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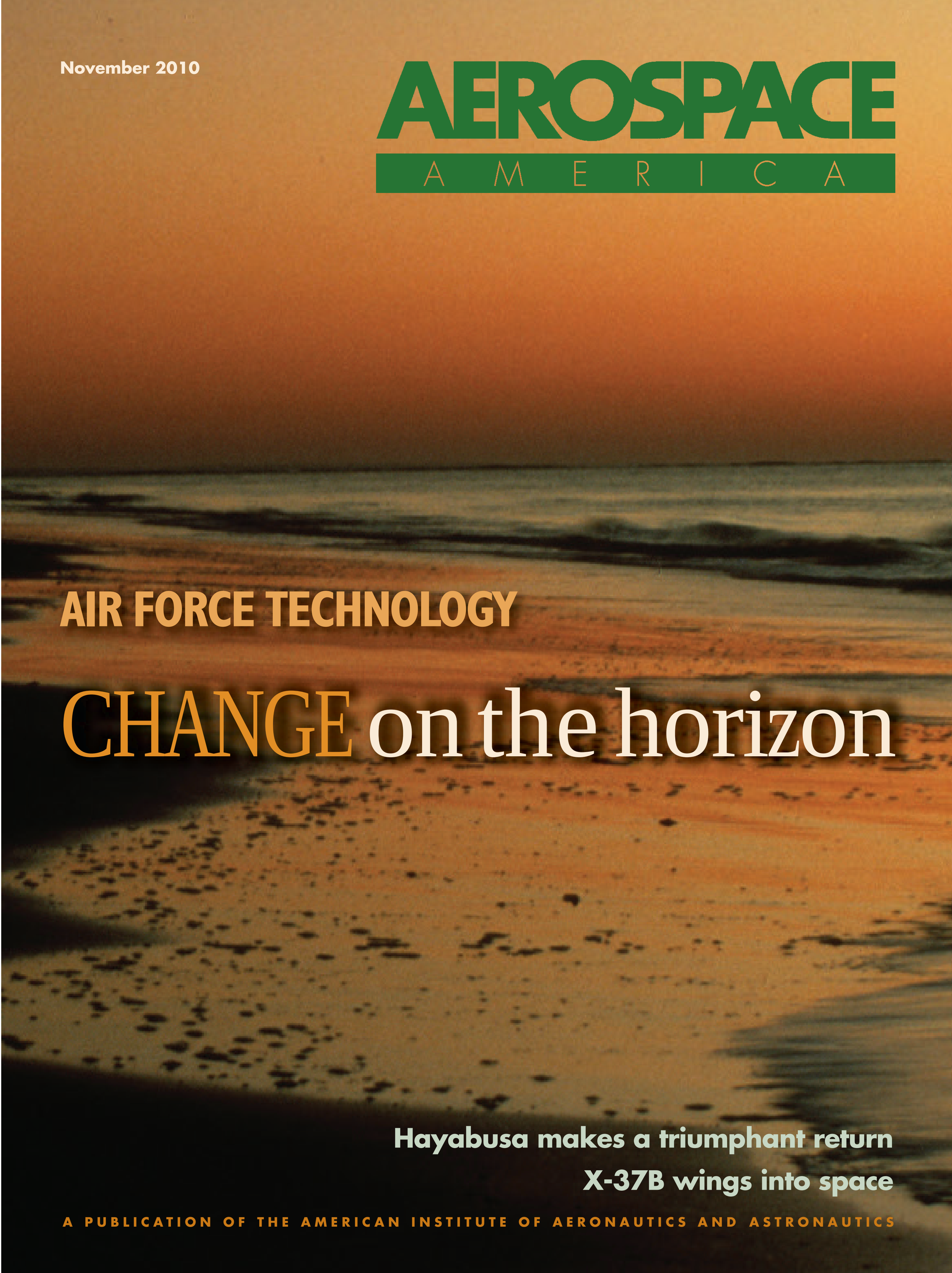

AIR FORCE TECHNOLOGY

CHANGE on the horizon

Hayabusa makes a triumphant return

X-37B wings into space

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Hayabusa makes a triumphant return

On its mission to an asteroid, Japan's Hayabusa spacecraft was plagued with malfunctions and delays. But the creativity and persistence of the program's science team brought the crippled vehicle back to a flawless reentry, including the successful delivery of a payload that may yet hold major surprises.

On June 13, the Japan Aerospace Exploration Agency's (JAXA) Hayabusa spacecraft completed its 6-billion-km round-trip mission to an asteroid. In many ways, its journey could be viewed as a robotic equivalent of Apollo 13: In both cases, ground control teams and onboard intelligence triumphed over seemingly insurmountable odds, overcoming a multitude of technical snafus to return a crippled spacecraft to Earth.

The Japanese probe truly became the little interplanetary spacecraft that could…and dutifully did. During its long voyage through deep space, reaction wheels used to stabilize its attitude failed; its chemical engine suffered a fuel leak; communications with Earth were lost for weeks; and repeated problems plagued its ion engine propulsion system.

A few months after Hayabusa's 2003 launch, even its solar panels were degraded slightly by a solar flare, reducing the amount of electricity received by the craft's ion engine.

At a cost of $200 million, the Hayabusa program focused on wringing out new hardware and testing ion propulsion, autonomous navigation, sampler, and reentry capsule concepts. But the craft was much more than a flying testbed. When its return sample canister parachuted down into the Australian Outback after its seven-year journey, Hayabusa was hailed as an icon of scientific curiosity and sheer persistence.

Sampling a rock of ages

The asteroid mission began to take shape in the mid-1980s, spurred by studies at Japan's Institute of Space and Astronautical Science (ISAS), now part of JAXA.

JAXA launched Hayabusa from Kagoshima Space Center aboard an M-V rocket on May 9, 2003. A swing-by of the Earth in May 2004 accelerated the craft, which reached its target—asteroid 25143 Itokawa—on Sept. 12, 2005, after traveling about 2 billion km. In September and October of that year, Hayabusa completed its remote sensing tasks and measurements of the asteroid. The following month it made back-to-back touchdowns in an effort to sample the rock and deliver the specimens to Earth.

Itokawa was discovered in 1998 by the LINEAR (Lincoln near-Earth asteroid research) program, an effort conducted by MIT's Lincoln Laboratory with funding from the Air Force and NASA. The asteroid received the provisional designation 1998 SF36. In 2000, it was officially named after Hideo Itokawa, a professor who had died the previous year. Af-

Sharp-shooting cameras on Hayabusa provided impressive close-up views of asteroid Itokawa. Credit: JAXA/ISAS.

fectionately known as "Dr. Rocket" in Japan, he had played a seminal role in the early stages of the country's space program.

Asteroid Itokawa is a potato-shaped object about 600 m long, classed as an S-type—of siliceous, or stony, composition. Asteroids are believed to be celestial time capsules that retain information from the beginning of the solar system's formation. Bringing a sample of the space rock back to Earth for laboratory study could yield precious clues for piecing together information on the origin and evolution of the solar system.

After liftoff the mission's name was changed from MUSES-C to Hayabusa, Japanese for "peregrine falcon." Propelling the craft were four xenon-fed ion engines. The xenon ions were generated by microwave electron cyclotron resonance and accelerated in an electric field. For its acceleration grid, the unique system used a carbon/carbon composite material resistant to erosion.

The ion engine array also featured neutralizers designed to turn the high-speed jetted ions into electrically neutral plasmas. If the spacecraft were to keep injecting positively charged ions, it would become negatively charged and attract positive ions. That would prevent Hayabusa from being propelled forward; hence the need for neutralizers.

"The Hayabusa can be called a 'high-tech spaceship,' as its key technologies—a plasma reactor that supports cutting-edge industries, robot technology with visibility, development of heat resistance, and power-saving technology—are expected to be applied to various other fields," says Hayabusa project manager Junichiro Kawaguchi.

Hayabusa's September reentry was celebrated at Operations Center 2. Credit: JAXA/ISAS.

Touchdown!

Asteroid rendezvous took place in September 2005. When Hayabusa arrived at a point 20 km from Itokawa, a reflective target marker was dispatched to the surface to assist in the spacecraft's descent. Although Hayabusa had an autonomous navigation system, the marker was used to gauge the speed of the spacecraft's horizontal movement as it landed.

Later that year, Hayabusa succeeded in making two touchdowns on the asteroid, one on November 20 and another on November 26, in efforts to use the sampling gear.

by Leonard David
Contributing writer

On that first landing, the craft touched the asteroid's surface, bounced twice, and came to rest in one place for 30 min. On the second touchdown, the tip of the craft's sampling unit was able to contact the asteroid's surface for about one second, after which the spacecraft made an immediate ascent. Experts believe that in both cases the sampling equipment, which involved firing pellets into the asteroid's surface, did not function as planned. However, it is possible that the speed of the spacecraft's contact with Itokawa stirred up the scene, with particles of the asteroid perhaps finding their way into the collection unit.

Although trouble-plagued, Hayabusa did chalk up a milestone, performing the first ascent from any other solar system body except the Moon.

Overall, the road to and from asteroid Itokawa was fraught with difficulty, says Hitoshi Kuninaka, group leader for spacecraft systems at JAXA's Space Exploration Center. Because of Hayabusa's equipment failures, its return to Earth was deferred by three years from the original date of 2007.

The craft had innumerable problems with its solar arrays, ion engines, lithium-ion battery cells, and attitude-controlling reaction wheels, encountering several delays and losses of communication. For example, in departing the asteroid after its second landing, Hayabusa suffered a fuel leak from its reaction control system. As the escaping fuel turned to gas and shot out into space, the spacecraft lost attitude and its antenna lock on Earth. The resulting communications link loss, although temporary, lasted more than seven weeks.

Homeward bound

Hayabusa literally limped back to Earth, with the very weak pressure of sunlight helping it to regain attitude control. Adding to the misery of ground operators, the probe's ion engines made an irregular stop in late 2009. A final workaround involved the "cross-operation" of previously separate pairs of neutralizers and thrusters. "By using this method, we generated thrust and managed to guide Hayabusa to Earth," Kuninaka says.

This cobbled-together attitude stabilization method—using a single reaction wheel, the ion beam jets, and photon pressure—enabled Hayabusa to struggle homeward.

"Hayabusa had enough redundancy, but some of that redundancy was developed after the malfunction," says Kuninaka, "including the improvement of onboard software and the ground support system."

In April and early June of this year, Hayabusa performed delicate trajectory correction maneuvers to prepare for receiving precision guidance into the designated Australian landing zone. A team of Japanese and U.S. navigators directed the spacecraft on the last leg of its expedition. They calculated the final trajectory correction maneuvers the ion propulsion system would have to perform to ensure a triumphant homecoming.

Import from outer space

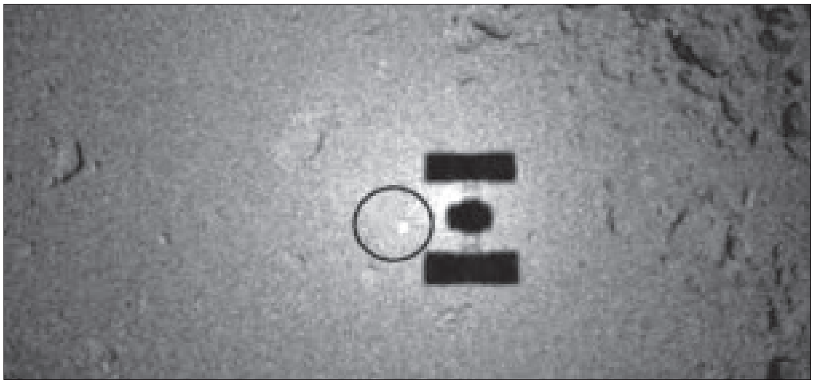
Three hours before Hayabusa's reentry into the Earth's atmosphere, the sample return capsule was to separate from the mothership. A specially developed heat shield protected the 40-cm capsule from blistering temperatures of 10,000-20,000 C. The shield, fabricated in-house, used two main ingredients: carbon-fiber-reinforced plastic and carbon phenolic resin.

At an altitude of roughly 10 km, a pyrotechnic mechanism in the capsule triggered the jettisoning of both the heat shield and a lid from the sample return capsule. The two pieces of the heat shield then fell to Earth separately as a parachute was deployed by the capsule to slow its plummet into the Woomera Prohibited Area test range. The capsule's location was tracked using radar and a radio beacon onboard the returning canister.

JAXA had to do some legal paperwork to enable its foreign-made hardware to drop in on Australia. Hayabusa was an import, not just from Japan but from outer space as well. Furthermore, the Australian government had concerns about introducing possible contaminants reminiscent of the fictional "andromeda strain" of book and movie fame.

Japan obtained import consent via the Authorized Return of Overseas Launched Space Object from the Space Licensing and Safety Office of the Australian government.

Hovering above Itokawa, Hayabusa casts a shadow on the asteroid. The bright dot is a deployed marker to aid the probe's landing on the space rock's surface. Credit: JAXA/ISAS.



Hayabusa's June 13 reentry was closely watched by a NASA-sponsored Hayabusa Reentry Airborne Observing Campaign. An international lineup of scientists on board the agency's instrument-packed DC-8 Airborne Laboratory recorded the entry of the spacecraft bus and capsule.

Flying at 39,000 ft in a race-track pattern some distance from the capsule's anticipated touchdown ellipse, researchers used a clutch of gear and instruments mounted to aircraft windows—spectrographs and several types of cameras: high-definition TV, high-frame-rate, intensified, and near-infrared-sensitive—to snare the light from the capsule, now a speeding fireball, during its swift reentry.

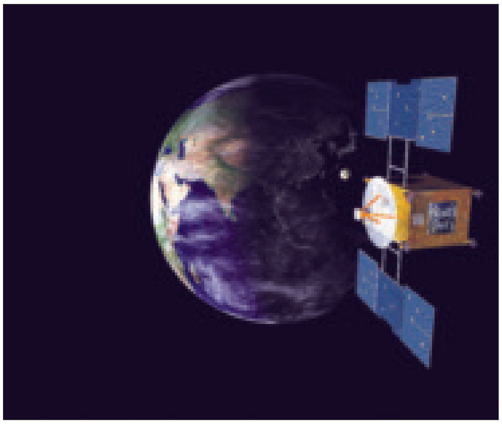
"It couldn't have been better," notes SETI Institute's Peter Jenniskens, principal investigator of the Hayabusa observing campaign. "Everyone had put so much energy and effort into pulling it all together. It was nerve-wracking—there were so many worries."

"Awe-inspiring and jaw-dropping“

Jenniskens has a habit of being in the right place at the right time for watching human-made meteors. He ran a similar airborne campaign for NASA's Stardust sample return capsule entry in January 2006 and took part in observing the September 2004 Genesis spacecraft reentry. In September 2008 he was a principal investigator for the joint ESA/NASA multiinstrument aircraft campaign that monitored the controlled destructive reentry of Europe's 13-ton automated transfer vehicle, the Jules Verne, over the South Pacific.

More than a year of planning for Hayabusa's nosedive to Earth came down to just 40 seconds, Jenniskens recalls. There were many uncertainties: Would the capsule be isolated from the main spacecraft's breakup? How bright were things going to be? Would the intense light from the spacecraft bus demolition swamp the return capsule itself?

At the appointed time, Hayabusa sped its way toward terra firma at well over 26,000 mph. "When the event actually happened, we immediately recognized that the thing moving ahead of everything, and a little bit below it, must be the capsule," Jenniskens says. "It was just phenomenal. It was awe-inspiring and jaw-dropping…just to see this whole capsule sitting there and seeing all this stuff going on around it—and then it survives."



An artist's view depicts the return of Hayabusa and the release of its sample capsule toward Earth. Credit: C. Waste and T. Thompson, courtesy NASA/JPL-Caltech.

The airborne campaign gathered a beautiful set of data, says Jenniskens. The reentry was rich in phenomena, with numerous bus pieces ejected at very high speeds and surprisingly high angles. Spectroscopic features were identified, including the moment when the lithium batteries were destroyed.

"We're using the colors of the flares, the types of signatures, to potentially reconstruct the breakup process. Of course, all this is going to take time. We have a whole mountain of data to face," Jenniskens notes. The information is potentially a bonanza, particularly for understanding the intense breakup process, to ensure safety on the ground in the case of a deliberate reentry. Similarly, studies of the high-speed fall of the 18-kg return capsule might lead to lighter thermal protection systems or aid in validating computer models.

Hopeful signs

In early October, there was heightened excitement by officials at JAXA. Analysis of the tiny contents within the Hayabusa sample capsule may indeed be particles of the visited space rock. According to researchers, some 100 rocky particles have been detected, apparently diverse in composition.

While JAXA officials remain cautiously optimistic, more analysis of the materials is needed. The extremely tiny bits will undergo further inspection at SPring-8, a large synchrotron radiation facility located in Harima Science Park City, Hyogo Prefecture, Japan. SPring-8 derives its name from super photon ring-8 GeV, with 8 giga-electron volts, being the power output of the ring.

Given this powerful tool, scientists hope to determine whether microbits of the asteroid were captured by Hayabusa—or if they are bits of Earthly contamination.

"It's surprising how difficult it is to predict how the mechanical and thermal stresses actually work out on these breakups. Our observations, in a way, give ground truth to what really goes on," he concludes.

Right on time, right on target

Shooting ahead of the debris field in the tumultuous breakup of the Hayabusa bus, the thermally protected return capsule continued on its path toward the target ellipse.

Ground observation equipment was set up to record Hayabusa's plunge. Three opti-

Hayabusa's scientific sleuthing

Hayabusa weighed 510 kg at launch, toting into space a tightly packaged suite of scientific instruments:

- *A wide-view and a telescopic camera for imaging Itokawa in multiple spectral bands to determine its shape and surface features and to map mineral distributions.*
- *A near-infrared spectrometer to determine the distribution and abundance of the asteroid's surface minerals.*
- *A laser altimeter for measuring the range to the asteroid's surface, to build up high-resolution topographic profiles and provide both an accurate spacecraft position and a global shape model.*
- *An X-ray fluorescence spectrometer to determine the chemical composition of surface materials.*

Hayabusa also contained a small surface hopper called MINERVA, short for micro/nano experimental robot vehicle for asteroid. Japan's first planetary exploration rover, MINERVA was built to move around on the asteroid autonomously, hopping about from spot to spot taking surface temperature measurements and churning out high-resolution images with each of its three miniature cameras.

In addition, Hayabusa carried a deployable target marker covered with a reflective coating. When illuminated by a flash of light from Hayabusa, the marker served as a lighthouse to guide the vehicle's descent onto the asteroid. To prevent the marker from bouncing off the asteroid because of the low gravity there, the device was filled with beads of polyimide resin—bean bag style—to dissipate energy as it contacted Itokawa's surface. The marker also contained 880,000 names from 149 countries around the world.

The "business end" of Hayabusa was essentially a sampler horn, a 1-m-long cylindrical tube projecting from underneath the spacecraft. When a sampler mechanism makes contact with an asteroid, a pellet is fired to fracture the object's surface. The anticipated result is that bits and pieces of the asteroid spew up into the sampler horn's interior. The sample-catcher is then inserted into the recovery capsule, followed by a lid-closure operation that includes latching and sealing the lid.

All in all, a creative way to snag specimens, given the gravity on asteroid Itokawa: less than 1/100,000th that on Earth.

cal stations were installed near the prohibited area to profile the capsule's ablating thermal protection system. Infrasound and seismic sensors were installed on four stations to detect atmospheric shock waves emitted from the incoming capsule. The return capsule itself deployed a parachute that provided high reflectivity for radar signals and a radio responder to locate it within desert brush.

"It's kind of weird. You've worked on this mission for so long. Then all of a sudden you realize, holy cow, this thing is coming back," says Paul Abell, a planetary scientist from NASA Johnson and a member of the Hayabusa science team. Abell was one of four individuals who served on a contingency ground recovery team. "We were there in case there was an off-nominal return, the parachute didn't work…[or] the beacon didn't activate," he explains.

As they traipsed to a nighttime position in the Australian Outback at around 10:30 p.m., Abell recalls, the skies were perfect, with no Moon and no clouds. "The atmosphere was electric. Then, right on target, right on time, we saw it come in…both the mothership and the capsule. We knew we were in a recovery situation. The fireworks were spectacular.… like Roman candles," he says.

Lessons learned

The Hayabusa mission, Abell believes, offers important lessons: Never give up on a situation, and always come up with innovative ideas for handling certain failures. "The Japanese have shown that, if you are flexible and resilient, you can do a lot of things with a modest spacecraft—even in dire situations," he points out.

Abell stresses the huge importance of international cooperation by Japan, Australia, and the U.S. in bringing about Hayabusa's success. Having those lines of communication open early in a program is vital. Being flexible and preparing for just-in-case contingencies is an important take-home message, he says.

"Yes, Hayabusa was a technology demonstration, but the science it returned is absolutely huge, everything we learned about

The recovery team in Woomera, Australia, inspects Hayabusa's sample return capsule after its-seven year voyage to and from asteroid Itokawa. Credit: JAXA/ISAS.

the asteroid.…It has changed our whole way of thinking about these small objects…how they are put together, their internal structure, the nature of rubble-pile asteroids," Abell says. "It was the experience of a lifetime. The Japanese should be absolutely thrilled."

Tiny specks in a big container

Recovery teams located not only the reentry capsule but also the two parts of the heat shield cast off during the descent. The capsule, with its parachute, landed less than 1 km from the predicted touchdown point.

In early July, JAXA announced that tiny particles had been found in the sample container. This was confirmed by specialists at the agency's Sagamihara Campus, where Hayabusa's collection hardware was brought and opened. But they could not be certain whether the particles were from Itokawa or from Earth. Detailed and painstaking scrutiny would be needed to discern the true origin of the specks.

The curation center at the Sagamihara Campus was built to provide tremendous flexibility in handling extraterrestrial samples. There the capsule was first inspected in detail; it was then opened in a laboratory clean room. Specialists at the JAXA sample curatorial facility are performing a preliminary cataloging and analysis of the capsule's contents. Assisting the Japanese astromaterials experts are scientists from NASA and Australia.

"They've done their homework," says Carlton Allen, head of the Astromaterials Acquisition and Curation Office at NASA Johnson's ARES (Astromaterials Research and Exploration Science) Directorate.

Allen visited the Hayabusa curatorial lab about a month before the capsule's return to Earth. He and other NASA officials had interacted with the Hayabusa curatorial team for years as they built the facility and honed their skills in using it. "They had a spacecraft in unknown condition, possibly damaged, but they wanted to preserve as much science as they possibly could," Allen tells *Aerospace America*. "So they wanted to build a lab where they could work with something that might be damaged, dented, partially broken…and if everything worked, they could responsibly test and curate the samples."

Early indications are that the sample container seals held. "If they cleaned it well before launch and the seals held, whatever is in there should be from the asteroid," Allen says.

At Sagamihara, scientists are dealing with microscopic dust grains in a big container. To study the material, they have developed a very imaginative and novel system that uses electrostatic forces to pick up and transfer individual dust grains, he says.

"We're going to buy a copy of that system and test it out in our labs," adds Allen, who sees it as another tool for handling extraterrestrial samples in the future.

How daunting is the study of ultrasmall particles such as those possibly brought back to Earth by Hayabusa?

"We've known from our cosmic dust collection—and more recently from the Stardust mission—how to deal with particles of this size, to subdivide them, and then slice them up into lots of different samples that can be sent all around the world," Allen says. "Small particles are not a problem. [Working with] them is not easy, but we know how to do it."

Follow-on activities

Michael Zolensky is one of two NASA scientists engaged in examining the specimens. He is the agency's curator of stratospheric dust and also works in the ARES directorate at NASA Johnson.

Zolensky believes that, despite the spacecraft's sampling difficulties, the landing itself may well have coated the inside of the collection equipment with dust from Itokawa. If so, the captured microscopic grains of asteroidal material would, indeed, speak volumes.

"Hayabusa is probably going to return less than a gram of sample, at the most a few grams…possibly much less than that," Zolensky says. Nevertheless, an incredible number of things can be done with even a sample that tiny, he adds.

A team of scientists, most of them from Japan, will study the samples for a year and then release them to "anyone on the planet who is qualified to study them," says Zolensky.

Because of Hayabusa's success, JAXA has received a thumbs-up to conduct preliminary design work on Hayabusa 2. This time the target will be 1999 JU3, a C-type (carbonaceous) asteroid.

Hayabusa's achievement has also resulted in a collaboration by Japan's NEC and U.S.-based Aerojet-General. The two companies will work together on a new ion engine technology aimed at the lucrative communication and broadcast satellite market.

In summing up Hayabusa's mission, NASA's Abell says, "It was just amazing how everything came together. [The team] should be very proud of their accomplishments. It was a tremendous effort on their part…absolutely stunning."

The spacecraft reached asteroid Itokawa on September 12, 2005, after a journey of roughly 2 billion km. The asteroid is about 600 m long and of siliceous, or stony, composition.