Hayabusa: Navigation Challenges for Earth Return

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Hayabusa was a JAXA sample-return mission to Itokawa navigated, in part, by JPL personnel. Hayabusa survived several near mission-ending failures at Itokawa yet returned to Earth with an asteroid regolith sample on June 13, 2010. This paper describes NASA/JPL's participation in the Hayabusa mission during the last 100 days of its mission, wherein JPL provided tracking data and orbit determination, plus verification of maneuver design and entry, descent and landing.

Nomenclature & Acronyms

ACS	=	Attitude control system
AZI	=	azimuth
B.R	=	error along R component in B-plane (1σ unless noted otherwise)
B.T	=	error along T component in B-plane (1σ unless noted otherwise)
Delivery	=	spacecraft state and covariance at a specific time (usually before a TCM), mapped to B-plane
DCO	=	(tracking) data cutoff
DSN	=	Deep Space Network
EDL	=	Entry, descent, and landing
eFPA	=	entry flight path angle (angle between local vertical and velocity vector at Entry altitude)
Entry	=	"top of the atmosphere" (often at altitude = 200 km, but can vary)
eV	=	velocity at Entry altitude
IES	=	Ion engine system
HGA	=	High gain antenna (X-band)
JAXA	=	Japan Aerospace Exploration Agency
JPL	=	Jet Propulsion Laboratory
LFT	=	linear flight time
OD	=	orbit determination
perigee	=	the distance (and time) of closest approach to Earth
RCS	=	Reaction control system (attitude thrusters)
smia	=	Semi-minor axis (half-width of dispersion ellipse)
SMIA	=	Semi-major axis (half-length of dispersion ellipse)
SRC	=	Sample return capsule
SRP	=	Solar radiation pressure
TCM	=	Trajectory correction maneuver
TOA	=	Time of arrival
Usuda	=	JAXA Deep Space Station (64 m)
WPA	=	Woomera Prohibited Area

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1. Introduction

Muses-C was launched by the Japan Aerospace Exploration Agency in May 2003[1] but was renamed Hayabusa (Japanese for falcon) after launch. The mission plan called for a round-trip exploration of Itokawa, an Earth-crossing C-type asteroid. The two key objectives of the mission were to demonstrate low-thrust ion propulsion and return a regolith sample from the asteroid to Earth. Both objectives were accomplished, but for reasons described in this paper the sample was returned later than originally planned.

Itokawa proximity-operations occurred between October 2005 and late November 2005. During the final regolith-sampling run a spacecraft-damaging malfunction occurred, and JAXA controllers lost contact with the spacecraft for about one month. The damage turned out to be extensive yet it did not prevent Hayabusa from embarking on a homeward voyage in March 2007. The mission concluded when the sample return capsule carrying a regolith sample landed on Earth on June 13, 2010.

NASA-JPL and NASA-DSN supported Hayabusa navigation from launch to Earth-return; this paper addresses the Earth-return approach phase of Hayabusa, a period consisting of approximately the last 100 days of the mission. The JPL navigation support consisted of orbit determination, maneuver verification and observation, and entry, descent and landing verification.

2. Background

A. Spacecraft Sub-systems

Spacecraft characteristics are described in Table 1 and Figure 1.

A low-thrust ion engine system supplied spacecraft thrust [1]. The engine was designed only to change spacecraft energy in order to perform interplanetary transfers. It consisted of a power source and four thrusters labeled A, B, C, and D (see Figure 2), although only one thruster at a time was operated. Thruster A never functioned because of a defective ion source (at least not until the end of the mission) but the remaining thrusters functioned as designed. The next subsection describes thruster performance in more detail.

The ion engine was not intended for small-body orbital operations (so was turned off at Itokawa) nor was it intended for Earth-reentry targeting (so it was to be turned off during the Earth-approach phase). The ACS and RCS subsystems were designed for orbit maintenance and reentry targeting maneuvers. But the RCS suffered significant damage at Itokawa and was no longer useable after 2005. The ACS (consisting of three reaction wheels to provide angular momentum control) was also in bad shape, with only a single wheel operational after 2005. Many other components had failed or were degraded as a result of the malfunction. The status of various spacecraft sub-systems as of early 2010 is summarized in Table 2, as well as (in some cases) the alternatives. The spacecraft was in poor condition as it began its Earth-return journey.

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[1] The University of Tokyo institute ISAS launched Muses-C, but subsequently this group and the Japanese federal agency NASDA were combined and re-named JAXA, a new organization. Thereafter the (former) ISAS group within JAXA was renamed JSPEC (Japan Space Exploration Center).

Table 1: Spacecraft Parameters

		Comment
Total mass (wet)	415 kg	as of March 26, 2010
SRC mass	16 kg	"
Hydrazine mass	0 kg	"
Xenon propellant mass	20 kg	"
Bus dimensions	1.5x1x1 m	x, y, z
Solar panel	4.5x1 m	x2, not articulated (1.3 kW per side @ 1au)
High gain antenna	1.6 m diameter	X-band
SRC dimensions	40x20 cm	(diameter, height) of sphere-cone
Low-thrust engine	7 mN thrusters	x4 (Xe propellant)
RCS	22 N thrusters	x8 (bi-prop)
ACS	reaction wheels	x3

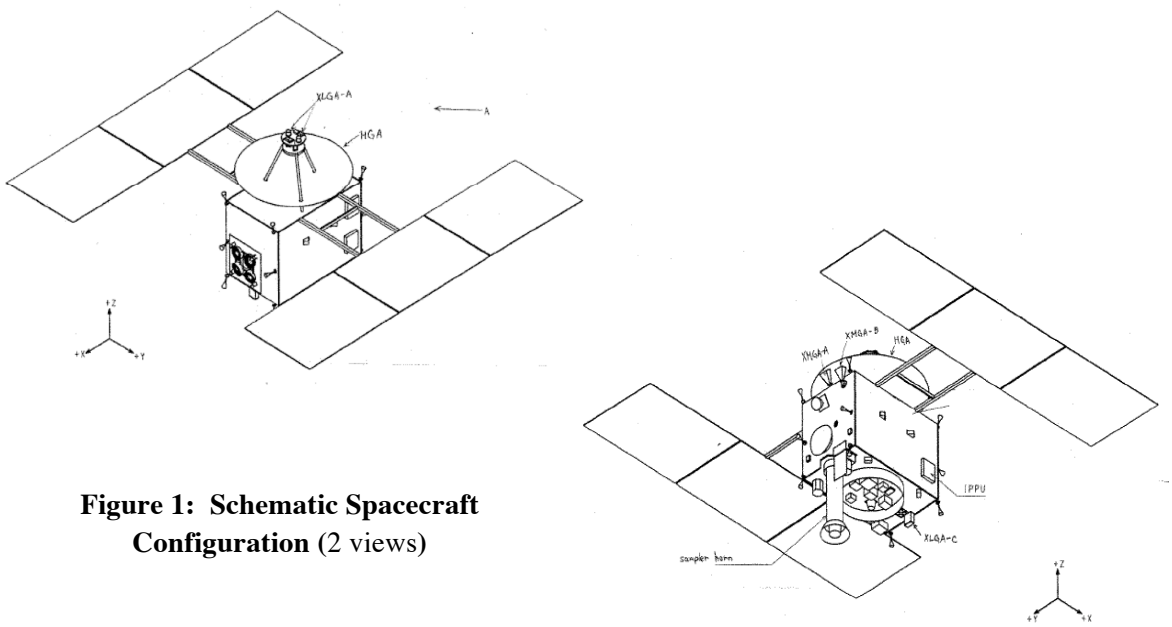

Figure 1: Schematic Spacecraft Configuration (2 views)

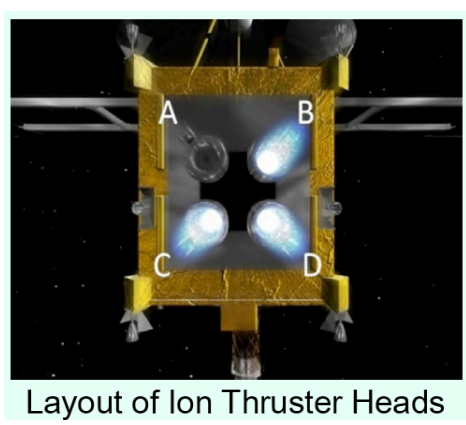

Figure 2: IES Thruster Configuration (ion plume direction along +X) (JSPEC)

Table 2: Sub-system Status (Jan. 1, 2010)

Sub-system	*Status*	*Work-around*
Attitude Control	2 of 3 reaction wheels failed. Chemical RCS thrusters: no propellant. Star trackers: operational.	Stabilized with solar radiation pressure and neutralizer jets (cold gas). Single remaining wheel useful for Zaxis turns.
Power	Batteries dead. Solar panels degraded.	Solar power only. Point solar panels within ±10º of Sun to provide sufficient power.
TCMs	Chemical RCS thrusters: no propellant.	Use ion engines. Attitude during TCM controlled by SRP & thruster gimbals. Request NASA-JPL support for TCM real-time monitoring.
Ion Propulsion	3 of 4 thrusters inoperable; remaining thruster functions at low level only; some components OK.	Combine Neutralizer A with Ion Source B to yield ~90% of nominal single-engine thrust.
Thermal	Passive only. Sunlight cannot enter IES nozzles (eliminating vectorized maneuvers).	Maintain solar panel normal vector within ±3º of Sun. Down-track ΔV only.
Telecom	HGA functional but unusable because of pointing, power, & thermal constraints.	Rely on low-gain antennas. Request NASA-DSN support for tracking & commanding.
Bus	All sub-systems reduced to single-string.	None.
Sample Return Capsule	Unknown (no telemetry).	None.

B. Thruster Performance

The anomaly at Itokawa required a mission re-design and this forced a longer return journey. Thrusters B, C, and D performed as designed, but the longer journey included more thrusting than called-for in the original mission plan and this led to degradation and loss of thruster performance over time, as thrusters exceeded their design limits. Eventually all the thrusters failed: thruster A (already noted), followed by B, C, and finally D.

Thruster B failed shortly after the return voyage began when the voltage on its ion-neutralizing grid exceeded the power supply (May 2007). Thruster C was turned off in October 2009 because of poor performance (it was operating at 50% of capability and failure was imminent). Thruster D failed less than one month later, on November 4, 2009, also because of high neutralizer voltage. This string of failures left Hayabusa apparently without an operable propulsion system, with five months of thrusting remaining.

After the D failure an innovative solution was proposed by the Project [2]. The proposal was untested but ultimately the notion succeeded and propelled Hayabusa to its Earth rendezvous. The fix consisted of disabling an IES capacitor, cross-strapping two of the partially in-operable engines (A, B) and, utilizing the operable halves of each, combine them to generate thrust almost equivalent to that of a single nominal thruster (~90%). Electrons from Neutralizer A were combined with the mass flow (ions) from Ion Source B. Power and mass consumption increased by a factor of two with this off-nominal configuration, but sufficient margins existed to complete the thrust phase.

The performance of the IES for the entire mission is summarized in Figure 3.

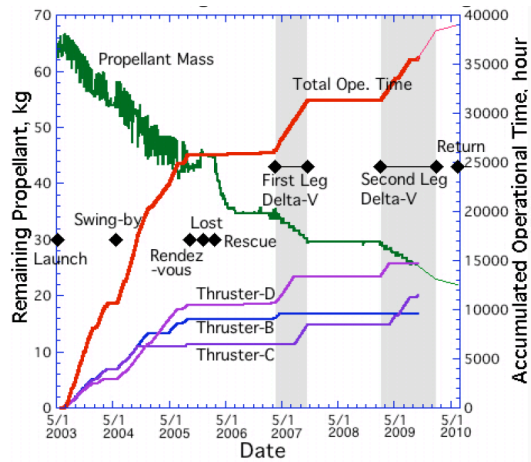

Figure 3: Ion-engine system performance (JSPEC)

The vertical shaded bands denote the major thrust arcs for the return journey. The figure does not have the fidelity to show all thrust periods. For example, five Earth-targeting TCMs between April and June 2010 were implemented using the IES. Those occurred within a span of 11 weeks for a total of about 10 days of additional thrusting. In all, the final accumulated time on the IES at the end-of-mission was 39,700 hours. The total velocity change was $\Delta V = 2130$ m/s. The time spent on the A+B combination totaled 3160 hours with a ΔV equal to 30 m/s.

C. Trajectory

After regaining control of the spacecraft following the malfunction, a revised return trajectory was determined. Since Itokawa is an Earth-crossing asteroid, Hayabusa's return trajectory was similar to the asteroid's orbit. Thus returning to Earth from the vicinity of Itokawa required only small adjustments in perihelion distance, orbit inclination, and ascending node [1]. Representative orbit elements of Hayabusa's return trajectory are given in Table 3. Even the physical parameters of its trajectory (*a, e, i*) are (very) roughly similar to Earth's; it was timing that needed the most adjustment in order to achieve a rendezvous. Changes in those parameters over time are plotted in Figure 4. Figure 5 shows a plot of pertinent orbits around the Sun.

Table 3: Hayabusa Osculating Orbit Parameters

Epoch May 31, 2010

Element	*Value*	*Comment*
a	1.31 AU	Sun-centered
e	0.2530	Sun-centered
i	1.663°	Sun-centered, EMO2000
w	147.7°	Sun-centered, EMO2000
W	82.53°	Sun-centered, EMO2000
TA	30°	Sun-centered (as of June 13)
Period	552 days	
Perihelion	2010/5/15 15h	UTC
V_{inf}	4.813 km/s	Earth-centered

In March 2007 the spacecraft began its return voyage. By March 2010 after 19 months of thrusting (distributed over 3 years) Hayabusa was positioned for an Earth swing-by. At that time spacecraft perigee was located just outside the Earth's sphere-of-influence at a point such that if control of the spacecraft were lost, no uncontrolled impact with Earth would occur.

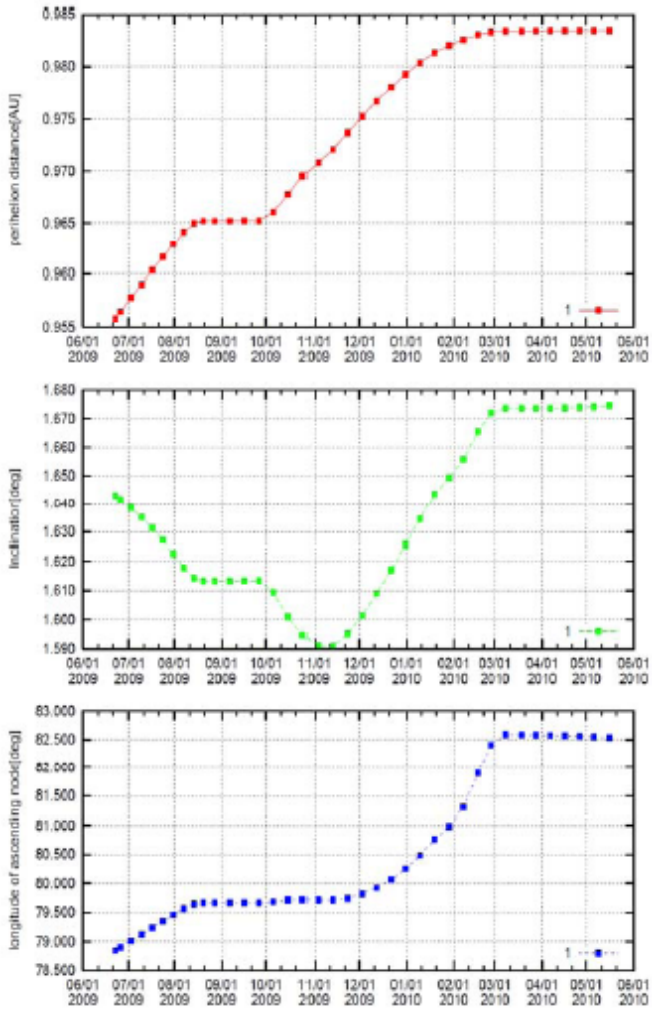

Figure 4: Orbit Parameters v. Time (JSPEC)

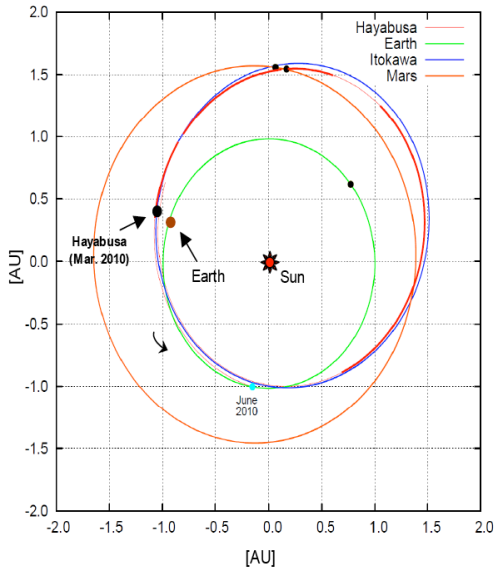

Figure 5: Return-to-Earth Orbit (JSPEC)

The IES Thrust Phase ended when a rendezvous in the vicinity of Earth was assured. But the Thrust Phase did not place the spacecraft into the Earth re-entry corridor. Additional thrusting was required to refine the final approach path. So five TCMs were scheduled during the Approach Phase in order to achieve the entry conditions necessary for re-entry. The surface target was the Woomera Prohibited Area, an Australian government range north of Adelaide. For the nominal 2007-return mission, the TCMs would have been performed with RCS thrusters. In 2010 the TCMs would be performed with the IES since the RCS was not functional (even though the IES was not designed for this purpose).

The two plots in Figures 6 and 7 illustrate successive magnifications of the landing site. Figure 6 depicts the ground-track of the re-entry capsule and Figure 7 shows a schematic map of Australia, including a representative landing dispersion ellipse and landing-beacon stations erected to radio-locate the capsule on its descent through the

atmosphere. The SRC was released from the spacecraft bus via a spring mechanism three hours before Entry. The bus followed the SRC into the atmosphere – it did not perform an Earth-avoidance divert maneuver. The bus burned up during entry and did not reach the surface.

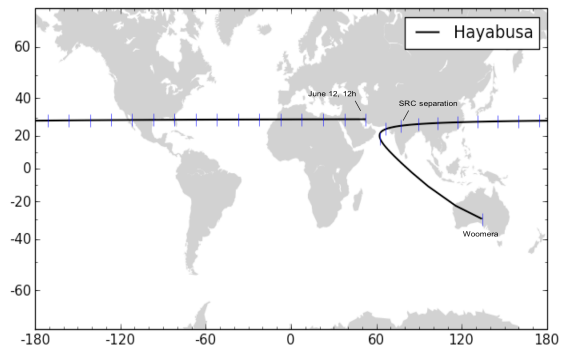

Figure 6: Ground-track of Final 24 Hours (1 hr tics)

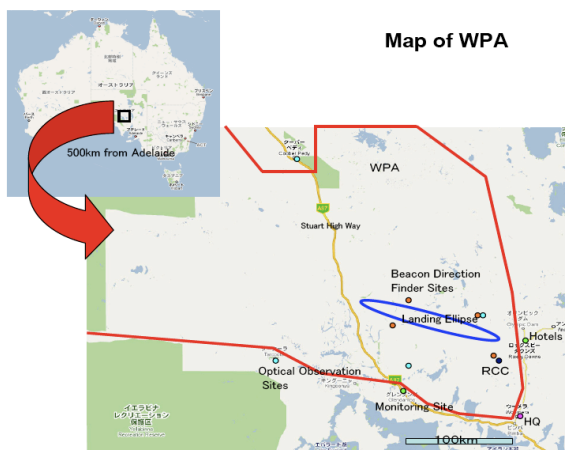

Figure 7: Australian Landing Range
The blue ellipse defines the 4σ TCM-4 landing dispersion used for planning (JSPEC)

3. Navigation

Ground stations operated by both DSN and JAXA supplied navigation tracking passes. JAXA's major tracking stations are all located in Japan, whereas DSN has stations distributed nearly symmetrically around Earth. Usuda (one of the Japanese stations) tracked the spacecraft when Hayabusa was in view from Japan. DSN stations tracked the spacecraft for the other two-thirds of the day (i.e. when not viewable from Japan) using stations in Spain and California, although the tracking was not continuous but only upon request of JAXA. Mostly this occurred during TCM executions and in the final two weeks of the mission, although DSN was also called upon at other times when expanded coverage was required (e.g. spacecraft safing, telecommunication periods with low signal-to-noise).

Notable events during 2010 are summarized in Table 4.

Table 4: Hayabusa Events

Event	*Start Time [UTC]*	*Duration*	*ΔV [m/s]*
Thrust Phase II	Ended March 27	1 year	420
TCM-0	April 3, 12:00	41 hours	2.07
TCM-1	May 1, 11:00	64 hours	3.38
TCM-2	May 22, 22:00	92.5 hours	5.07
TCM-3	June 3, 03:00	50 hours	2.75
TCM-4	June 9, 03:00	2.5 hours	0.14
SRC release	June 13, 10:50	instantaneous	0.17 on capsule
SRC atmosphere entry	June 13, 13:51:11		

Table 5: Targets – Planned v. Implemented

Times on June 13, 2010

	<- Planned (2009) ->			<- Implemented ->			
Event	*Time of [UTC]*			*Time of [UTC]*			
End of Thrust Phase II	*Perigee* 13:56:43	*B.T* 15,464	*B.R* 5,080	*Perigee* 13:35:23	*B.T* 29,278	*B.R* 6,711	*Perigee rad* 17,559
TCM-0	*Perigee* 13:56:43	*B.T* 15,464	*B.R* 5,080	*Perigee* 13:57:00	*B.T* 18,435	*B.R* 4,821	*Perigee rad* 8,588
TCM-1	*Perigee* 13:56:43	*B.T* 15,464	*B.R* 5,080	*Perigee* 14:33:17	*B.T* 19,375	*B.R* 6,711	*Perigee rad* 9,662
TCM-2	*Perigee* 13:56:43	*B.T* 15,464	*B.R* 5,080	*Perigee* 14:01:38	*B.T* 16,398	*B.R* 4,093	*Perigee rad* 7,006
TCM-3	*Perigee* 13:49:26	*B.T* 15,078	*B.R* 4,917	*Entry* 13:50:54.9	*FPA* -12.80°	*Latitude* -26.89°	*Entry rad* 6,573.8
TCM-4	*Perigee* 13:49:54	*B.T* 15,115	*B.R* 4,940	*Entry* 13:51:11.7	*FPA* -12.31°	*Latitude* -27.21°	*Entry rad* 6,573.7
SRC atm entry	*Entry* 13:46:39	*FPA* -12.55°	*Latitude* -26.91°	*Entry* 13:51:11.7	*FPA* -12.31°	*Latitude* -27.21°	*Entry rad* 6,573.7

The Approach Phase thrusting strategy was clarified near the end of the Thrust Phase II (i.e. to compensate for the further reduced IES capability and tighter margins in thermal constraints). Targeting maneuvers needed to be limited to down-track directions in order to maintain sufficient darkness within the interior of the IES nozzles (the nozzle cone angle with respect to the Sun needed to stay ~90°). Down-track thrust controlled time-of-arrival but it couldn't adjust components orthogonal to the flight path (at least not directly). Thus the only way to reach the re-entry corridor was to zigzag across the B-plane by adjusting flight time (and with whatever small cross-track component adjustments could be achieved using the IES gimbals). Using this *ad-hoc* approach strategy, B-plane targets shifted as necessary in order to satisfy entry, flight system and thrust constraints. This led to a non-optimal sequence of maneuvers, yielding an unprecedented track of targets across the B-plane. See Table 5 and Figure 8.

As one example, in Figure 8 visually compare the size of a TCM-3 to move from the *original* TCM2 target to the TCM3 target in the entry corridor with the revised TCM3 that goes from the *implemented* TCM2 target to the same TCM3 target. The ΔV magnitude increased significantly.

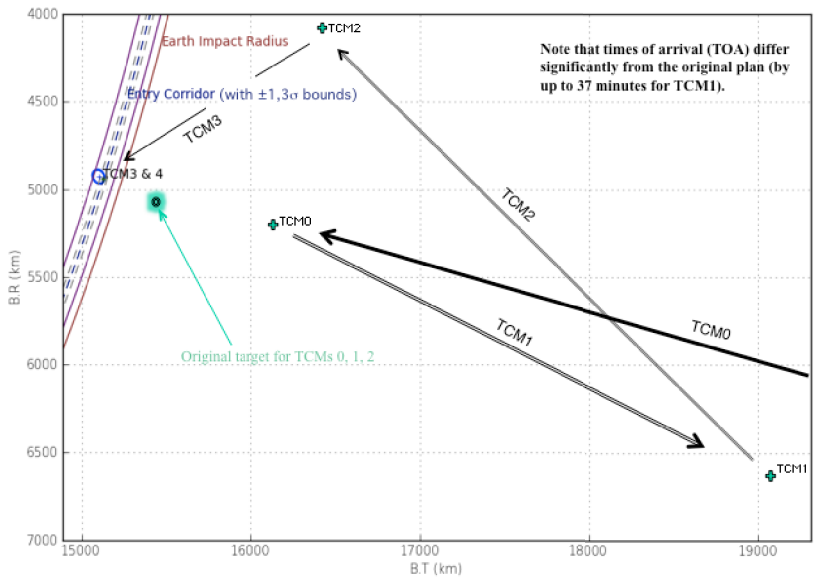

Figure 8: Implemented Targets in B-plane (marked by green "+"s)

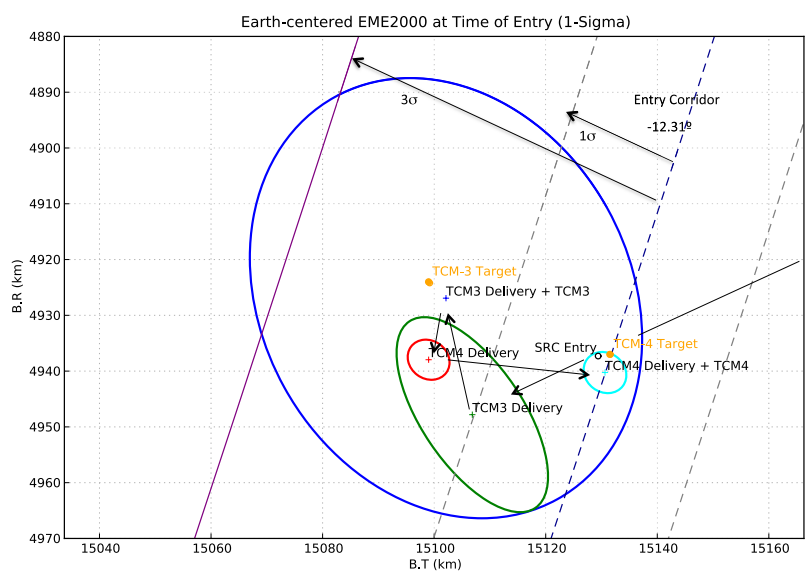

Figure 9: TCM-3 & TCM-4 Deliveries in the Earth-arrival B-plane, 1σ

Tracking coverage during TCMs was important because (technically) maneuvers were performed open-loop and monitoring was necessary. But with an active monitoring strategy the TCMs did, in effect, have positive feedback (people-in-the-loop) so the results usually agreed closely with the final, implemented target (not necessarily the same as the nominal target). High-fidelity maneuver execution was possible in principle this way since ΔV could be integrated as the burn progressed and throttled as needed – the spacecraft could be "driven" to the desired location in the B-plane (that is, if a two-way link was available).

The delivery and reconstructed B-plane solutions for TCM-3 and TCM-4 along with error dispersions are shown in Figure 9. The figure also shows the final entry corridor for the sample return capsule. The arrows between error ellipses in the figure are notional and placed there as an aid to understanding the general movement of solutions in this coordinate plane. Note that error dispersions are larger for the solutions including a maneuver. (For example, 'TCM3 Delivery+TCM3' is larger than 'TCM3 Delivery'.) That happens because in the first case maneuver execution errors are included in the solution's error mapping. So in the figure, 'TCM3 Delivery' is where the OD says the spacecraft currently is going. TCM-3 subsequently is designed to move the spacecraft to the TCM-3 target (which by design it achieves - almost). But the execution error of the maneuver increases uncertainty in the outcome until after the maneuver has completed, whereupon the 'TCM3 Delivery+TCM3' ellipse collapses to the 'TCM4 Delivery' ellipse (which shows, with the benefit of post-maneuver data, that TCM-3 missed the TCM-3 Target by approximately 15 km).

The reconstructed entry point of the sample return capsule at the entry interface altitude is noted in Figure 9 as "SRC Entry", missing its target by about 3 km in the B-plane but well-within the 1σ entry corridor bounds.

The reaction of the SRC on the bus at the moment of release is shown in the doppler residual plot of Figure 10. The observed frequency shift of 8 hz corresponds to a SRC release velocity equal to 17 cm/s with respect to the spacecraft bus. The angle between the velocity vector and the line-of-sight was 30º.

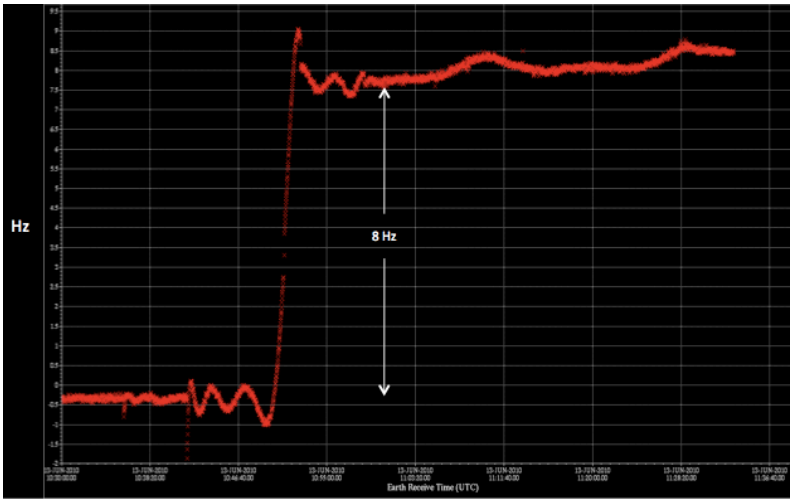

Figure 10: Doppler Residuals, Confirmation of SRC Release

4. Entry, Descent and Landing

A target-biasing strategy during Earth-approach was designed in order to minimize risk to Earth-dwellers. The original target for TCMs 0, 1, and 2 remained beyond Earth's impact radius so any loss of control of the spacecraft

would result in a harmless swing-by of Earth (all three TCMs used the same target, see Figure 8). TCM-3, placed 10 days from encounter, was a critical maneuver designed to move the return capsule onto an atmosphere-entry trajectory. TCM-4 refined the targeting of TCM-3.

During flight operations, although the eventual targets for TCMs 0, 1, and 2 changed substantially from those established by the nominal plan, a target-biasing strategy continued to be followed. Not until TCM-3 was the spacecraft placed on an Earth re-entry path.

The penultimate target on the ground was a point located near the center of WPA. Because Australian Government regulations prohibit landings outside of WPA, the 4σ TCM-3 delivery errors mapped to the surface (the "ground footprint") needed to lie entirely within WPA. Therefore the TCM-3 maneuver needed to be timed (scheduled) such that the estimated error dispersions from TCM-3 mapped to the surface fell within the borders of WPA. Using the predicted OD dispersions from Table 8 (subsection 5-b), we determined in advance that a date of June 3 for TCM-3 ("Entry-10" days) satisfied this criteria.

Once established the time of TCM-3 could not change significantly due to schedule constraints. Yet as shown above (e.g. Figure 8) the magnitude of TCM-3 grew larger than planned, so the TCM-3 errors mapped to the ground exceeded the WPA bounds by a factor of 2. See Figure 11. A predicted uncertainty this size almost resulted in a mission-abort command from the Australian government, but the ground footprint shrank significantly after TCM-3 and subsequently fit within WPA, thereby satisfying the landing requirement.

Two atmosphere models were used in the EDL calculations (for comparison): EarthGRAM2007 and EarthGRAM99 [3]. These models were similar but the 2007 version included an updated wind model. As seen in the figure the results from each model were practically equivalent.

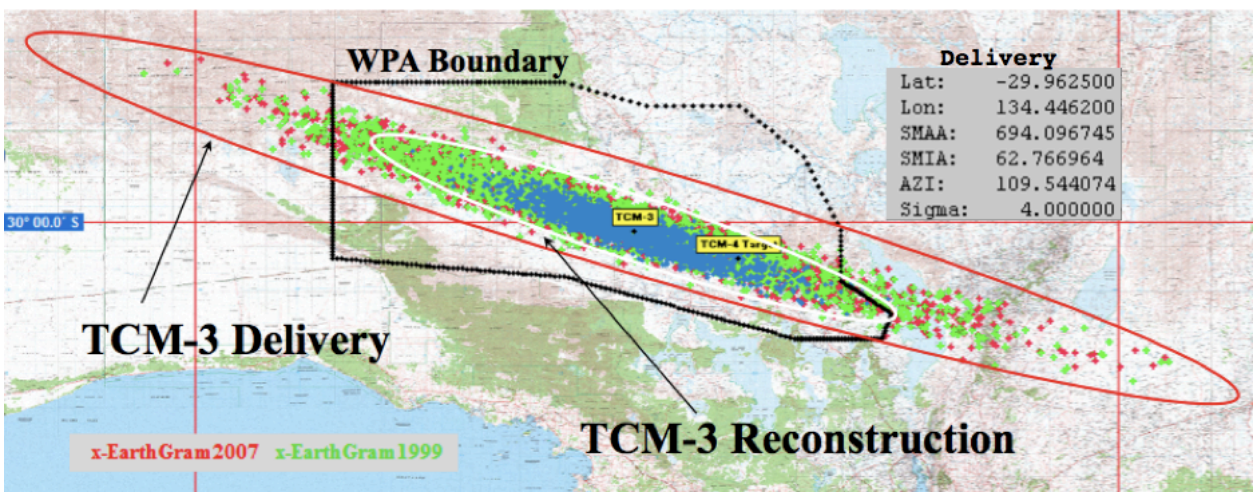

Figure 11: TCM-3 Ground Dispersions, 4σ (units in km and °)

The purpose of TCM-4 was to shift the landing point from the center of WPA to a location closer to recovery facilities, a site about 200 km to the south-east. That ultimate target is shown in Figure 11. Reaching it involved only a small flight path correction, therefore leaving some flexibility for the timing of the maneuver's occurrence. Nominally TCM-4 was scheduled for June 10, three days before atmosphere entry.

The predicted ground footprint at the time of capsule release is plotted in Figure 12. The larger ellipse outlines the dispersion on the surface (green dots) while the smaller dispersion (blue dots) represents the uncertainty in the location of the capsule at an altitude of 10 km where the parachute opened. The final resting point of the SRC is marked with the label 'HAYABUSA', near the western edge of the ellipse.

The dispersion at ground level is significantly larger than the chute-open dispersion due to wind uncertainties in the atmosphere model. The EarthGRAM2007 wind model is conservative in that wind fluctuations are based on monthly mean distributions accounting for all possible wind uncertainties during the month of landing (and for all times of the day). On June 13 the model predicted prevailing winds would carry the capsule approximately 18 km east from the point of parachute deployment. As it happened, on the day of landing winds-aloft were contrary. JAXA personnel present at the landing site measured the winds-aloft in order to improve capsule drift predictions, but those measurements didn't reach JPL until later. The real winds blew north-to-northwest but were erratic.

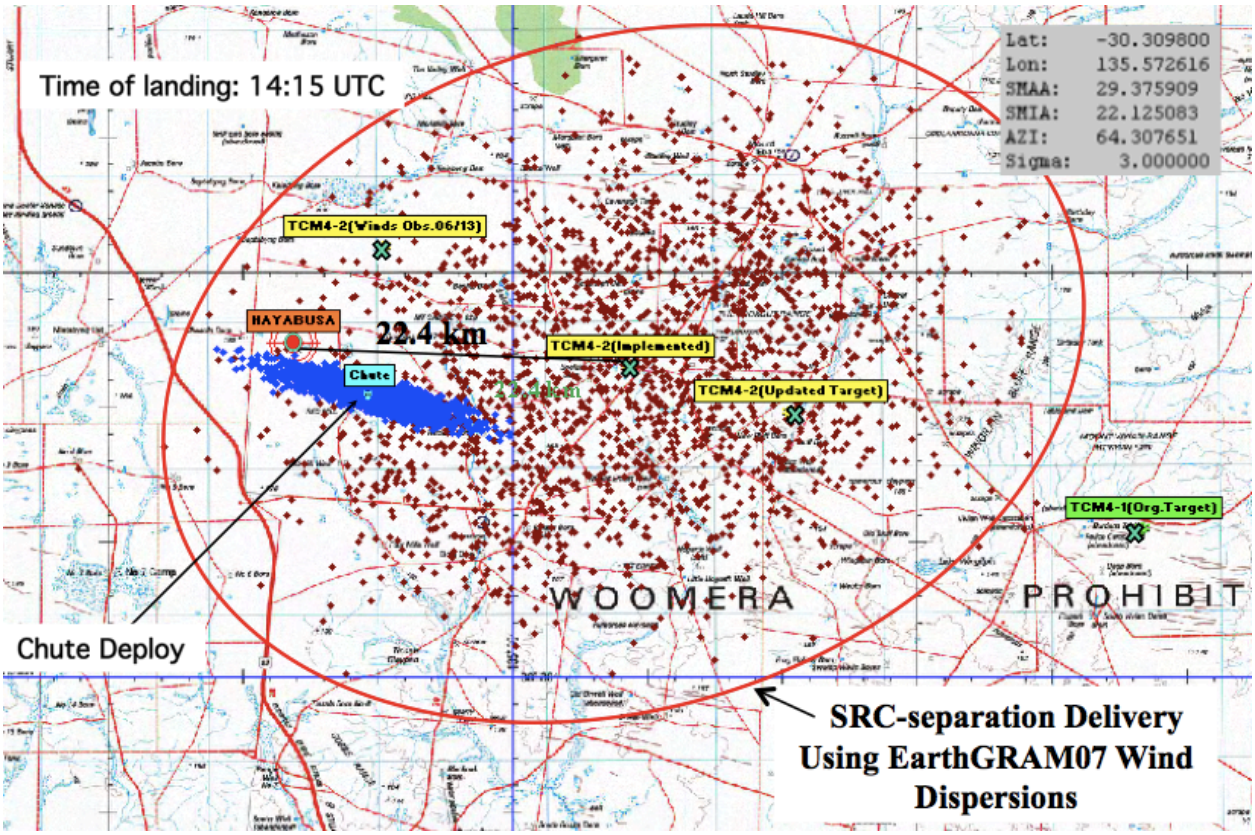

Figure 12: Predicted Ground Dispersions (3σ) & Reconstruction (units in km and º)

Figure 12 also shows the history of landing point targets. The original TCM-4 landing target is located furthest to the east. After TCM-3 concluded, that target was revised and moved to the point noted as 'Updated Target'. But that target turned out to exceed the capability of the IES (as better post-TCM-3 fixes of spacecraft state were obtained). So the final aim-point labeled 'Implemented Target' was established 10 km to the west (using the best information available on June 8).

The capsule missed the implemented target by 22 km (~2σ). It was recovered only 5 km from the geographical location directly beneath the chute-open point. Since the landing day was blustery, we suspect that gusts may be responsible for keeping the capsule / parachute in the vicinity of the chute-open coordinates. After touchdown, we

reconstructed the SRC descent and landing using measured winds. That model predicted a landing location only 8 km to the north of the recovery point at the marker labeled 'Winds Obs. 06/13' (< 1σ away from the final target).

5. Results and Comparisons

A. Reconstruction

Reconstruction of the OD for the inbound phase is shown in Tables 6 and 7. These tables show our best estimates of the miss of each TCM from the implemented target. The implemented target, however, was often not the final target, as JAXA usually re-targeted mid-way through each maneuver if conditions so warranted. This happened for TCM-0 and consequently the size of the miss was significant (see Table 6). For subsequent maneuvers each TCM was on-course to achieve sub-sigma accuracy, but for operational reasons the Project decided to terminate those maneuvers prematurely (leaving say, a several sigma miss from the nominal target). For this reason the miss vectors noted in the Tables are often multi-sigma.

Table 6: Orbit Determination Reconstruction

Mapped to Earth B-plane

June 13, 2010

Event	*Perigee Time [UTC]*	*Radius [km]*	*B.T [km]*	*B.R [km]*	*1σ Error SMiA, smia TOA*	*Miss from Target*	*DCO [UTC]*	*Comment*
End of Thrust Phase	13:35:43	17,774	29,574	6,516	±1,439 km ±381 km ±22.2 s	B.T = 296 km (0.2σ) B.R = -195 km (0.5σ) TOA = 20 s (0.9σ)	Mar 27 12:00	Error ellipse θ = 18°
TCM-0	13:54:53	10,115	20,451	5,142	±89 km ±79 km ±5.2 s	B.T = 2,016 km (22σ) B.R = 321 km (4σ) TOA = -127 s (25σ)	Apr 1 20:00	Error ellipse θ = 22°
TCM-1	14:33:12	9,611	19,322	6,690	±35 km ±15 km ±1.3 s	B.T = -53 km (1.5σ) B.R = -21 km (1.5σ) TOA = -5 s (4σ)	Apr 29 13:00	Error ellipse θ = 80°
TCM-2	14:01:33	6,986	16,379	4,104	±16 km ±9 km ±1.4 s	B.T = -19 km (1.2σ) B.R = 11 km (1.2σ) TOA = -5 s (3.4σ)	May 19 16:30	Error ellipse θ = 14°

Table 7: Orbit Determination Reconstruction

Mapped to Atmosphere Entry Time

June 13, 2010

Event	*Entry Time [UTC]*	*Entry Radius [km]*	*eFPA*	*Latitude*	*1σ Error eFPA, Lat, TOA*	*Miss from Target*	*DCO*
TCM-3	13:50:53.0	6,573.7	-12.82°	-26.92°	±0.055° ±0.036° ±1.1 s	eFPA = -0.02° (0.3σ) Lat = -0.03° (0.8σ) TOA = -1.1 s (1σ)	June 1, 12:00
TCM-4	13:51:11.3	6,573.7	-12.33°	-27.16°	±0.015° ±0.012° ±0.3 s	eFPA = -0.01° (0.7σ) Lat = -0.23° (20σ) TOA = -0.8 s (2.8σ)	June 8, 06:00
SRC atm entry	13:51:11.1	6,573.7	-12.32°	-27.15°	±0.004° ±0.002° ±0.1 s	eFPA = -0.02° (5σ) Lat = 0.04° (20σ) TOA = 0.05 s (0.5σ)	June 13, 10:50
Bus atm entry	13:51:11.9	6,573.7	-12.31°	-27.17°	±0.0004° ±0.0001° ±0.01 s	*N/A*	June 13, 13:13

To clarify, Tables 6 and 7 compare reconstructed results with the nominal (implemented) target. Note that TCMs usually were commanded to end early, thereby leaving a residual targeting error with respect to the implemented target. So agreement with prediction is not formally close for that reason (but for a low-thrust mission this is not a relevant metric in any case).

B. Comparison with Early Predictions

The nominal Approach Phase navigation plan prepared in advance did not hold up well. Power limitations, thruster failures, thruster under-performance, component failures, and thermal constraints: this list of anomalies all contributed to abandoning the nominal navigation strategy. New strategies evolved out of the old (e.g. Table 5).

Nevertheless despite the change in character of this mission over time, it is still instructive to examine how well the early error analyses performed as predictive tools. Those error analyses were statistical studies and calculated their predictions with respect to a reference trajectory. So this section answers the question: *How good were the predictions, statistically?*

Tables 8, 9, & 10 compare the predicted uncertainties with the formal Delivery uncertainties [4].

Table 8 compares OD uncertainties. The relative position of each TCM with respect to re-entry is noted in the table (e.g. "-85d" indicates 85 days from Entry). We note that the OD error analysis generally was conservative vis-à-vis results.

The predominant reason for the conservatism was the non-gravitational acceleration model (see the Appendix). Since spacecraft attitude control was expected to be unconventional (which it was), this conservatism in prediction was believed to be prudent. But in actual mission operations we found that the spacecraft was quiet and well behaved with respect to disturbance perturbations (perhaps because all significant sources of gas-leaks had already vented). A secondary reason for the significant improvement in OD knowledge was the greater availability of tracking data – more DSN passes were acquired than scheduled in the navigation plan. Therefore as a result of smaller perturbations and more observations, spacecraft state knowledge was well determined, with uncertainties smaller than predicted. For example, the OD delivery for TCM-3 exceeded *requirements* (also the prediction) by a factor of 3.

In the right-most column of Table 8 the linear flight time delivery error for TCM-2 is larger than TCM-1 whereas one would expect, in analogy with the predictions, that the number should be smaller. The TCM-2 delivery solution used a data arc with an epoch established before the time of TCM-1 (a strategy unlike the other four maneuver solutions). The inclusion of TCM-1's thrusting errors in the TCM-2 solution increased LFT error, contributing about 50% of the total LFT uncertainty.

Table 8: OD Error Assessment [km, s], 1σ

Prediction for Delivery	*Predicted B.R*	*Predicted B.T*	*Predicted LFT*	*Delivery*	*B.R*	*B.T*	*LFT*
TCM-0 (-85d)	±169	±509	±17	TCM-0 (-71d)	±80	±87	±5.6
TCM-1 (-43d)	±53	±73	±8.9	TCM-1 (-43d)	±29	±14	±1.2
TCM-2 (-22d)	±25	±26	±4.3	TCM-2 (-22d)	±16	±9.0	±1.4
TCM-3 (-10d)	±9.1	±8.8	±1.6	TCM-3 (-10d)	±2.7	±3.3	±0.3
TCM-4 (-4d)	±3.7	±3.6	±0.6	TCM-4 (-4d)	±1.1	±0.7	±0.1
Separation (-3h)	±0.2	±0.3	±0.01	Separation (-3h)	±0.15	±0.25	±0.03

A similar summary for maneuvers is shown in Table 9. As in Table 8, Table 9 compares predicted magnitudes (derived from the nominal OD listed on the left side of Table 8) with implemented magnitudes. The predicted

versus implemented comparison is stark of course and illustrates the significant deviation from the *a priori* navigation plan that the flight team needed to respond to during the final months of the mission. The statistical analysis in the navigation plan did not anticipate all the limitations and novelties encountered in the Approach Phase. TCMs 0, 1, and 2 were modeled as small, statistical maneuvers, but in flight operations they became large, deterministic maneuvers. TCM-3 was modeled as a deterministic maneuver all along, but it almost tripled in size when implemented. Thus even though OD uncertainties improved with respect to predictions, that improvement was insignificant because the implemented flight path corrections introduced large execution errors.

Table 9: Maneuver Performance Assessment [m/s], 1σ

Maneuver	*Predicted Mean Magnitude*	*Reconstructed Magnitude*
TCM-0	0.081 ±0.002	2.07
TCM-1	0.37 ±0.20	3.38
TCM-2	0.033 ±0.016	5.07
TCM-3	1.15 ±0.03	2.75
TCM-4	0.43 ±0.05	0.14
TOTAL	2.09 ±0.21	13.41

In contrast, knowledge of the entry flight path angle shows good agreement with the pre-arrival error analyses, even though the actual flight path into the atmosphere ended up differing in entry angle from the nominal by 2%. The proximity of the probe to Earth yields a strong gravity signature in the observables, and this led to accurate predictions at the atmosphere entry-interface.

Table 10: Atmosphere Entry Error Assessment, Altitude=200 km, 1σ

Event	*Predicted eFPA*	*Predicted eV*	*Del'vd eFPA*	*Del'vd eV*
	±12.55°	11.650 km/s		12.036 km/s
Post-TCM-3	±0.05°	±8 m/s	±0.06°	±8 m/s
Post-TCM-4	±0.01°	±2 m/s	±0.02°	±2 m/s
Post-separation	±0.003°	±0.3 m/s	±0.004°	±0.4 m/s

6. Summary

This single paper cannot do justice to the combined navigation efforts of JAXA and JPL. JPL's contribution is highlighted here, but JAXA has all the skills necessary to perform interplanetary navigation, as shown by this very mission. The JAXA spacecraft operators persevered against great odds and their repeated rescues of Hayabusa are testament to their accomplishments.

However JAXA does lack the systematic distribution of ground stations necessary for satisfactory control of deep space missions (or indeed, Earth-return missions). For this reason the Hayabusa Project turned to JPL and DSN to augment their capabilities. Adding the JPL-DSN combination gave the Project greater control and insight during critical mission phases. Furthermore with this partnership the Hayabusa Project demonstrated that international collaborations with NASA are workable (as others have) and in fact are becoming more common.

Orbit determination analyses performed by JPL had shown, in advance, that navigation requirements could be met and the capsule successfully returned to Earth. Actual performance however, exceeded predictions. As each multi-day TCM progressed, JPL-DSN supplied JAXA with necessary maneuver performance data in real-time. And JPL accurately predicted the atmosphere entry-time and landing site of the sample return capsule in the Australian outback. The capsule chute-open location (at 10 km altitude) was within 1σ of prediction. In the troposphere, contrary winds-aloft (blowing from the east instead of the usual west) carried the parachute away from the target; the capsule and parachute came to rest about 2.5σ from the predicted landing point. The capsule was recovered visually by helicopter within 30 minutes of touchdown.

The spacecraft bus followed the capsule into the atmosphere, reaching the entry-interface altitude about 1 second later although along a different flight path. The bus burned up in the atmosphere without compromising the capsule. The breakup of the bus was captured on film and can be viewed at the sites noted at the end of this line [5,6].

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Appendix: OD Filter Configuration

Error Source	Estimated?	*A Priori* Uncertainty (1σ)	Correlation Time	Update Time	Comments/References
DSN 2-way doppler (mm/s)		0.5			X-band. (Also acquire 3-way when avail.)
Usuda 2-way dopplr (mm/s)		1			X-band
DSN range (m)		2			X-band
Usuda range (m)		20			X-band
ΔDOR measurements (ns)		~2			Uses 2-way range lobes instead of tones
Epoch state					
Position (km)	√	10,000	–	–	
Velocity (km/s)	√	1	–	–	
Range bias (m)	√	4, 50	0	per pass	4 m for DSN, 50 m for Usuda
Doppler bias (mm/s)	√	0.1	–	per pass	only estimated for Usuda
Quasar position (nrad)	–	2, 2	–	–	Ra, Dec
Earth ephemerides & GM	–	DE403	–	–	Standard DE403 covariance
Station locations (cm)	–	3	–	–	Usuda errors are 5-10X larger
Pole X, Y (cm)	–	10	–	–	~15 nanoradian for pole, ~0.2 ms for UT
UT1 (cm)	–	10	–	–	
Ionosphere – day,night (cm)	–	75, 15	–	–	Media cals applied by respective agencies. Ion errors applied to all data; trop errors applied only to DSN data.
Troposphere – wet,dry (cm)	–	4, 1	–	–	
Solar pressure					Bus model. Area = 12.2 m^2
G_r	√	0.25	–	–	Radial component. Nominal = 1.2
Thrusting / Turning Events					
TCMs (thrust, ra, dec)	√	1%, 1°, 1°	–	–	TCMs are performed with the IES (thrust=7 mN). Attitude changes, spin-up/down are performed with xenon cold-gas jets. Velocity errors are wrt EME2000. Acceleration error is spherical, also wrt EME2000. (An acceleration term is estimated, but the bias is assumed to be 0.)
Slews (mm/s)	√	0.2, 0.2, 0.2	–	–	
Turn to sep att. (mm/s)	√	1, 1, 1	–	–	
Spin-up/down (mm/s)	√	1, 1, 1	–	–	
SRC-release (mm/s)	√	15, 1, 14	–	–	
	–		–	–	
Non-gravitational accelerations (km/s^2)	√	1.0×10^{-11}	0	30 min	