Hayabusa's Adventure around a Tiny Asteroid Itokawa

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Hayabusa Mission & Science Team
Asteroid Sample Return Mission
"HAYABUSA"
Asteroid Sample Return Mission
"HAYABUSA"
It's a Small World!

Asteroid Itokawa vs ISS

540 m

80 m

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It's a Small World! (Part-2)

Punta del Este
It's a World of "Little Prince"

(25143) Itokawa

= 

Le Petit Prince

星の王子さま
Contents

- Brief summary of Hayabusa mission
- Mission : as time sequence
  - Cruising Phase
  - Near & Around Itokawa
  - Descent & Touchdown
  - Mass Determination
  - From now on
- Scientific Results
- Post Hayabusa Mission
Brief Summary
of
Hayabusa Mission
MUSES-C

• MUSES = Mu Space Engineering Spacecraft
  = Technological demonstrator by MU rocket

• C = third spacecraft (A: HITEN, B: HALCA)

• After the successful launch, it was named "Hayabusa," which mean falcon in Japanese. "halcón"
New Technology in Hayabusa

Five Key Technology to be demonstrated:
1. Interplanetary Cruise via Ion Engines as Primary Propulsion
   Microwave driven & CC Grid Ion Engine
3. Sample Collection from Asteroid Surface under Micro Gravity
4. Direct Reentry for Sample Recovery from Interplanetary Orbit
5. Combination of Low Thrust and Gravity Assist

Other New Technology introduced:
Bi-Propellant Small Thrust Reaction Control System (20N),
X-band Up/Down Communication, Complete CCSDS Packet Telemetry,
Duty Guaranteed Heater Control Electronics,
Wheel Unloading via Ion Engines, PN-Code Ranging,
Lithium Ion Re-chargeable Battery, Multi-Junction Solar Cell, etc.
Scientific Objectives

• To know the nature of sub-km sized S-type asteroid
• To investigate the relationship between asteroids and meteors
• To have key information for the origin and evolution of asteroids
Remote Sensing Instruments onboard Hayabusa

- **Multi-Spectral Telescopic Imager (AMICA)**
  - CCD viewing angle 5.7° with 8 band-pass filters
  - About 1500 still images obtained

- **Laser Altimeter (LIDAR)**
  - Measurement accuracy of 1 m at 50 m altitude
  - 1,670,000 hits obtained

- **Near-Infrared Spectrometer (NIRS)**
  - 64-channel InGaAs detector at wavelengths of 0.8~2.1 micron
  - Viewing angle 0.1° (6-90 m per pixel spatial resolution)
  - More than 80,000 spectra obtained

- **X-ray Fluorescence Spectrometer (XRS)**
  - CCD viewing angle: 3.5°, 160 eV resolution at 5.9 keV
  - 6,000 spectra from the asteroid surface obtained
Mission Scenario

Launch
9 May 2003

Earth Swingby
19 May 2004

Asteroid Arrival
12 Sept. 2005

Observations, sampling

Earth Return
June 2007 → June 2010
Hayabusa Mission by CG
Asteroid (25143) Itokawa

26 Sept. 1998: Discovered by LINEAR
1998 SF36
June 2001: Numbered (25143)
August 2003: (25143) Itokawa

Asteroid Itokawa was named after the late Prof. Hideo. Itokawa, the Father of Modern Japanese Rocketry
Mission
- Cruising Phase -
Orbit History until Asteroid Arrival

9 May 2003
Launch

19 May 2004
Swingby

12 Sept. 2005
Arrival

Conjunction
MUSES-C

Hayabusa = 'falcon'

04:29:25 UTC
(13:29:25 JST)
The ion engine system (IES) was started from the end of May 2003.

The Orbit determination under the thrust of the ion engine is difficult, so we made "ballistic period" (=ion engine is stopped) of about three days once in a month, and performed the orbit determination.
Earth Swingby

Launch: 9 May 2003
Swingby: 19 May 2004
Conjunction: 12 Sept. 2005
Arrival: 12 May 2004

Targeting by IES

Position on B-plane

Error of the swingby point on B-plane is about 1 km.

Targeting by Chemical Thruster

May 19, 2004, 06:21:42 UTC
Altitude: about 3700 km

Maneuver:
- 20 April 2004
- 12 May 2004
Images Obtained at Earth Swingby

Moon at 340,000km

Earth at 340,000km

Earth at 60,000km

Earth after swingby

Earth at 295,000km
Solar Conjunction

Launch
9 May 2003

Swingby
19 May 2004

Conjunction
12 Sept. 2005

Arrival

Noise of Doppler

Doppler Noise RMS

km/s

1.0E-04

1.0E-05

1.0E-06

1.0E-07

1.0E-08

SEP[deg]

0

5

10

15

20

25

30

NASA model
Hayabusa
Nozomi (1/16 scale)

OD Error (1σ)
28 June 2005: 200km, 75cm/s
29 July 2005: 1800km, 72cm/s

30 July 2007
COSPAR Capacity Building Workshop on Planetary Science, Montevideo, Uruguay
Optical Navigation

Launch: 9 May 2003
Swingby: 19 May 2004
Conjunction: 12 Sept. 2005
Arrival: 

Asteroid Direction

Range from Earth

OD Error (1σ):
Just after the solar conjunction (29 July 2005)
45 km, 6 cm/s (← 1800 km, 72 cm/s)
At the end of August (29 Aug. 2005)
1 km, 2 cm/s
Images of Itokawa

**July 29 - Aug. 12, 2005**

Fist images taken by Star Tracker

**Aug. 22-23, 2005**

Images by Optical Navigation Camera

**Aug. 23-24, 2005**
Aug 28, 2005:
The IES finished its role on the way to the asteroid.

Operation : 25,800 hour/operation
Single Unit : 10,400 hour
Delta-V : 1,400 m/s
Prop. Consumption: 22 kg
Mission
- Near & Around Itokawa -
Orbit at Proximity Phase

- **Phase**: Cruising Phase
  - **Dates**: Jul. 29
  - **Distance**: 86,000 km
  - **Events**: First Acquisition

- **Phase**: Approach Phase
  - **Dates**: Aug. 28
  - **Distance**: 4,000 km
  - **Events**: Optical Nav. Start

- **Phase**: Proximity Phase
  - **Events**: Check-out of navigations, High altitude observations, SRP estimation, High phase observations, Gravity estimation
  - **Dates**: Sep. 12
  - **Distances**: 20 km, 10 km, 3 km

- **Position**: Itokawa
  - **Angle**: 8~10 deg
  - **Thrusters**: Ion Engine Thrusters, Bi-propellant Thrusters
Final Approach  
= Optical Navigation

Rotation! (Sep. 5, 2005)
Images of Itokawa at Approach Phase

2005

- 9/4 02:36 UTC, 1000km
- 9/5 15:30 UTC, 700km
- 9/6 03:32 UTC, 450km
- 9/7 16:00 UTC, 220km

- 9/8 16:15 UTC, 125km
- 9/9 16:28 UTC, 70km
- 9/10 16:42 UTC, 30km
Arrival at Itokawa

Sept. 12, 2005, at the distance of 20km
Gate Position to Home Position

86,000km
4,000km
20km
10km
3km
Itokawa

DRW mode
(Dual Reaction Wheel)

RCS mode

Parabolic Motions

Troubleshooting

Stable Hovering

Gate Position
GP to HP
Home Position
Itokawa Tour
Partial Revolution

Z-HP [Km]

0 2 4 6 8 10 12 14 16 18 20 22

09/16 09/23 09/30 10/07 10/14 10/21 10/28
Gate Position to Home Position

86,000 km
4,000 km
20 km
10 km
3 km
Itokawa

Gate Position
Home Position
GP -> HP
Tour
Orbit

Itokawa
Images of Itokawa: whole

Eastern Side

Western Side

Head

Bottom

Release 051101-1 ISAS/JAXA

Release 051101-2 ISAS/JAXA

Release 051101-3 ISAS/JAXA

Release 051101-4 ISAS/JAXA
Global Shape of Itokawa: Sea Otter in Space?

Ecliptic plane of our solar system and this asteroid are considered to resemble a sea-otter on sea. This asteroid is divided into the head and body parts with constricted neck circular region. Ventral saddle-like parts and dorsal one are covered with smooth surface. Right is an ascii art which had been distributed in operators during the Rendezvous.
Images of Itokawa
Smooth and Rough

Release 051101-16 | ISAS/JAXA

Point A
MUSES-Sea

2005-10-19T21:45 (UTC)
distance: 3.8 km
10 m

Release 051101-17 | ISAS/JAXA

Woomera
Point B

2005-10-20T00:45 (UTC)
distance: 4.1 km
10 m
Images of Itokawa
Smooth and Rough
Images of Itokawa
Rough surface

Release 051110-6.2 ISAS/JAXA

Release 051110-6.1 ISAS/JAXA
Images of Itokawa
Large Boulders

"Pencil"
"Yoshinodai"
Images of Itokawa
Craters

Fuchinobe (D=36m)

Komaba (D=27m)

Kamisunagawa (D=10m)
Images of Itokawa
Other features

Black boulder

Facet
Images of Itokawa
Close-up

Spatial Resolution: 6-8 mm
Images of Itokawa
Close-up

At 59m
6mm/pixel

ST_2566271576
Images of Itokawa

color variation

Release 051101-12 ISAS/JAXA
Images of Itokawa
color variation

R(w-band) / R(b-band)  Ishiguro et al. (2006)
Images of Itokawa
Bright Region

[Diagram of Itokawa showing labeled regions: N, Yatsugatake, Muses Sea, Shirakami, Usuda, with a scale of 50m]
Explanation of Color Variation

Rubble pile + collisions

Space Weathering

Shaking ➔
Surface movement exposes underlying brighter zone.
Near Infrared Observation

* Surface of Itokawa indicates olivine and pyroxene mineral assemblage.
* Reflectance spectrum of Itokawa is similar to that of ordinary chondrites.
X-ray Observation

* X-rays from Itokawa (right) has larger Mg/Si and smaller Al/Si than those of X-rays from the standard sample (left).
* Itokawa is similar to ordinary chondrites in composition.
Potential and Slope Maps

Mission
- Descent & Touchdown -
Descent Rehearsal and Touch-down

1. Rehearsal #1 .................................... Nov. 4th
2. Nav & Guide Practice ..................... Nov. 9th
   (Target Marker Release#1)
3. Rehearsal #2 .................................... Nov. 12th
   (MINERVA Lander Release)
4. Touch-down for Sampling#1 ............ Nov. 20th
   (Target Marker Release#2)
   (Two Touch-downs + One Landing)
5. Touch-down for Sampling#2 ............ Nov. 26th
   (One Touch-down + One Sampling CMD Issued)

Itokawa

2005
Touch-down sequence

Based on the image obtained at altitude 500[m]
Go/NoGo is judged

vertical descent

<Touch-down Phase>
Hovering and Descent
FBS for obstacle detection
Touch and Go

<Descent Phase>
Image Based Navigation with Landmark Tracking

Sun Direction

<Final Descent Phase>
Surface synchronization
TM release and Position tracking by TM

Attitude alignment with the surface by LRF

30 July 2007
Approach and Descent Path #2

Planned and Actual Path (Semi-Inertial)

Planned and Actual Path (Itokawa-Fixed)
Rehearsal No.1 (Nov. 4, 2005)
Navigation & Guidance Practice (Nov. 9, 2005)
Touch-down for Sampling

Touch-down for Sampling#1

Touch-down for Sampling#2
Target Marker
MINERVA
What happened at 1st touch-down?

1st touch-down

2nd touch-down
What happened at 1st touch-down? -> answer

Obstacle was detected by FBS
TD sequence was terminated
S/C maneuvered at the initial velocity and free-fall was performed
There are high possibilities for Hayabusa to collect any sample by natural touchdowns
After 2nd Touching Down

• Hayabusa had lost contact due to fuel gas eruption for 45 days since December 8th.

• A beacon, un-modulated signal from the spacecraft was acquired on January 23rd, 2006.

• Since then, Hayabusa is operated without losing its contact.
Mass Determination
Mass Estimation

“Free Fall” Period:
No thruster control Applied

A

B

C, D

E

1st touch down
# Results of Mass Estimation

## 1st result

<table>
<thead>
<tr>
<th>Groups</th>
<th>Period</th>
<th>Distance from Itokawa</th>
<th>Model of Itokawa</th>
<th>GM $10^{-9}$ km$^3$/s$^2$</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9/12～10/2</td>
<td>20 - 7 km</td>
<td>point mass</td>
<td>2.34</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>R&amp;RR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>10/21-22</td>
<td>3 km</td>
<td>point mass</td>
<td>2.29</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>R&amp;RR, Opt., LIDAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>11/12</td>
<td>1427 - 825 m</td>
<td>polyhedron</td>
<td>2.39</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>LIDAR, Opt.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>11/12</td>
<td>800 - 100 m</td>
<td>polyhedron</td>
<td>2.36</td>
<td>6%</td>
</tr>
<tr>
<td></td>
<td>Opt., LIDAR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>11/19</td>
<td>20 - 10 m</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>LRF</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Mass and Bulk Density of Itokawa

Estimated GM in each period (GM=Gravity Constant x Mass)

<table>
<thead>
<tr>
<th></th>
<th>GM (10^-9 km^3/s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.98</td>
</tr>
<tr>
<td>B</td>
<td>2.17</td>
</tr>
<tr>
<td>C</td>
<td>2.27</td>
</tr>
<tr>
<td>D</td>
<td>2.21</td>
</tr>
</tbody>
</table>

GM : (2.34± 0.07) x 10^-9 km^3/s^2

Mass : (3.51 ± 0.105) x 10^{10} kg

Volume = (1.84 ± 0.092) x 10^7 m^3

Bulk Density : 1.9 ± 0.13 g/cm^3

Macro-porosity = 40%

Ordinary chondrite Density ~ 3.2 g/cm^3
Macroporosity of Itokawa

3.51 x 10^{10} (kg)


Mission
- From now on -
Current Status

Current (July 2007) status is as follows:

• The chemical thrusters cannot be used.
• Two out of three reaction wheels are broken.
• The ion engines are OK.

• Orbit control : by the ion engines

• Attitude control : by one reaction wheel, the ion engines, and the solar radiation pressure
Return to the Earth

- New trajectory (red line) leaving Itokawa vicinity in April 2007, returning to Earth in June of 2010 is shown here.
- The Xenon gas consumption meets the current amount that remains.
We hope ...
Scientific Results
- short summary -
Fundamental Parameters of (25143) Itokawa

Ground-based observation

**Rotational Period:** $P = 12.1324$ hours

**Spin Axis:** almost perpendicular to the ecliptic plane, retrograde

**Size, shape:** by Kaasalainen, by Ostro

Observation by Hayabusa

**Size:** Principal Axis: $X=535$ m, $Y=294$ m, $Z=209$ m ($\pm 1$ m)

**Spin Axis:** Orientation in space $[\beta, \lambda]=[128.5, -89.66]$

Nutation is within error range.

**Mass:** $(3.510 \pm 0.105) \times 10^{10}$ kg

**Volume:** $(1.84 \pm 0.092) \times 10^{7}$ m$^3$

**Bulk Density:** $1.90 \pm 0.13$ g/cm$^3$
Formation Scenario of Itokawa

“Rubble Pile” Hypothesis

1. The parent body is disrupted by impact
2. A portion of fragments coagulated each other forming the “Head” and “Body” sections, independently
3. The Head and the Body were merged as a contact binary asteroid


- Extremely low bulk density for an S-type asteroid and high macro-porosity of ~40%
- Global shape is round rather than blocky
- Surface is covered with many boulders
- No large structures extending to the entire body (e.g., long linear ridge found on Eros and Phobos) found
- Parts of some facets are exposed on the surface (?) 
- Slope is generally low (relaxed in many areas)
- Large boulders cannot be formed during impacts to result the craters existing now on Itokawa. They must be associated with much larger impact events.
What Hayabusa found on Itokawa

• Itokawa is the first very small asteroid with clear indications of “rubble-pile” structure.

• Itokawa maybe formed by gravitational coagulation of ejected fragments from a catastrophic disruption of its large parent body by an impact.

• Itokawa is the smallest body of the solar system that spacecraft ever explored, but it has a lot of features on the surface.

• Itokawa, which is S-type asteroid, is mother body of ordinary chondrite meteorites.

• We saw the actual view of a potentially hazardous asteroid for the first time.
Post Hayabusa Mission
**Hayabusa-next**

Itokawa

S-type: stone

Wilson-Harrington

Hayabusa-Mk2

Hayabusa

Hayabusa-2

1999 JU3

Hayabusa-next

C-type: organic, water-content mineral

Proposed to Cosmic Vision of ESA

dormant comet nucleus

Future Plans

S-type Asteroid
- Abundant in the inner part of the asteroid belt
- Relation between the ordinary chondrites
- Origin of planets

C-type asteroid
- Abundant in the outer part of the asteroid belt
- Contains organic matters
- Important information about the origin of life

P, D-type or dormant comet
- More primitive body and no (rare) meteorite related to these objects
- Origin of the solar system

Comet nucleus, trans-Neptunian objects
(rather difficult)
Gracias!
Information
A: Launch ...................... May 9, 2003
B: Earth Swingby .......... May 19, 2004
C: Asteroid Arrival ....... Sept. 12, 2005
D: Asteroid Departure ... Feb. 2007
E: Earth Return ............. June 2010

(Hayabusa:Red, Itokawa:Blue, Earth:Green)
Orbital Evolution of Itokawa

Past
- Inner edge of the asteroid belt
- Secular resonance v6, or Mars encounter

Present
- Apollo type orbit
- Chaotic motion

Future
- Collide with the sun or inner planets
- Collision probability with the Earth is about once in one million years.

by P. Michel and M. Yoshikawa
Chaotic Motion of Itokawa

0 year

1,000 y

10,000 y

10,000,000 y

1,000,000 y

100,000 y