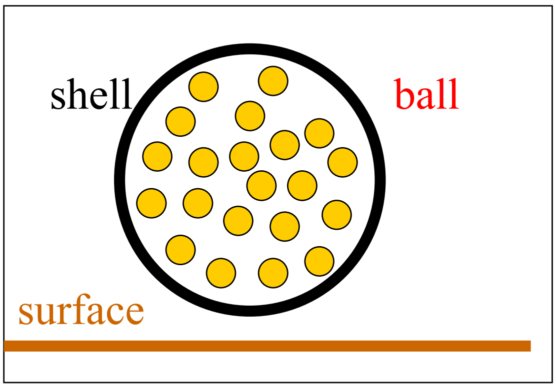
•In Hayabusa mission, visual landmark based navigation was developed.

Visual Landmark :Target Marker (TM)

- There may be no natural landmark near landing point. So as an artificial landmark, TM is released from spacecraft and is to be tracked by onboard camera.
- TM is covered with reflective sheet and camera has a flash lamp. Then camera can take flash-on and -off images to find TM even on bright asteroid surface.
- TM is required to have very low restitution coefficient to settle on the surface quickly.

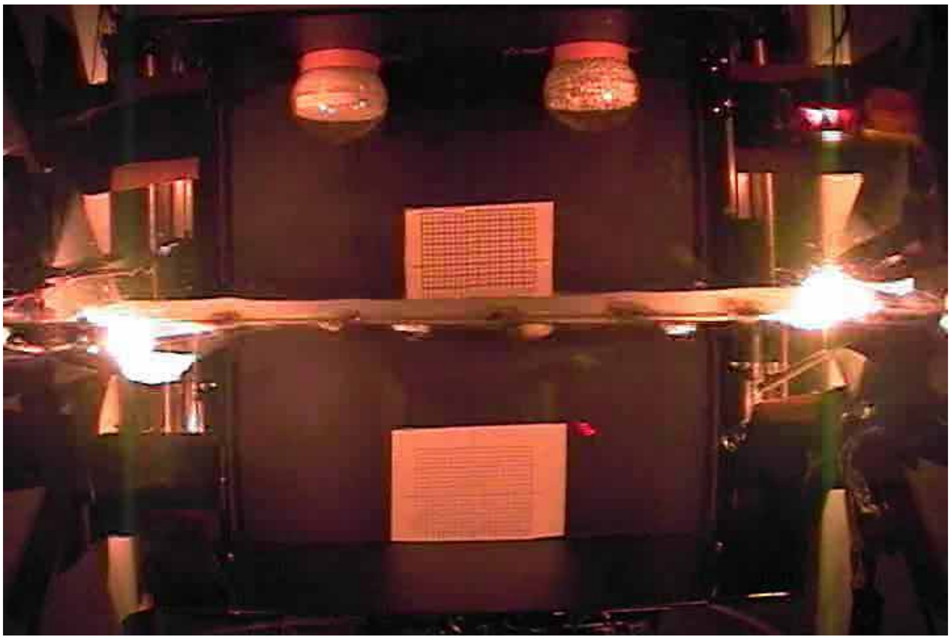
Target Marker (TM)

- To develop an object with low restitution coefficient under microgravity, Japanese traditional Otedama concept is introduced.
- Otedama is made of some amount of small beads inside a soft cover cloth.
- When Otedama collides with other object, inner beads are expected to reduce the total collision energy and also reduce restitution coefficient.
- Based on Otedama concept, a rigid shell with a lot of rigid balls is developed for visual artificial landmark.



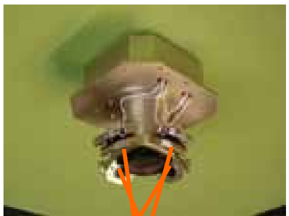
Effectiveness of Target Marker

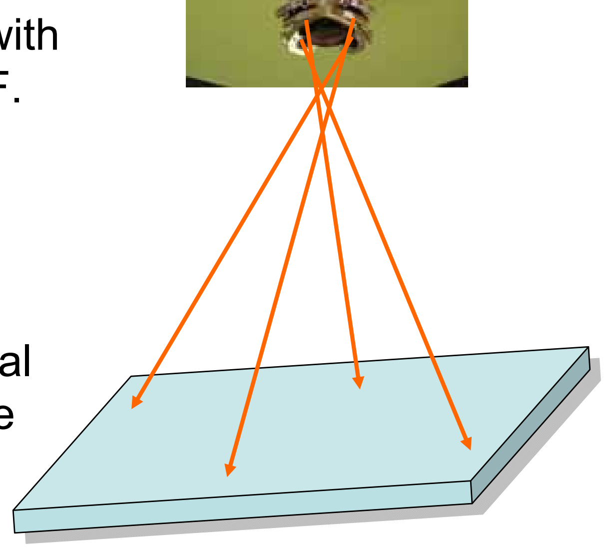
Microgravity tests were conducted by using drop tower facility



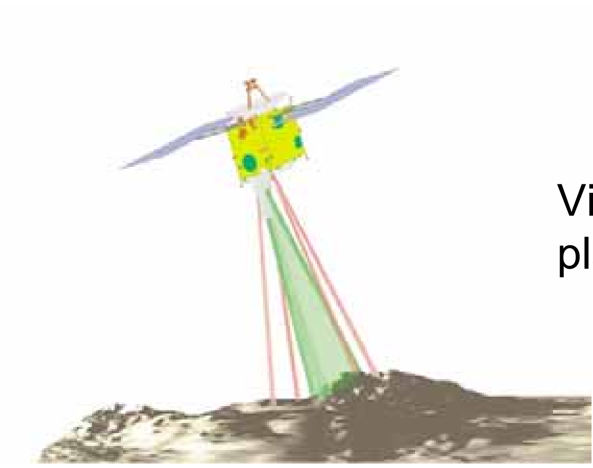
Attitude and Altitude Detection

Altitude and Attitude w.r.t. the global surface are estimated and Attitude alignment and hovering with the surface are performed by LRF.

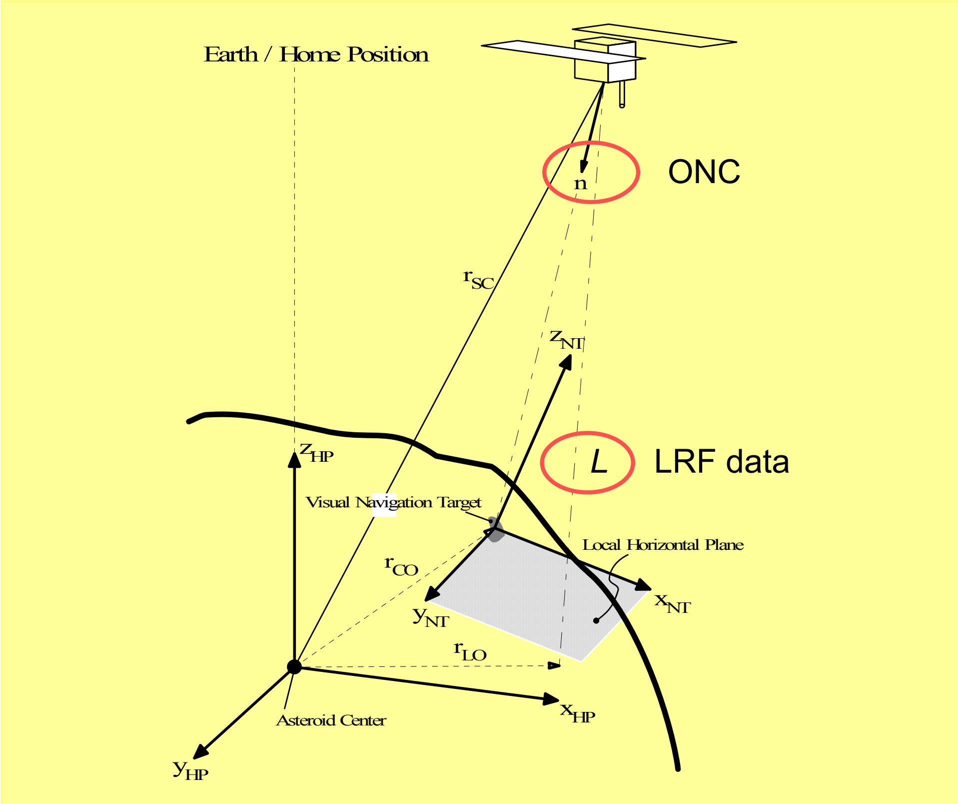




Virtual plane



Navigation Algorithm



Navigation Algorithm

Relative position and velocity can be estimated by Kalman Filter Techniques.

Observation Equation

$$\xi \equiv \begin{pmatrix} L \\ n_x / n_z \\ n_y / n_z \end{pmatrix} = G(\mathbf{x_0})\mathbf{x}$$

L : LIDAR or LRF measurement

(n_x, n_y, n_z): Line − of − sight vector

Navigation Algorithm

Dynamics and State Propagation

$$\mathbf{x_i} = \begin{pmatrix} \mathbf{I}_{3x3} & \Delta T\ \mathbf{I}_{3x3} \\ \mathbf{O}_{3x3} & \mathbf{I}_{3x3} \end{pmatrix} \mathbf{x_{i-1}} + \begin{pmatrix} (\Delta T/2)\ \mathbf{I}_{3x3} \\ \mathbf{I}_{3x3} \end{pmatrix} \left(\mathbf{dv_{i-1}} + \mathbf{dv_G}\right)$$

$$\mathbf{P_i} = \begin{pmatrix} \mathbf{I}_{3x3} & \Delta T\ \mathbf{I}_{3x3} \\ \mathbf{O}_{3x3} & \mathbf{I}_{3x3} \end{pmatrix} \mathbf{P_{i-1}} \begin{pmatrix} \mathbf{I}_{3x3} & \Delta T\ \mathbf{I}_{3x3} \\ \mathbf{O}_{3x3} & \mathbf{I}_{3x3} \end{pmatrix}^{\mathbf{T}}$$

$$+ \begin{pmatrix} (\Delta T/2)\ \mathbf{I}_{3x3} \\ \mathbf{I}_{3x3} \end{pmatrix} \begin{pmatrix} q_x & 0 & 0 \\ 0 & q_y & 0 \\ 0 & 0 & q_z \end{pmatrix} \begin{pmatrix} (\Delta T/2)\ \mathbf{I}_{3x3} \\ \mathbf{I}_{3x3} \end{pmatrix}^{\mathbf{T}}$$

Guidance Algorithm

$$\Delta v_Z = k_{VC} \cdot (v_{CC} - v_Z)$$

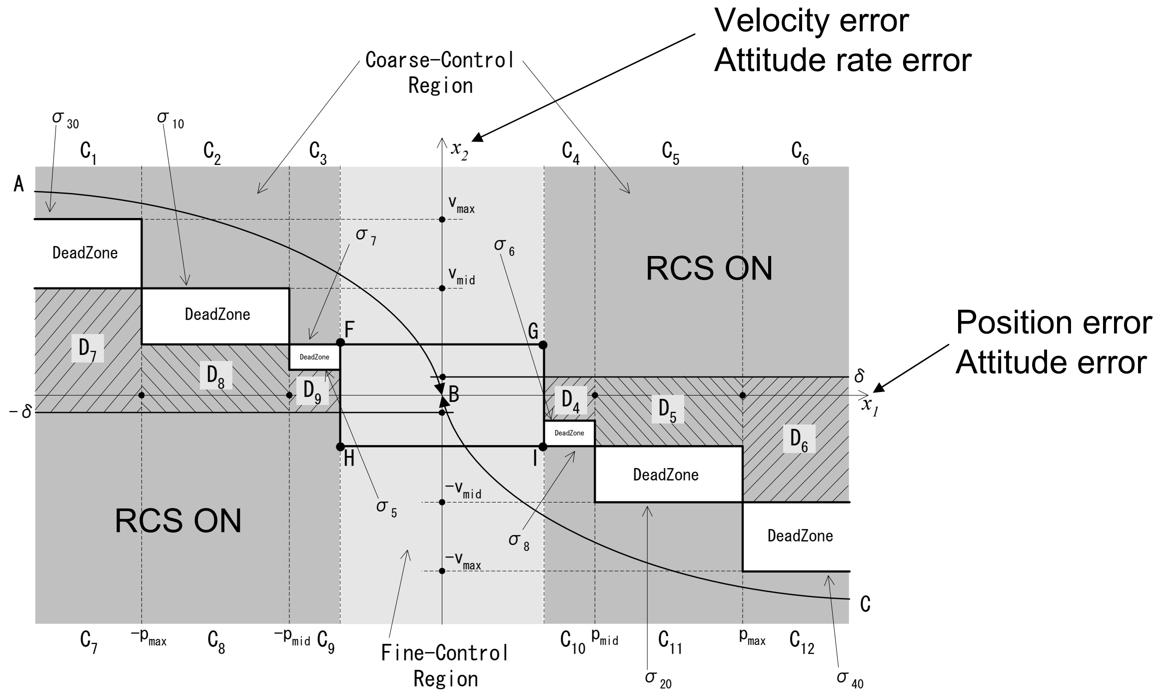
v_{CC} :Planned descending velocity

$$\Delta v_X = k_P \cdot r_X / dT_G + k_D \cdot v_X$$

$$\Delta v_Y = k_P \cdot r_Y / dT_G + k_D \cdot v_Y$$

Logic of Thruster Switching

6DOF controller for sampling guidance

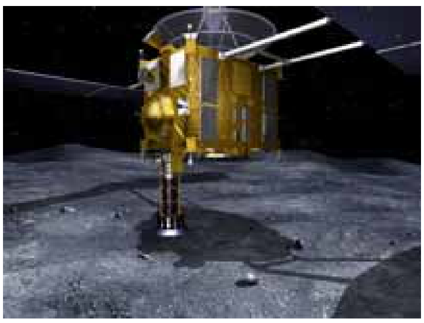


Hayabusa Touchdown for Sampling

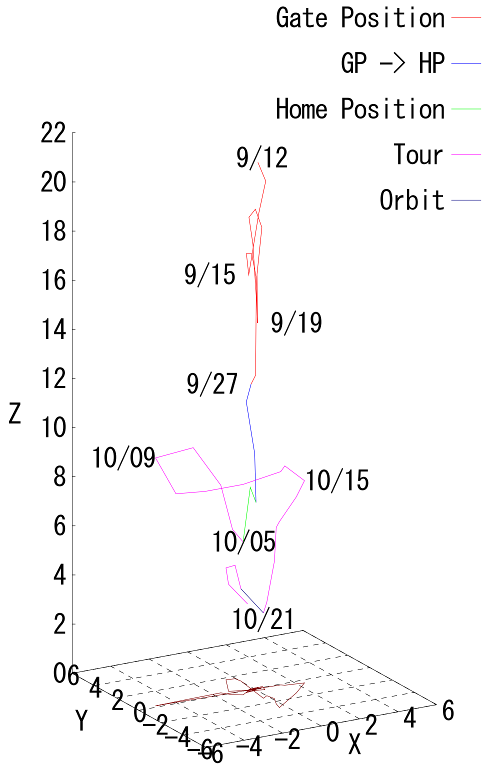
1. Asteroid is a small body and gravity field is so small. Then it is difficult for spacecraft to land and stay on the surface under microgravity. And also spacecraft cannot stay for a long time because of thermal condition.
2. Whether the asteroid surface is hard like rocks, or soft, sandy is not known in advance.
3. Sampling method is required to have robustness to the terrain and the condition of the surface.

So-called "Touch and Go Way" is introduced as a sampling method

- spacecraft shoots a small bullet to the surface just after touch-down
- collects ejected fragments with sampler
- lifts off before one of solar cell panels might hit the surface.



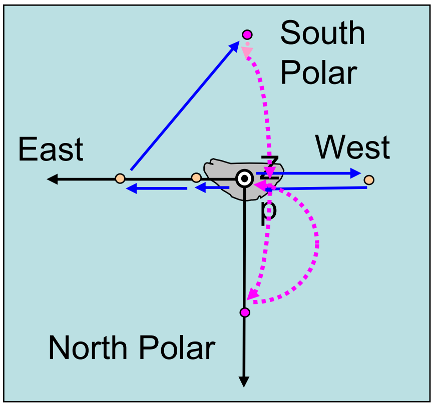
Flight Results for Hayabusa Mission



Hayabusa arrived at the target asteroid Itokawa on September 12th in 2005.

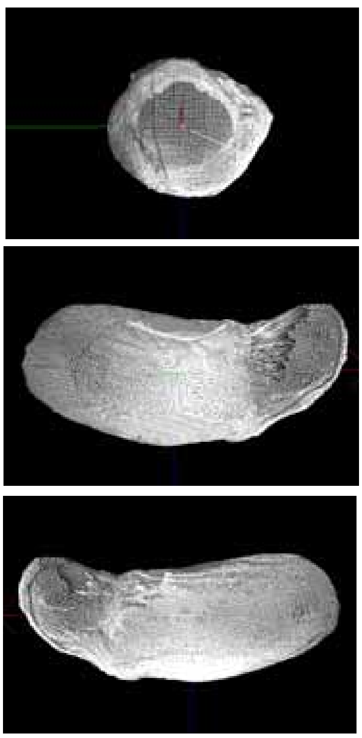
From 12th to 27th September,
Global observation at Gate Position

From 30th, detailed observation at Home Position



Observation Tour was performed from various position and phase angles including 1/8 orbital trajectory.

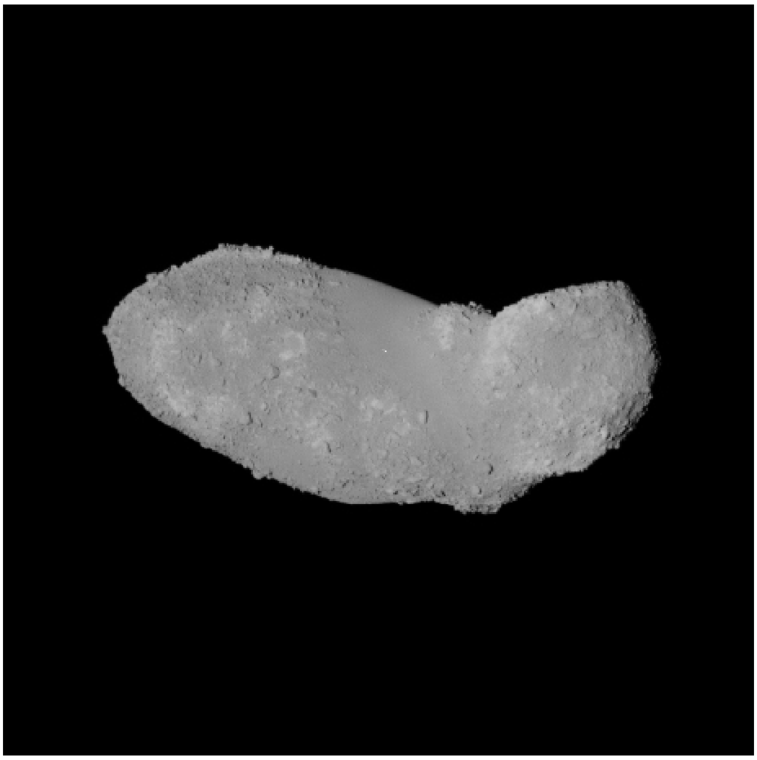
3D Shape Reconstruction



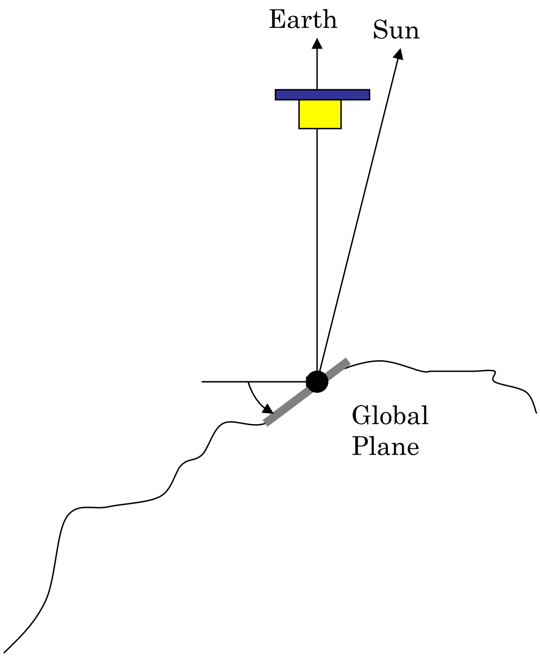
Three dimensional shape model was constructed and the motion of Itokawa was estimated by SLAM (Simultaneous Localization and Mapping) technology,
based on LIDAR data, moving stereo vision, shape from shading, etc.

Size(m):	X=535, Y=294, Z=209
Spin Rate:	12.1324 hours
Spin Axis:	[128.5, -89.66] ([90.53, -66.30]
Mass:	3.510 x 1010 ±0.105 x 1010 kg
Density:	1.90±0.13 g/cm3

Target Asteroid Itokawa



Constraint for Touchdown Site Selection

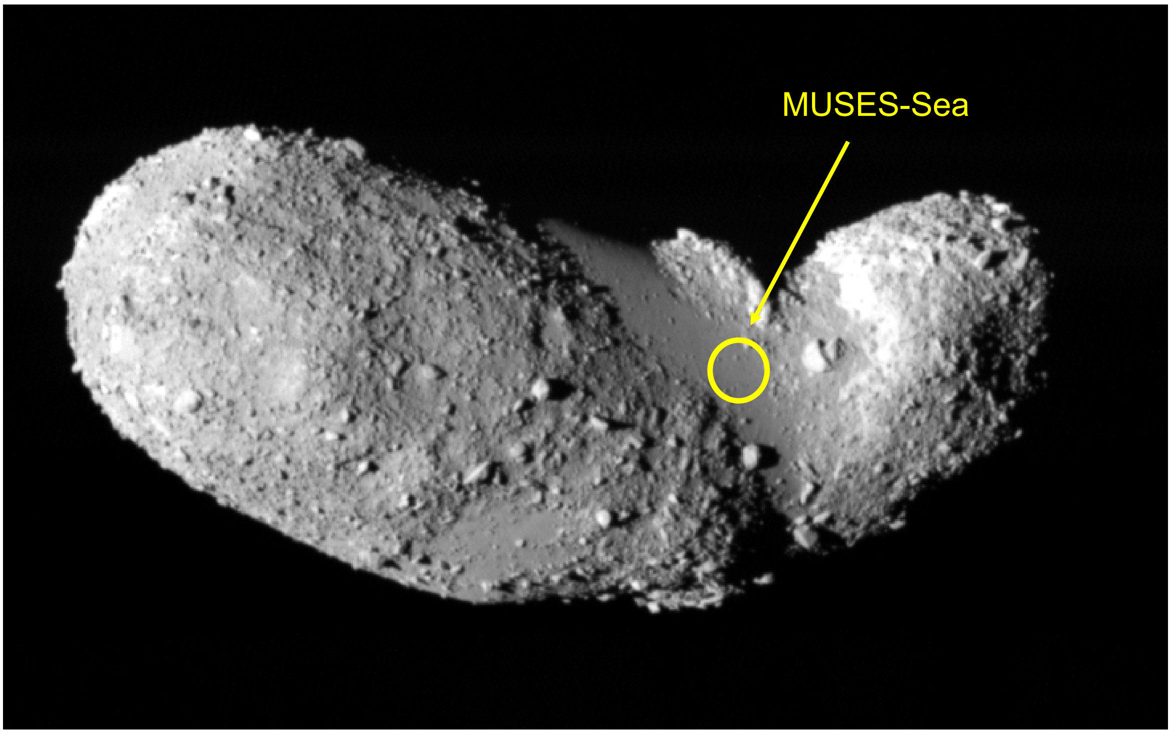


Touchdown area:
- flat large area (diameter 60 m)

Roughness
- the height of obstacles within the touchdown area to avoid obstacle collision with solar panels
- < 0.5m

Inclination
- the inclination with respect to the earth or the sun because of power supply
- < 30 deg

Touchdown Target Site



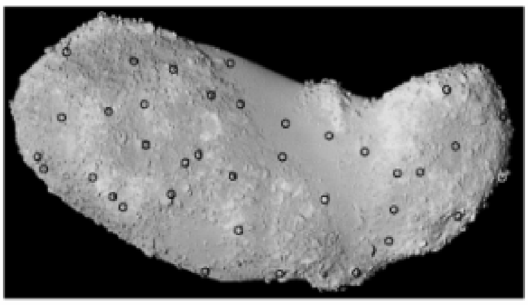
Landmark Based Navigation

For pin-point landing, landmark based navigation was introduced with help of ground station.

●**GCP-NAV** (Ground Control Point - NAVigation)

Feature points ("landmarks") in the image of "Itokawa" were extracted and matched with "3D feature points model" manually on the ground.

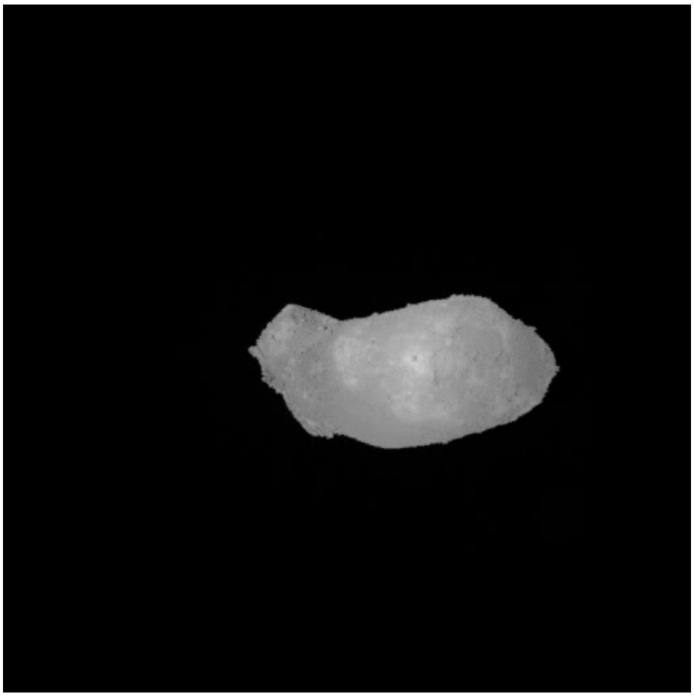
Descent trajectory was updated by the command



GCP

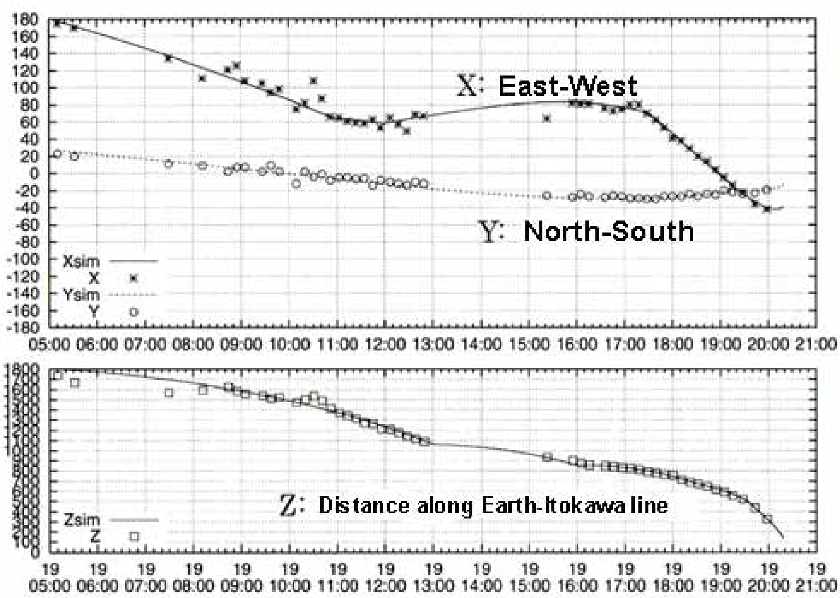
Flight Results (TD #1)

Descent Images at TD#1 (19th, November 2005)



Results for TouchDown #1

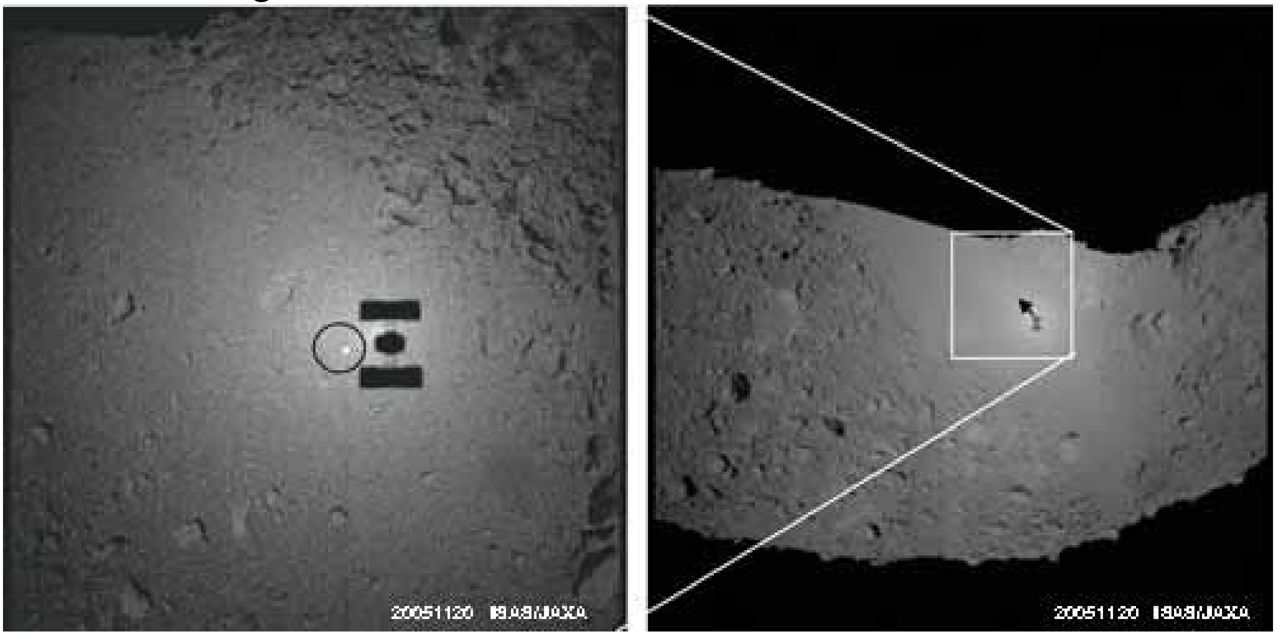
Final Descent Profile at TD#1 (19th, November 2005)



This shows the spacecraft position estimated based on the terrain landmarks along with the trajectory synthesized adaptively.
This proves the guidance and navigation were correctly and accurately conducted.

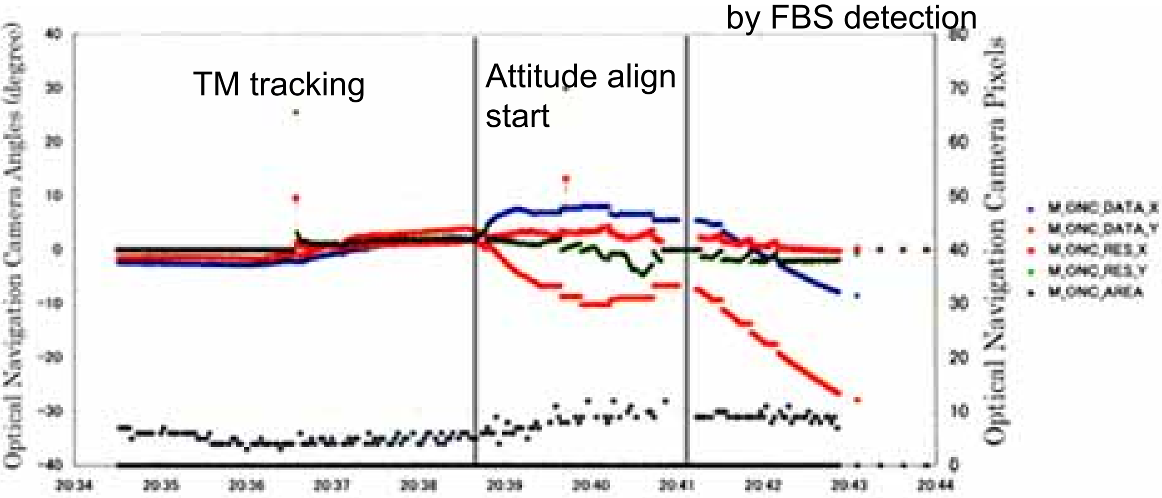
TouchDown #1

camera image at altitude 30m



Results for TouchDown #1

Target Marker Tracking Behavior

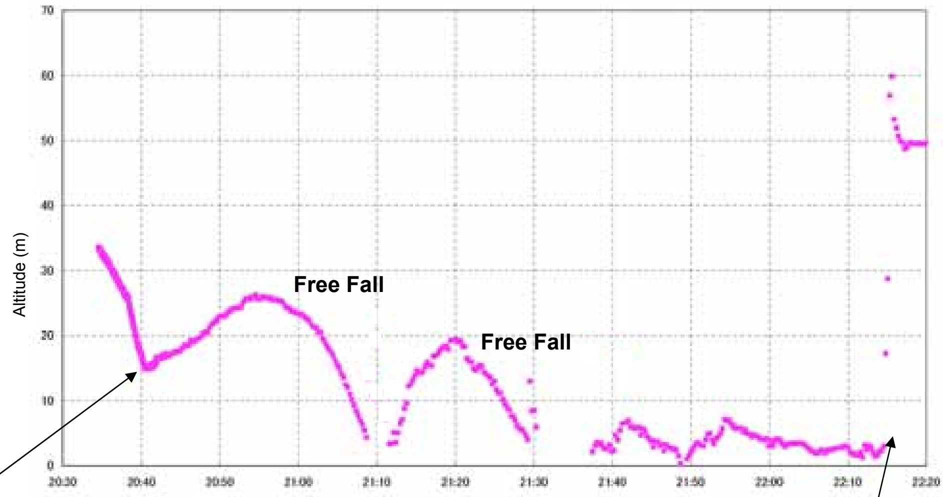


The target marker after the separation started tracked by the Hayabusa-carried onboard image processor and the guidance computer.
TM had been kept tracked through the transition to hovering mode.
(RES_X and RES_Y show the residual tracking errors)

Hayabusa could track the TM and synchronize with the surface.

Results for TouchDown #1

Estimated Altitude at TD#1 (19th, November 2005)



1st TD Bound

2nd TD Bound

3rd TD and Landing

Escape dV by ground command

Obstacle was detected
TD sequence was terminated
After two bounces, S/C stayed on the surface for 30 minutes and lifted off by command.

Summary of Touchdown #1

Landmark guidance above the touchdown site was perfect.

Target Marker was successfully released and tracked.

FBS detected obstacles and touchdown sequence was aborted, but unexpectedly Hayabusa landed on the surface.

As you can see the area around TM on the surface, there are no big obstacle. FBS may have detected the floating dust.

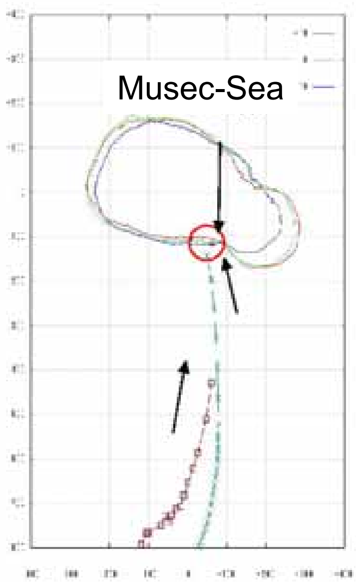
There are high possibilities for Hayabusa to collect any sample by natural touchdowns.

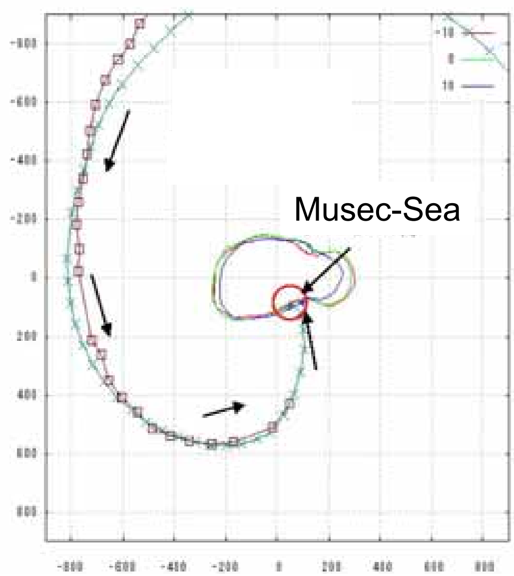
Flight Results (TD #2)

Descent Images at TD#2 (25th, November 2005)

TD#2 on 25th Nov. 2005

Planned trajectory and Hayabusa trajectory





Hayabusa was navigated and guided very well.

Summary for Touchdown Results

Number	Date	Content
TD #1	Nov.19th, 2005	Obstacle was detected by FBS Two bouncings were performed Hayabusa landed for 30 minutes Hayabusa lifted-off Itokawa by emergency command
TD #2	Nov. 25th, 2005	Succeeded in Touchdown After arriving to the Home Position, the spacecraft lost its attitude. Most of navigation data including images in the data recorder were lost, unfortunately.

Current Status

- Two reaction wheels are lost.
- Reaction Control Systems are not available, because they may cause a strong disturbance. Maybe there is no fuel for RCS.
- Some batteries are out of order.

- One reaction wheel is good.
- Ion Engine System is good.
- STT is good.
- Communication system is good.

Hayabusa team succeeded in attitude control by using one wheel, Ion Engine system, and solar pressure, and then Hayabusa spacecraft is on the way to the Earth.