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Hayabusa2 Sampler: Collection of Asteroidal Surface Material

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Abstract Japan Aerospace Exploration Agency (JAXA) launched the asteroid exploration probe "Hayabusa2" in December 3rd, 2014, following the 1st Hayabusa mission. With technological and scientific improvements from the Hayabusa probe, we plan to visit the C-type asteroid 162137 Ryugu (1999 JU3), and to sample surface materials of the C-type asteroid that is likely to be different from the S-type asteroid Itokawa and contain more pristine materials, including organic matter and/or hydrated minerals, than S-type asteroids. We developed the Hayabusa2 sampler to collect a minimum of 100 mg of surface samples including several mm-sized particles at three surface locations without any severe terrestrial contamination. The basic configuration of the sampler design is mainly as same as the 1st Hayabusa (Yano et al. in Science, 312(5778):1350–1353, 2006), with several minor but important modifications based on lessons learned from the Hayabusa to fulfill the scientific requirements and to raise the scientific value of the returned samples.

In this paper, we will report the details of the sampling system of Hayabusa2 with results of performance tests during the development and the current status of the sampling system.

Keywords Hayabusa2 · Sample return mission · Sampler · Ryugu

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1 Introduction

The first asteroidal returned samples collected by the Hayabusa spacecraft from the near-Earth S-type asteroid (25143) Itokawa were the first direct evidence showing that ordinary chondrites, the most common meteorites recovered on the Earth, came from S-type asteroids (Nakamura et al. 2011; Ebihara et al. 2011; Yurimoto et al. 2011). Detailed analysis of Itokawa surface particles revealed the long history of the asteroid from thermal processes in its parent asteroid to the current geological activity (Nakamura et al. 2011, 2012; Ebihara et al. 2011; Yurimoto et al. 2011; Tsuchiyama et al. 2011; Noguchi et al. 2011; Nagao et al. 2011).

Following the Hayabusa's successful return, the Japanese Aerospace Exploration Agency (JAXA) launched another asteroid mission Hayabusa2 to return samples from a near-Earth asteroid 162137 Ryugu (1999 JU3) on December 3, 2014. The target asteroid Ryugu is a C-type near-Earth asteroid with the low albedo of ∼0.06–0.07 (e.g., Vilas 2008; Hasegawa et al. 2008; Lazzaro et al. 2013; Pinilla-Alonso et al. 2013). The C-type asteroids show reflectance spectra similar to carbonaceous chondrites, one of the chemical clans of primitive meteorites. In contrast to other chemical clans of chondrites, many carbonaceous chondrites were not severely heated in their parent bodies, and contain larger amounts of hydrous minerals that formed in the presence of water and carbon as organic compounds than other chondrites. The C-type asteroids are thus highly likely to record the history of the solar system from the beginning to planet formation including the subsequent supply of volatiles to the terrestrial planets.

With detailed on-site remote-sensing observation and thorough investigation of the samples from Ryugu, the Hayabusa2 mission aims at investigating (1) evolution from planetesimal to a near-Earth asteroid (thermal processes in a planetesimal in the early solar system; heating and space-weathering on the surface of near-Earth asteroid at its current orbit), (2) potential destruction and accumulation of a rubble pile body that formed from a larger aqueously-altered parent planetesimal (planetesimal formation; impact processes throughout the solar system history), (3) diversification of organic materials through interactions with minerals and water in planetesimal (origin and evolution of volatile components in the early solar system; final state of organic matter and water prior to their delivery to rocky planets), and (4) chemical heterogeneity in the early solar system (mixing of high-temperature and low-temperature components during dynamical evolution of the protosolar disk) (e.g., Tachibana et al. 2014).

Hayabusa2 will arrive at Ryugu in mid-2018, and fully investigate and sample the asteroid multiple times during its 18-month stay. The spacecraft will depart the asteroid in late 2019, and return to Earth with samples in December 2020. In this paper and an accompanying paper (Okazaki et al. 2016), we describe the details of the Hayabusa2 sampling system (Hayabusa2 sampler hereafter) that was designed and developed accomplish the scientific goals of the mission. The scientific rationale for sample-return from primitive carbonaceous asteroid and scientific themes of analysis of samples returned from Ryugu are addressed by Tachibana et al. (2014) in detail.

2 Science Requirement of the Hayabusa2 Sampler

The investigation of the long evolution history of the solar system from the presolar epoch to the current geological activity of the near-Earth asteroid is the main target of sample analysis (Tachibana et al. 2014): (1) Galactic chemical evolution and Sun's parent molecular cloud chemistry, (2) Pre-accretional chemical evolution and planetesimal formation in the protosolar disk, (3) Properties of the parent planetesimal of Ryugu and the final evolutional stage of water and organic matter, (4) Geological evolution of asteroid in the solar system, and (5) Orbital evolution and surface geological processes of near-Earth asteroid.

Recent analytical techniques allow us to analyze small amounts of samples as in the case of 100 micron-sized Itokawa samples (Nakamura et al. 2011, 2012; Yurimoto et al. 2011; Ebihara et al. 2011; Noguchi et al. 2011; Tsuchiyama et al. 2011; Nagao et al. 2011). Although the required amount will be reduced further in 2020s, in order to obtain the typical and/or average feature of Ryugu, a minimum of 100 mg of surface samples including several mm-sized particles are required to fulfill the scientific goals above assuming that the samples are similar to hydrated carbonaceous chondrites. Details of scientific and analytical objectives of 100-mg of Ryugu samples are summarized in Tachibana et al. (2014).

It is also required to sample the surface materials at multiple locations with different geological features and to preserve them separately in a sample container in order to understand the geological evolution of the asteroid, which also leads to better understanding of the processes prior to the planetesimal formation and of the recent processes as a near-Earth object. Thermal effects during sampling must be minimal in order to avoid decomposition of hydrated silicates, loss of volatile components, and melting of samples.

The 1st Hayabusa sample catcher contained carbon-rich particles and inorganic particles as contaminants (Uesugi et al. 2014; Ito et al. 2014; Yabuta et al. 2014; Yada et al. 2014). Based on lessons learned from the Hayabusa mission, contamination to the Hayabusa2 samples is required to be minimal and any possible contamination must be recognized in advance. The sample container should be easier to be handled during the sample curation operation than the Hayabusa sample container to reduce the curation work and ensure fast initial analyses of the returned samples.

3 Sampling Operation

Touch-down operation for sampling will be made at the surface location without 50-cm sized or larger boulders and with the local surface angle of $<30°$ for safety. In the initial descent phase down to the altitude of 50 m, the horizontal position and velocity is controlled from the ground station using surface images taken by on-board cameras, that is, optical navigation camera telescope type (ONC-T) and that of wide angle type (ONC-W1), and the vertical velocity is controlled in the range of 0.1–1 m/s on board by using a laser altimeter (LIDAR). A target marker (TM) is deployed at the altitude of 50 m, and the further descent is in fully autonomous mode (Ogawa et al. 2012; Terui et al. 2016). The spacecraft tracks the TM that reflects light from an on-board flash lamp using ONC-W1. Then, LIDAR is switched to the laser range finder with four laser beams (LRF-S1) to measure altitude and determine the surface orientation relative to the spacecraft below the altitude of 40 m, and the spacecraft aligns its position to the local touch-down area (Kubota et al. 2006). After a free fall for the final 15-m descent, Hayabusa2 collects sample using the sampler system and the sampler horn that applies the same projectile method as that of 1st Hayabusa. The projectile is shot for sampling, which is triggered by the detection of the bending of the sampler horn detected by another short-range laser range finder (LRF-S2). The escape operation for ascent is followed after the projectile shooting. The touch-down with a single TM will be conducted with an uncertainty of several tens of meters. In the third touch-down planned after the impact experiment using the Small Carry-on Impactor (SCI) (Saiki et al. 2013), the uncertainty will be reduced down to several meters with three TMs. Figure 1 shows an exterior of Hayabusa2 and its components.

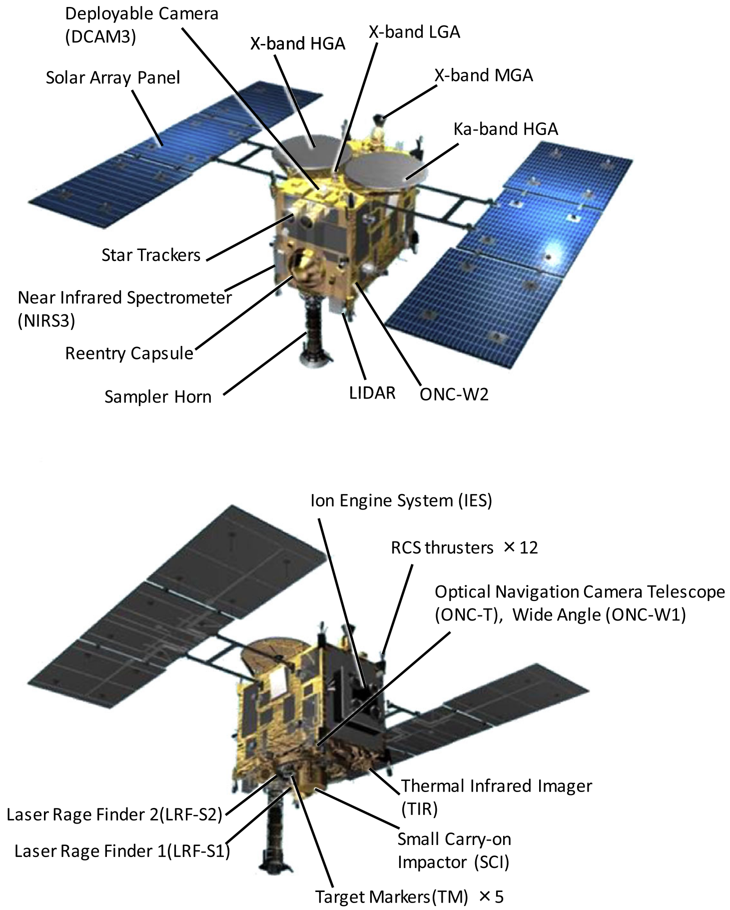


Fig. 1 Exterior of Hayabusa2 and components

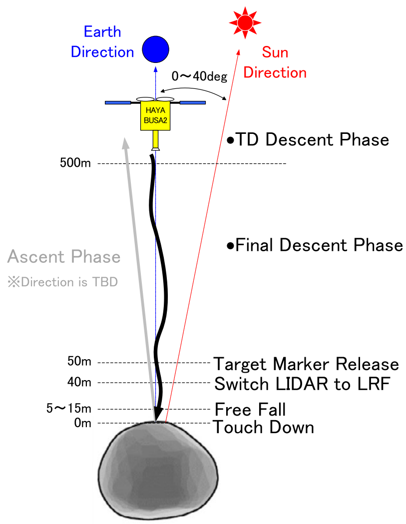
Figure 2 illustrates the geometry of touch-down mission phase and operational altitudes of touch-down. The schematic of detail operation plan after Hayabusa2 reaches to the altitude of 50 m, is shown in Fig. 3. Figure 4 is the artistic illustration of touch-down sampling of Hayabusa2 at Ryugu.

4 Outline of Hayabusa2 Sampler System

4.1 Sampling Mechanism of Sampler

Figure 5 shows the drawing of the Hayabusa2 sampler system. The sampler system is mainly composed of three parts; (1) a sample storage and transfer mechanism, (2) a sampler horn, and (3) a projector part (Sawada et al. 2012). The sampler horn is attached to the bottom face (−Z plane) of the Hayabusa2 main body. The sampler horn is stored and launch-locked in the flight configuration. Figures 6 and 7 shows pictures of the sampler horn with the flight configuration and of the sample storage and transfer mechanism, respectively. The sample

Fig. 2 Outline of touch down sequence



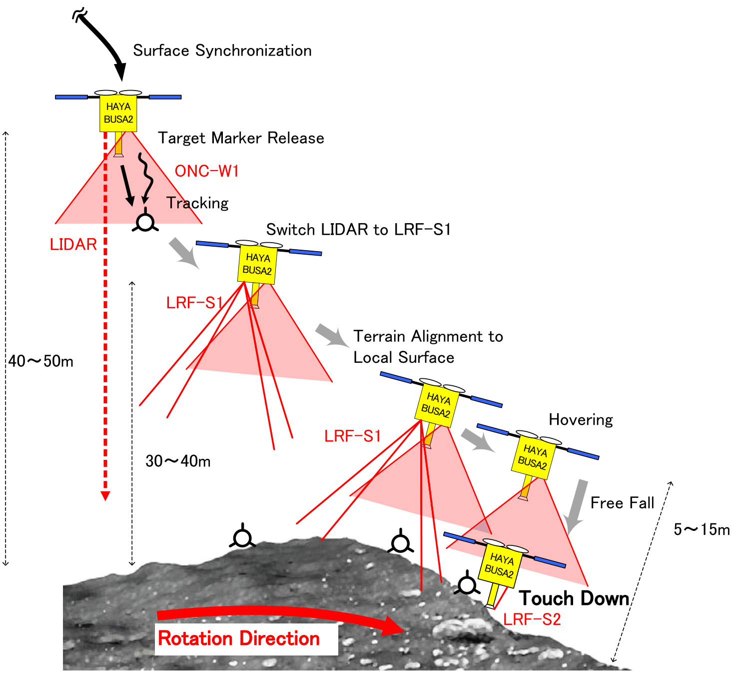


Fig. 3 Touch-down operation at the surface of asteroid

storage and transfer mechanism is assembled inside the main body of Hayabusa2 attached to the inner face of the plane where the earth re-entry capsule is located (−X plane)

The operation of the sampler throughout the mission is illustrated in Fig. 8. We first deploy the sampler horn as soon as possible after the launch of Hayabusa2. After Hayabusa2 arrives at Ryugu, we plan to conduct 3 sampling operations at different surface locations of

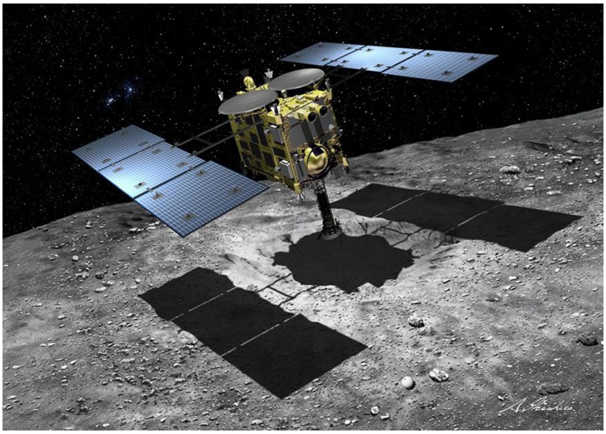


Fig. 4 Artistic illustration of Hayabusa2 touch-down sampling

the asteroid. In the sampling operation, a 5-g tantalum projectile will be shot at the velocity of 300 m/s inside the sampler horn immediately after that the tip of sampler horn touches the surface of the asteroid (Fig. 9). Surface materials ejected by the projectile will rise up through the sampler horn to a sample catcher. Although we examined possibilities of changing the projectile shape and the way of shooting (Yano et al. 2009), but we decided to use the same projectile-shooting sampling system as that of 1st Hayabusa considering a technology readiness level.

The samples collected at each location are stored into the 3 chambers inside the sample catcher respectively, to store grains larger than a few hundred micrometers separately, by changing the position of sample inlet by a rotatable reflector, which is implemented by activating a rotation mechanism. The rotational reflector can close the sample catcher after it makes three rotations, which will be described in detail below. After closing the sample catcher, the reflector rotation mechanism is evacuated to allow the sample catcher to be transferred into a sample container enclosed in an Earth re-entry capsule (Fig. 9). The sample catcher is then latched and sealed by pushing into the sample container.

The sampler horn of Hayabusa2 is almost the same as that of the 1st Hayabusa with minor modifications. We modified a tip part of the sampler horn to pick up surface pebbles even without the projectile shooting as a backup sampling method, of which details are described in Sect. 4.2.

4.2 Sampler Horn

The exterior of the deployed sampler horn (the on-orbit configuration) is shown in Fig. 10. The horn length is 1007 mm and the diameter of the aperture area that touches the asteroid surface is 140 mm. A back-up sampling mechanism was prepared at the tip of the sampler horn, where the tip is turned up like the teeth of a comb, to collect several-millimeter-sized surface samples by scooping them up (Fig. 11).

When the tip of the sampler horn touches the surface of the asteroid, the scoop-up part (Fig. 12) will stick into the surface and millimeter-sized pebbles will be picked up by the scoop-up part regardless of whether a projectile is fired or not. The lifted pebbles will be transferred into the sample catcher by deceleration of the spacecraft (Fig. 10). Even if the surface pebbled were positively charged (up to ∼5 V; Colwell et al. 2005) and stuck to the sampler horn with the electromagnetic force, the grains larger than 100 micrometer in

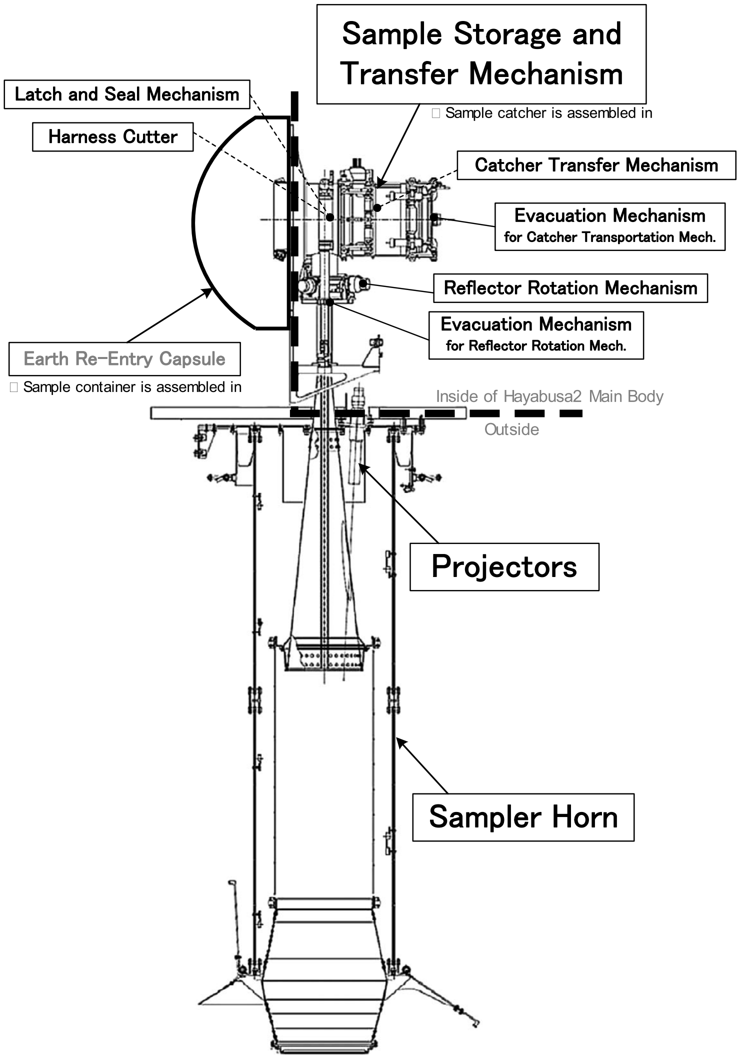


Fig. 5 Hayabusa2 sampler system

size could detach and be stored in the sample catcher during the deceleration operation with four 20-N chemical thrusters. The concept of this sampling method is very simple, but we consider this redundant sampling method is effective and reliable.

We made some tests under the force of gravity to optimize the shape of the scoop part and made a performance test under micro-gravity at the ZARM (Center of Applied Space Technology and Microgravity) drop tower at University of Bremen.

4.3 Sample Catcher

The sample catcher is a cylindrical container with three divided chambers that stores samples separately collected at three different surface locations. The number of the chambers was two for 1st Hayabusa, and an extra chamber was added for the Hayabusa2 sample catcher

Fig. 6 Sampler horn flight configuration

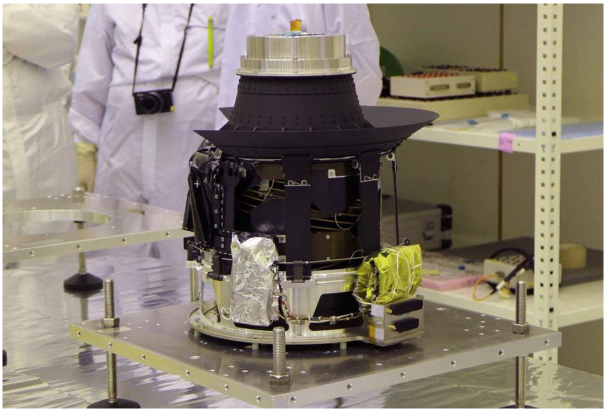
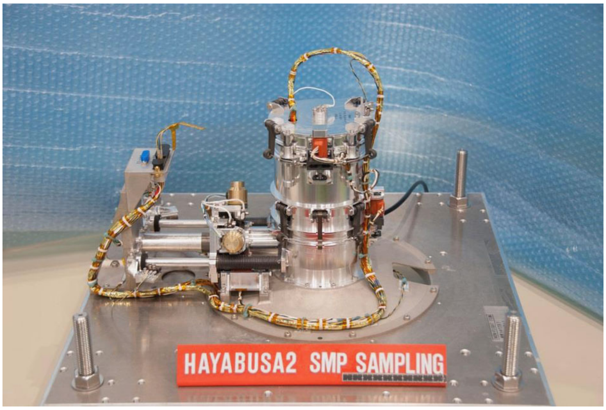


Fig. 7 Sampling mechanism flight model



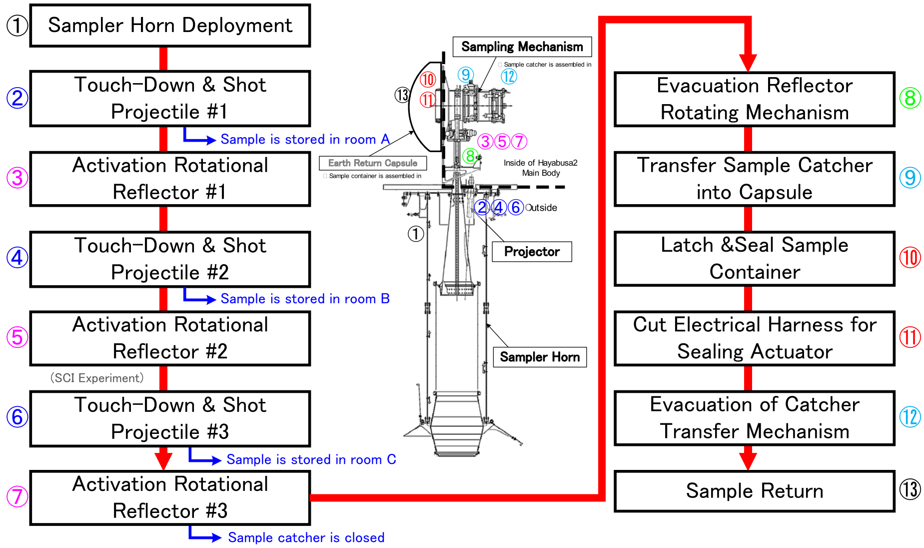


Fig. 8 Sequence of sampling and sample return mission

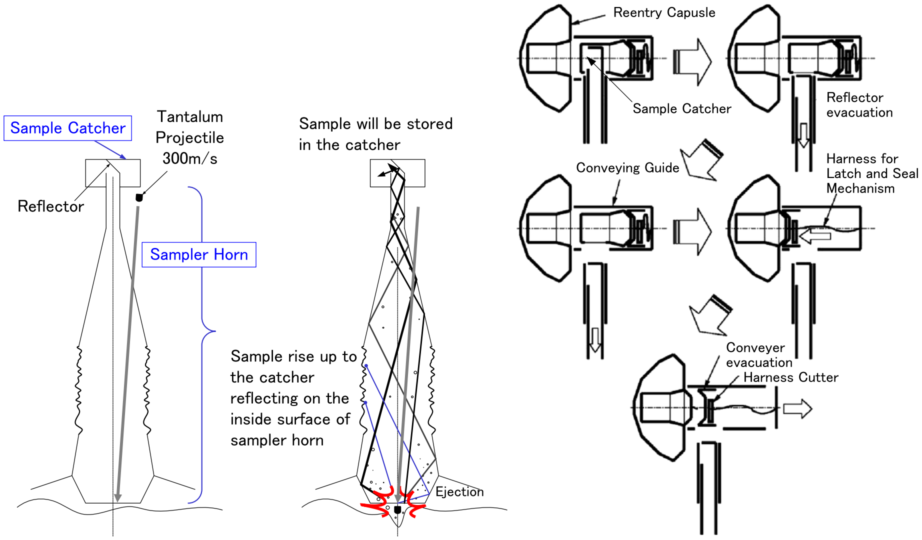
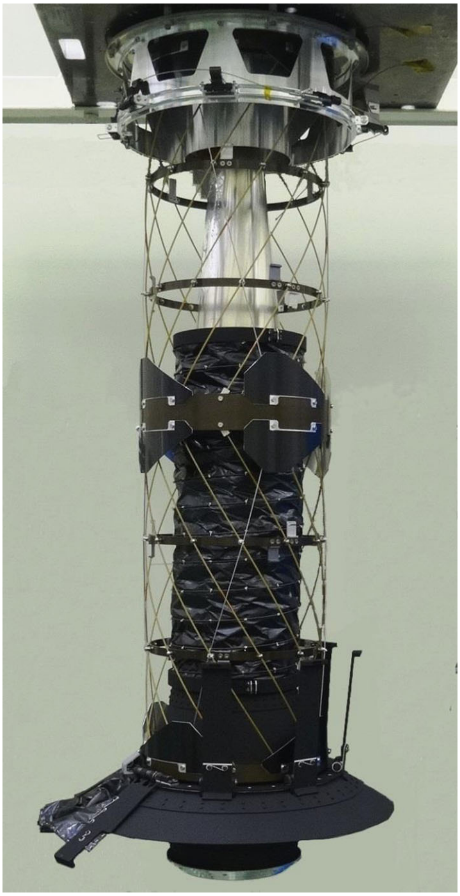


Fig. 9 Sampling system concept (projectile method)

Fig. 10 Sampler horn on-orbit configuration



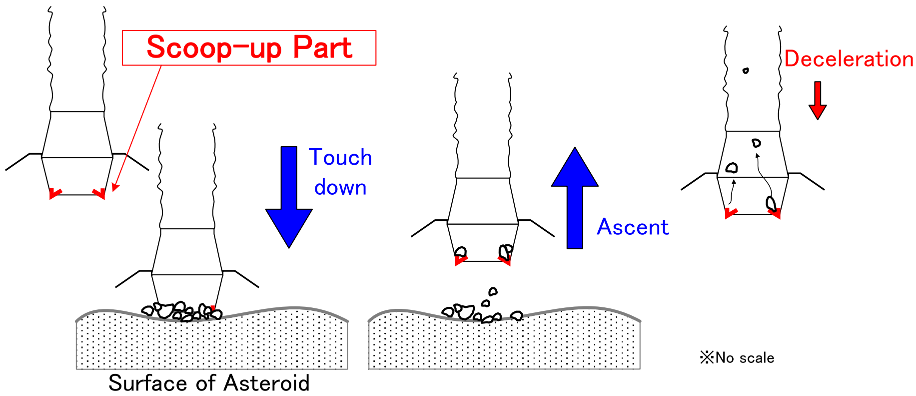


Fig. 11 Concept of scoop-up part

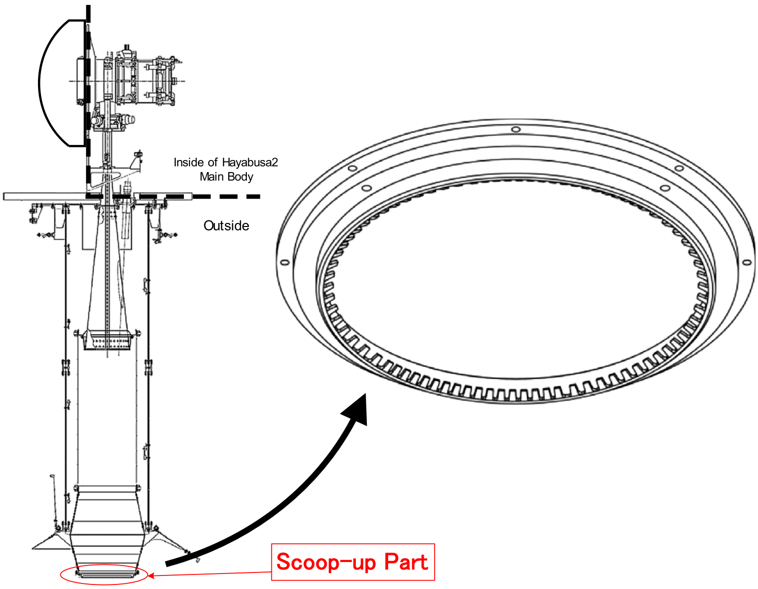
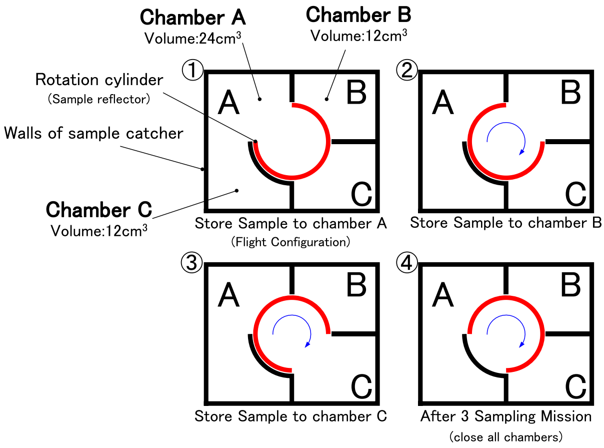


Fig. 12 Design of scoop-up part

without changing the total volume (Fig. 13). The maximum size of the sample catcher is constrained by a volume allocation that the sampler is allowed to use in the re-entry capsule. The size constrain is same as Hayabusa and it is directly linked to the maximum amount of sample. A total volume of chambers A, B and C is 48 cm^3, which indicates the catcher can store approximately 10g sample in case of 2 g/cm^3 in bulk density and 10% in yield coefficient.

A rotatable cylindrical reflector to store samples to a certain chamber can be rotated one-way and one-time with a one-way rotation mechanism using NEA (Non-Explosive Actuator). Three chambers will be closed by the rotatable reflector itself after three sampling operations (Fig. 13). Because the same sampler horn will be used for three touchdown operations and there are gaps (up to a few hundred micrometers) between the rotatable inlet and the chamber walls, there is a possibility of mixing particles, especially fine particles

Fig. 13 Operation of the sample catcher for 3 sampling and volume of each chamber



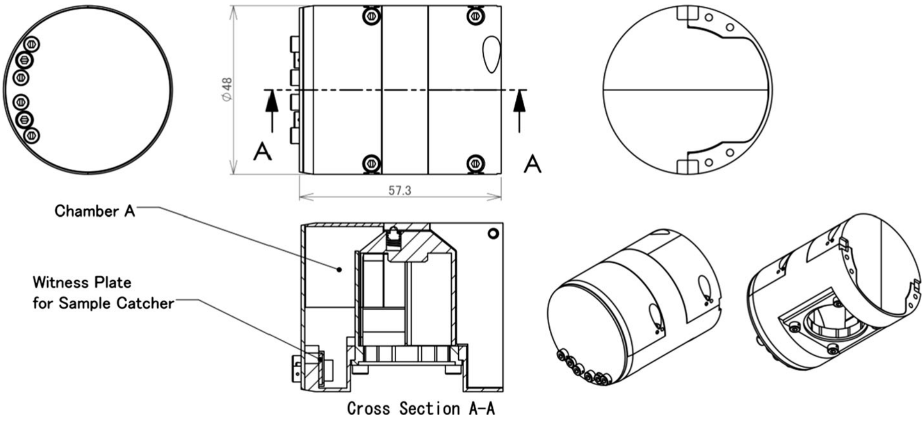


Fig. 14 Design drawing of Hayabusa2 sample catcher (unit: mm)

($\lesssim$ 100 μm), during the second and third sampling. Fine particles are thus regarded as representing a global feature of the asteroidal surface, including the space weathering effect (Tachibana et al. 2014).

The total volume is about the same as that of Hayabusa with two chambers, but one of the chambers was divided into two to have three chambers in total. The chamber with the largest volume will be used to store samples collected in the first touchdown because mm-sized particles obtained during the first touchdown will have little of no risk of mixing. The design drawing of Hayabusa2 sample catcher is shown in Fig. 14. The dimensions of catcher are 48 mm in diameter, and approximately 57 mm in length. The catcher in installs a witness plate for monitoring the actual environment of inside of the catcher (see Sect. 5.5.2).

The Hayabusa2 catcher has a design that is easy to be taken apart after its return to the Earth (Fig. 15). The inner surface of the catcher was mirror-polished to raise the visibility of fine particles. The shape design of each part is also improved from these of Hayabusa. The catcher cover 2 for chamber B, and the cover 3 for chamber C are designed to be a vessel-like shape so that we can retrieve and handle sample easily in a curation chamber. These improvements are also based lessons learned from the 1st Hayabusa mission.

The picture of sample catcher FM is shown in Fig. 16.

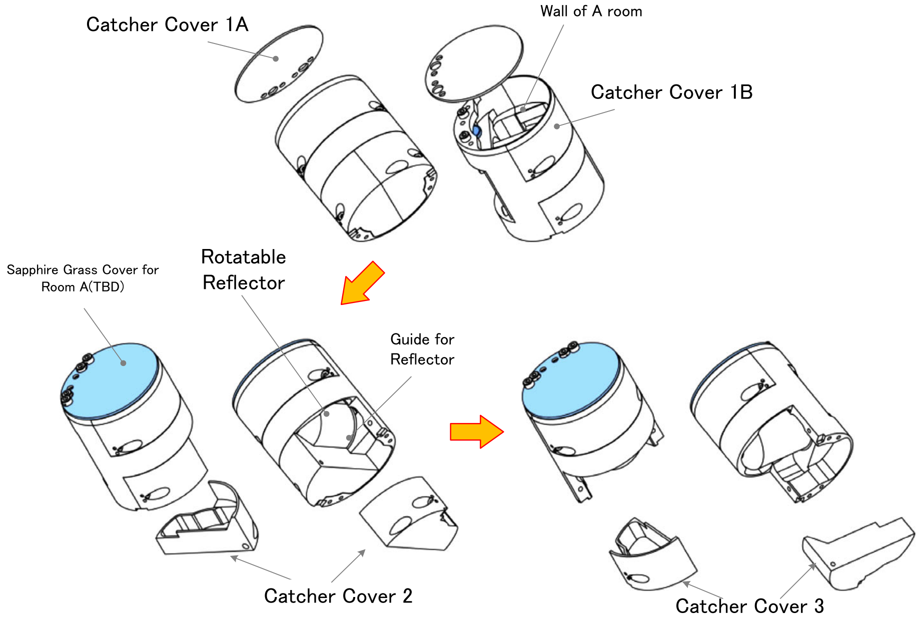


Fig. 15 Sample retrieving sequence of sample catcher after the Earth return

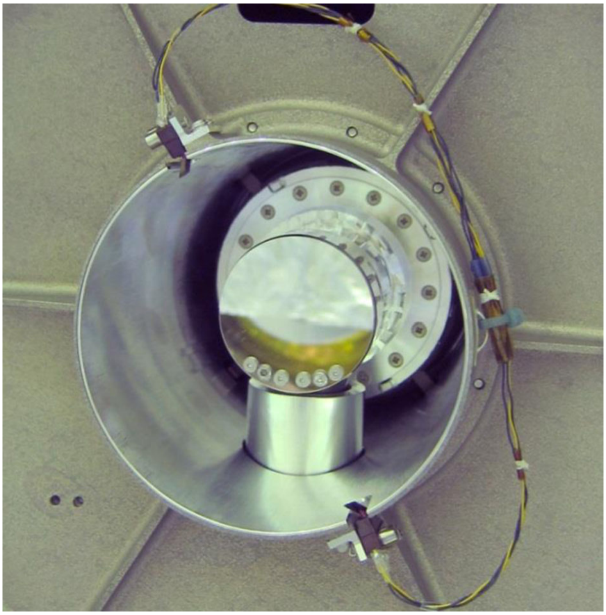


Fig. 16 Picture of the Hayabusa2 sample catcher flight model

4.4 Sample Container and Sealing Mechanism

The sample from a C-type asteroid is expected to contain relatively large amounts of volatile components such as water, labile organic molecules, and noble gases. We developed a new

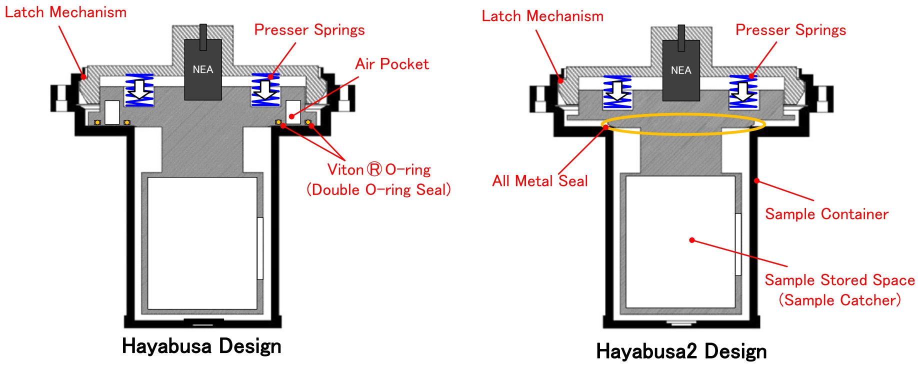


Fig. 17 Sample container sealing methods of Hayabusa2 and Hayabusa

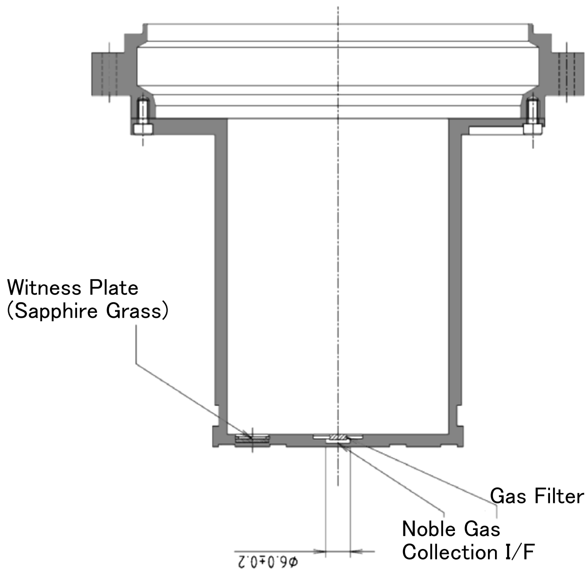


Fig. 18 FM design of Hayabusa2 sample container

aluminum metal sealing mechanism (Fig. 17) to store and recover such volatile components without any significant contamination from the terrestrial air after the Earth return, while the Hayabusa container sealed with double fluorocarbon O-rings had a leakage of ∼5000 Pa terrestrial air (Okazaki et al. 2011). The sealing system was designed to only allow a leak of 1 Pa of air for 100 hours at the atmospheric pressure, more details of which are reported by Okazaki et al. (2016). It should be mentioned about sealing performance that, the sealing mechanism can seal only the sample container. The sample catcher in the sample container has 3 chambers for three different sampling sites. However, each chamber is not sealed respectively, and there is a structural clearance (up to a few hundred micrometers) between respective chambers as mentioned in Sect. 4.3.

In addition to the new sealing mechanism, we added a gas sampling interface (I/F) to the bottom face of the sample container (Fig. 18). The center of the bottom face of the container (1 mm in diameter) was thinned and the container can be attached to the vacuum line to

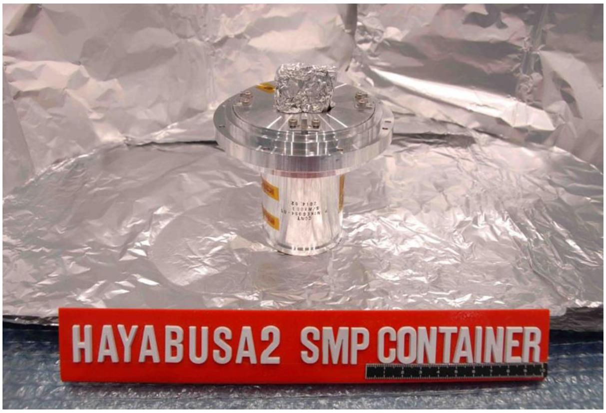


Fig. 19 Flight model of the Hayabusa2 sample container

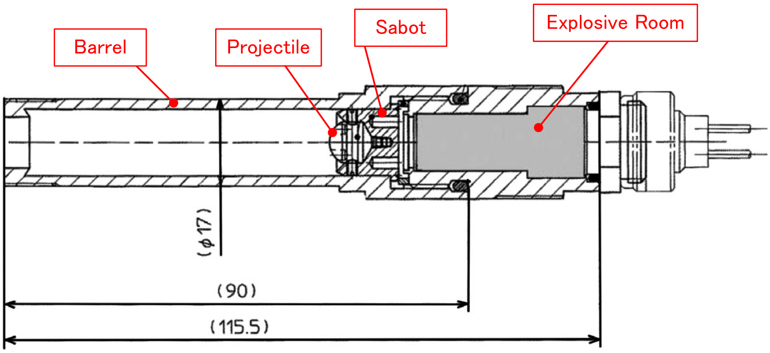


Fig. 20 Design drawing of projector (unit: mm)

extract volatile components through the line by piercing the thinned part with a tungsten carbide needle (Okazaki et al. 2016). We currently plan to collect volatile components as soon as possible after the capsule recovery at the re-entry site (Australia).

We also prepared an additional sapphire-glass witness plate at the inner-bottom face of the container to monitor contamination inside the container throughout the mission (Fig. 18).

The flight model of the sample container is shown in Fig. 19.

4.5 Projector and Projectile

An explosive-type projector is used to shoot a small projectile for sampling, of which mechanism and design are the same as 1st Hayabusa. In order to avoid contamination from an explosive and projector itself, we adopt a sabot method for the projectile shooting. The projector system consists of three projectors, each of which has a stainless steel (SUS304) barrel with a diameter of 17 mm, a 4.85-g tantalum projectile with an aluminum alloy (A1070) sabot, and an explosion room (Fig. 20).

The shooting operation of the projectile is summarized in Fig. 21. An electric power is supplied from the bus power control unit first to ignite the explosive in the explosion room. The projectile with the sabot is accelerated by explosion up to 300 ± 30 m/s inside the

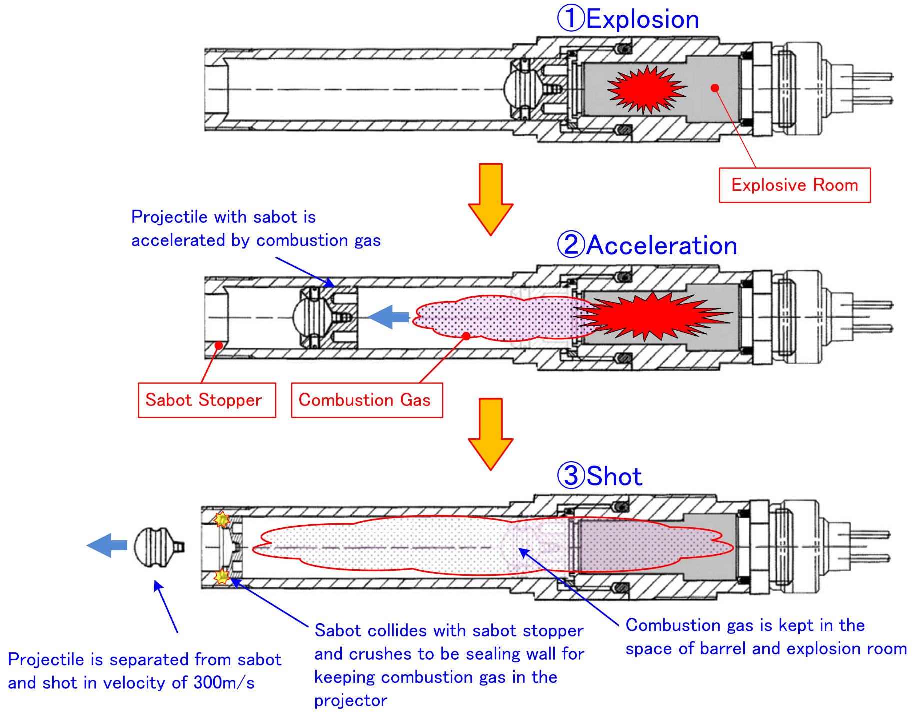


Fig. 21 Shooting operation of the projector system

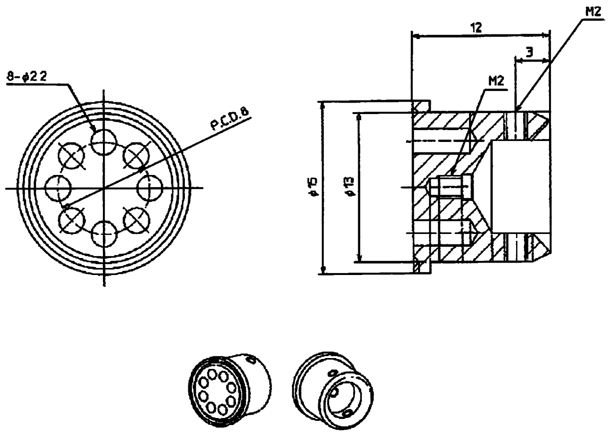


Fig. 22 Drawing of sabot for projectile (unit: mm)

barrel. When the projectile itself hits a sabot stopper, the sabot is stopped at the end of the barrel and the projectile is separated from the sabot and shot to the asteroid surface. The remaining sabot seals the barrel to prevent the leakage of explosive gas, which makes the contamination to the samples minimal.

The details of the projectile and the sabot are shown in Figs. 22 and 23, respectively, and their flight models are shown in Fig. 24. They are connected each other by a screw-tap set

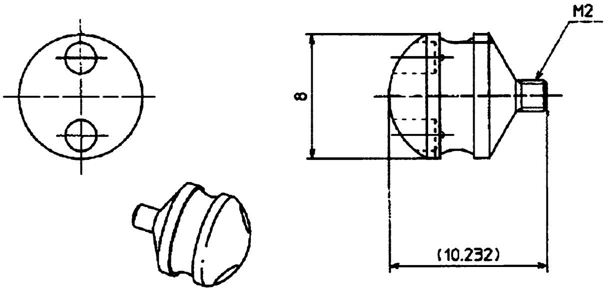


Fig. 23 Drawing of tantalum projectile (unit: mm)

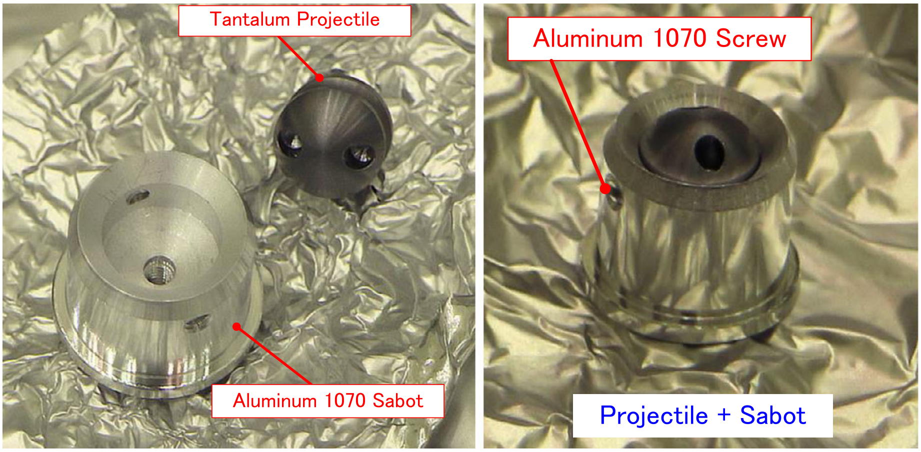


Fig. 24 Flight model of projectile and sabot

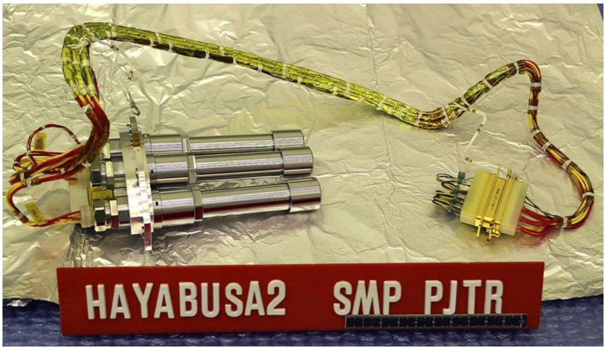


Fig. 25 Flight configuration of three projectors unit

at the bottom of the projectile, and the projectile is detached from the sabot by breaking a female-screw of the sabot at the sabot stopper.

Three projectors are combined and assembled to the projector holder with electrical cables inside the spacecraft (Fig. 25).

5 Development and Tests of Sampler FM

This chapter describes development and the results of performance tests of the Hayabusa2 sampler except for the metal sealing system, which will be reported by Okazaki et al. (2016).

5.1 Projector System

We first made projector-shooting experiments under the force of gravity on glass-bead targets to simulate bullet shooting at the surface covered with fine regolith.

The impact experiments were conducted using a 1/1-scaled analog sampler at the Space Plasma Laboratory at ISAS, JAXA. Glass beads with a diameter ranging from a few hundreds microns to 1 mm were put in a container and used as an analogue of the asteroid regolith. The container with glass bead samples were put in a vacuum chamber and were shot by a 5 g tantalum projectile at the impact velocity of $\sim$300 m/s. The mass of glass beads collected in an analogue catcher for individual experiments were larger than 100 mg, which is the amount of samples scientifically required (Tachibana et al. 2014), even under the force of gravity.

Experiments under microgravity are also necessary to understand the behavior of particles without gravity and to scale the collection yield under the force of gravity to that under microgravity. The experiments under microgravity were performed at the ZARM Drop Tower at University of Bremen (Fig. 26). Stable microgravity conditions can last several seconds in vacuum ($\sim$several Pa) at the ZARM Drop Tower.

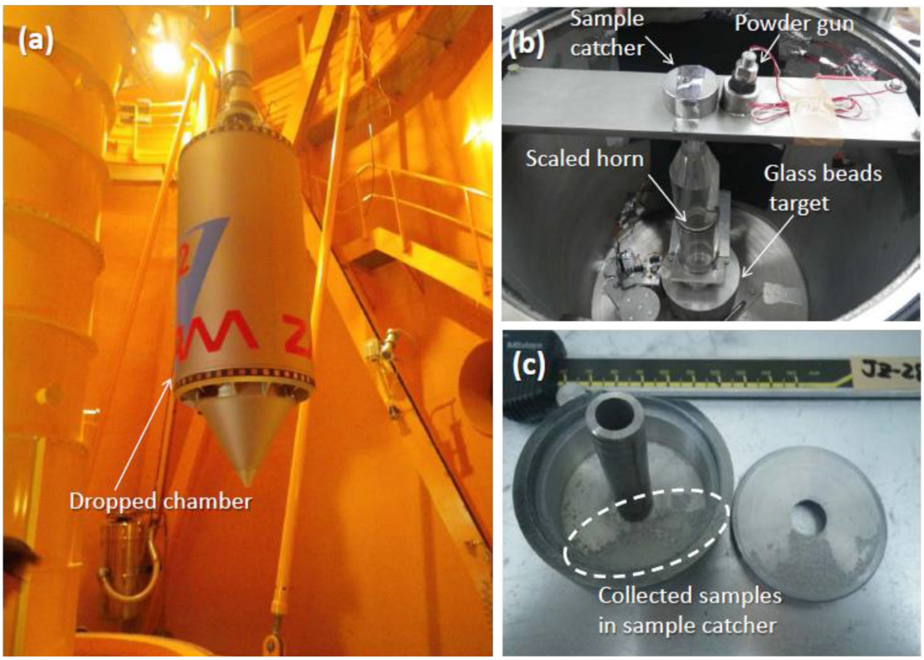


Fig. 26 Configuration of impact experiment at the ZARM Drop Tower. (**a**) The chamber for microgravity experiments. (**b**) The downscaled sampler analogue. (**c**) Collected samples in the analogue sample catcher

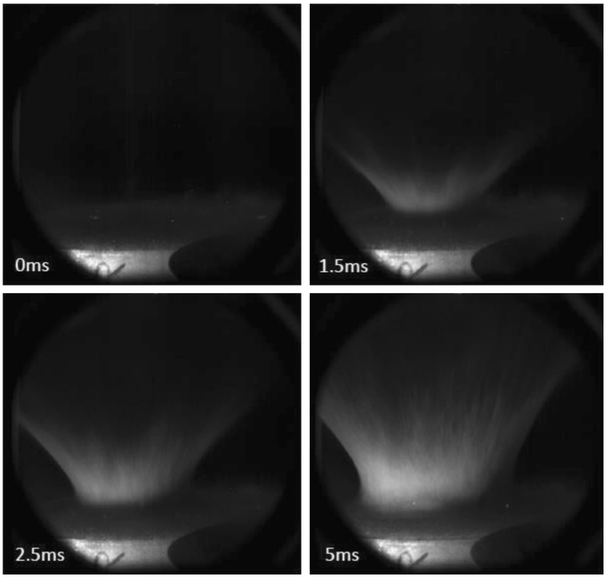


Fig. 27 Ejector behavior under microgravity. Time after the projectile shooting is shown in each picture

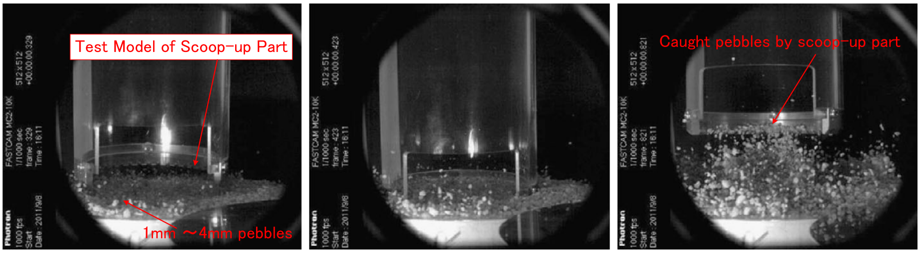


Fig. 28 Micro gravity experiment of scoop-up part test model

The same glass beads were used for the microgravity experiments, but due to the size limitation of the experimental setup, the projectile and the sampler horn were downscaled to 40% of their original sizes. The behavior of impact ejector was observed with a high-speed digital video camera at 2000–10000 frames per second. Snapshots during impact cratering under microgravity are shown in Fig. 27. The mass of collected glass beads were a few to ten times larger than those obtained with the 40% downscaled sampling system under the force of gravity. We therefore estimate that several hundred milligrams of regolith particles can be collected by each projector shot at the surface of Ryugu. More details of projector shooting experiments will be reported elsewhere (Okamoto et al. 2017).

5.2 Scoop-up Part of Sampler Horn

We conducted a micro gravity experiment for evaluation of the function of scoop-up part we proposed at ZARM drop tower. The scoop-up part used in the test was the same in scale as the real sampler horn, but had the scoop-up teeth partly. Figure 28 shows the experimental result of the micro gravity experiment. One to four-millimeter sized pebbles was used for the test. We aim to collect several millimeter-sized samples using the scoop-up part, and as

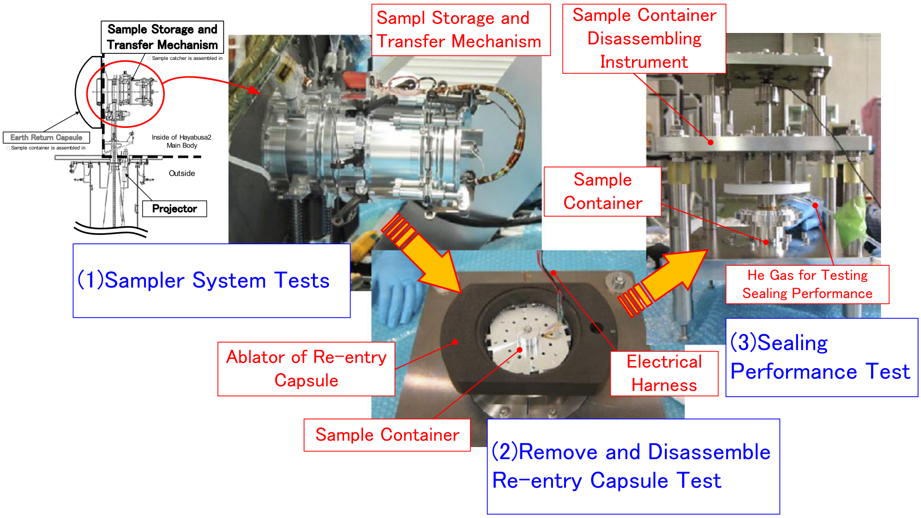


Fig. 29 End-to-end test of the Hayabusa2 sampler subsystem

shown in Fig. 28 the result indicates a good performance. The quantitative evaluation could not be made due to the limited number of microgravity experiments, but the performance tests under microgravity clearly showed that the scoop-up part could pick up many bubbles under microgravity.

5.3 Integrated Test for Sampler Subsystem

We made a system integrated test (end-to-end test) of the Hayabusa2 sampler flight model (FM) at the beginning of 2014 to verify functions and performance of the sampler FM and bus-system I/F.

In the end-to-end test of the sampler subsystem, we first conducted a sampler system tests (Fig. 29(1)). We implemented a sampler horn deployment by activating a NEA via bus-system electrical unit. Then we activated all actuators and mechanisms except projectors, rotation and removal of the rotatable reflector, transfer of the sample catcher, and latch and metal sealing mechanism. We could confirm the following functions worked properly without any trouble through the spacecraft bus-system.

(1) Sampler System Tests

- Rotation reflector mechanism
- Remove rotation reflector mechanism
- Transfer sample catcher into re-entry capsule
- Latch and sealing mechanism
- Cut electrical harness for sealing mechanism

Then, we removed the re-entry capsule from the main body of Hayabusa2 and disassembled the capsule to a certain unit so that we could conduct a sealing performance test and could also confirm a latch and sealing mechanism function (Fig. 29(2)). These functional test is very important because that we must implement completely same sequences after the re-entry capsule returns to Earth in 2020. Thus, we conducted these end-to-end tests as a rehearsal of sample retrieving operation. In the remove and disassemble test, we confirmed the following functions.

(2) Remove and Disassemble Re-entry Capsule Test

– Remove re-entry capsule from Hayabusa2
– Disassemble re-entry capsule
– Take sample container out from re-entry capsule
– Set sample container to container disassembling instrument

Finally, we set the sample container to the test model of sample container disassembling instrument to conduct the sealing performance test and a sample container disassembling test (Fig. 29(3)). We could verified that the sealing performance satisfied the scientific requirement (the leakage of < 1 Pa for 100 hours at one atmosphere total pressure). The container disassembling test was also conducted as a rehearsal of disassembling and installation to a sample curation system that we will prepare before 2020. We confirmed the followings in the sealing performance test.

(3) Sealing Performance Test

– Evaluate sealing performance
– Sample container disassembling test

After the all end-to-end test and rehearsal, we cleaned all important parts up by a precise cleaning method (see in Sect. 5.5.3) and replaced the sample container and the interface part of metal sealing to the flight models.

We reset all the actuators and mechanisms to the initial setting and finished assembling the sampler system into the flight configuration in March, 2014.

5.4 Functional Test of Sampler Horn

We conducted another end-to-end test on the sampler horn operation. We checked the mechanical interface to the laser range finder (LRF-S2) flight model that measures a distance between the LRF-S2 and a diffuse reflector plate attached on the surface of sampler horn tip unit and triggers the projector shooting; The distance to the diffuse reflector plate was measured with LRF-S2 to test the function of diffuse reflector plat and check the geometrical relationship of the reflector plate and LRF-S2.

The touch-down detection test with LRF-S2 was also made by moving the tip position of sampler horn manually. It was confirmed that the LRF-S2 could detect the changes of the distance to the reflector plate and of the reflectance of laser and trigger the sampling operation.

In addition to the performance test, we measured mechanical characteristics of the sampler horn flight model, where the movement of the sampler horn and the displacement-load relationship were measured by moving the tip position of the sampler horn to $\pm$X, $\pm$Y, and +Z direction relative to the spacecraft. Figure 30 shows a definition of direction of the sampler horn deformation. The data will be utilized for the analysis of touchdown operation sequence at the asteroid.

5.5 Environment Measurement and Contamination Control for Hayabusa2 Sampler

We flew highly pure nitrogen gas into the sampler system flight model after the completion of manufacturing by the launch to keep the system clean and monitor the environment that

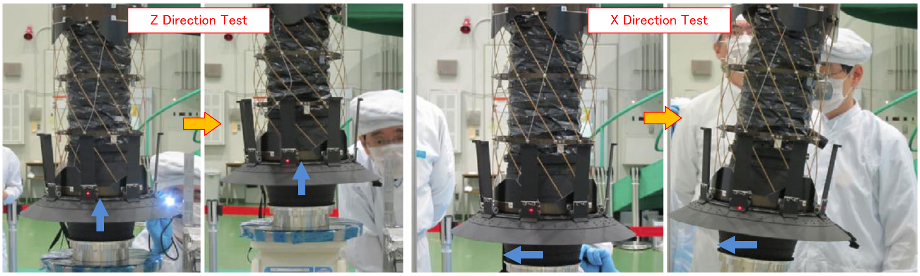


Fig. 30 Measurement of characteristics of sampler horn dynamics

the sampler system experiences with two sapphire glass witness plates inside the sample catcher and the sample container by the return to the Earth.

We also used the contamination monitor coupon sets to monitor and record the environment during manufacturing of the sampler, the installation to the spacecraft and transportation between facilities including the launch site.

5.5.1 N_2 *Gas Purge Operation*

The sampler system was kept purged by high-purity N_2 gas generated by evaporation of liquid nitrogen through a purge port after January 2014 through the spacecraft integration test except for some occasions such as the system thermal vacuum tests and the system vibration test of the spacecraft, where the purge tube had to be taken out. The N_2 gas purge is most important way to avoid contamination from a surrounding environment of the sampler. We could conduct N_2 gas purge in approximately 93% coverage versus a total exposure period to the atmosphere. Thus, we consider that we could keep the sampler FM in a pristine environment with minimal contamination from Earth-derived material.

The timeline of nitrogen purge is summarized as follows:

01/11/2014	N_2 gas purge to the sampling mechanism started
02/10/2014	The sampling mechanism was removed from the spacecraft for its final assemblage and test
02/10/2014–03/27	Suspension of N_2 gas purge
03/27/2014	The sampling mechanism was re-assembled to the spacecraft and N_2 gas purge re-started
05/23/2014–06/09	Suspension of N_2 gas purge for the system thermal vacuum test #1
06/09/2014–06/13	N_2 gas purge
06/13/2014–06/17	Suspension of N_2 gas purge for the system thermal vacuum test #2
06/17/2014–07/08	N_2 gas purge
07/08/2014–07/09	Suspension of N_2 gas purge for transportation to Tsukuba Space Center for the acoustic test of the spacecraft
07/09/2014–07/11	N_2 gas purge except during the acoustic test
07/11/2014–07/12	Suspension of N_2 gas purge for transportation to ISAS
07/12/2014–07/16	N_2 gas purge
07/16/2014–08/01	N_2 gas purge except during the system vibration test (3 h $\times$ 4 sets)
09/17/2014–09/23	Suspension of N_2 gas purge for transportation to the Tanegashima Space Center
09/23/2014–10/30	N_2 gas purge

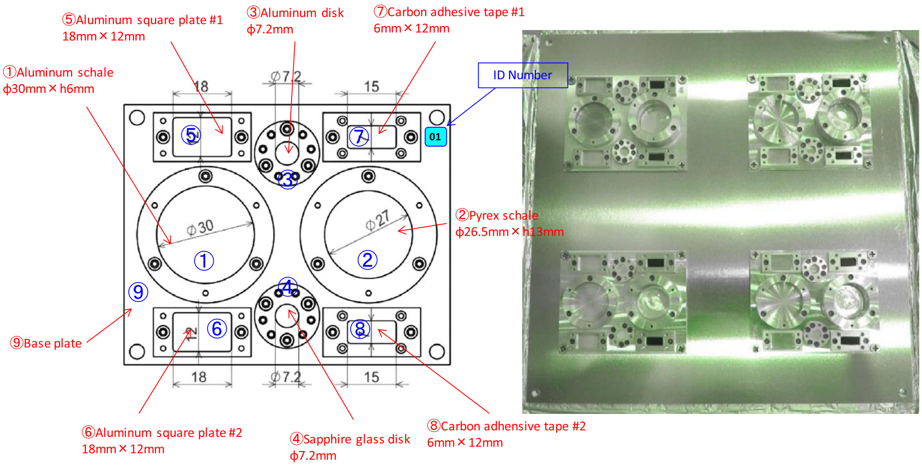


Fig. 31 Design of contamination monitor coupon set for the Hayabusa2 sampler

10/30/2014–10/31	Suspension of N_2 gas purge for transportation from the Spacecraft Test and Assembly Building 1 (STA1) to the Spacecraft and Fairing Assembly building 2 (SFA2)
09/31/2014–11/21	N_2 gas purge
11/21/2014	Suspension of N_2 gas purge for transportation from the SFA2 building to the Yoshinobu Vehicle Assembly Building (12 h)
11/21/2014–12/01	N_2 gas purge
12/02/2014	Stop N_2 gas purge (16:00 JST)

5.5.2 Contamination Monitor Coupon

We prepared a contamination monitor coupon set for monitoring an environment surrounding the sampler FM and for measuring how much Earth-derived material is possible to contaminate the sampler. The contamination monitor is extremely important to evaluate an affection of contamination to sample analysis and science significance quantitatively. The result of monitor will be also utilized for detection of what, when, how, the sampler is contaminated, in case that sample is contaminated by Earth-derived material actually after we analyze in initial curation work.

The contamination monitor coupon set consists of plates, dishes, and disks made of aluminum alloy (A1070), Pyrex borosilicate glass, and sapphire glass, respectively, on a base plate (Fig. 31). Carbon adhesive tape was also put on the base plate to collect particles directly. The contamination monitor coupon sets used at the Tanegashima Space Center are shown in Fig. 32. We used two or four sets simultaneously to cover the entire period from the participation of the sampler system to the system integrated test of the spacecraft (2013.11.29) to 21 hour before the launch (Table 1). Table 1 shows a log of contamination monitoring result. We will analyze all coupon set and make database of result based on Table 1, and the database will be utilized by sample analysts.

In addition, the sampler installs two witness plate made by sapphire glass to monitor inner environment of the sampler catcher and the sample container (Fig. 14, Fig. 18). Two witness plates can store the information of an entire mission phase environment (till 2020) as well as the ground test environment. The detail of witness plates is described in Okazaki et al. (2016).

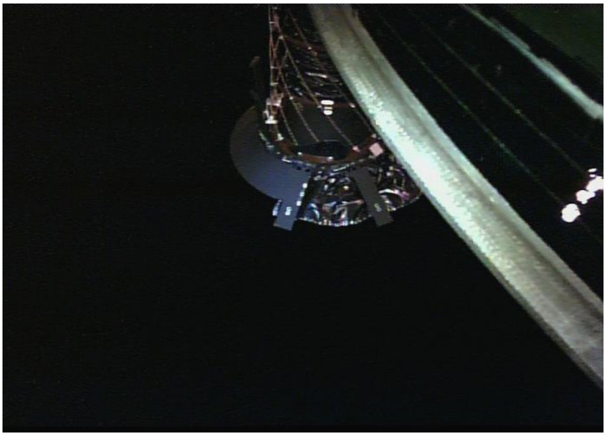


Fig. 32 On-orbit image of sampler horn after deployment

5.5.3 Cleaning of Sampler Parts

Ultrasonic cleaning using organic solvents and ultrapure water have been performed multiple times for the parts of the sample container at the ISAS Curation Facility (full-course cleaning). The stainless steel ultrasonic bath and stainless steel tweezers were used to prevent contamination of various metals and organics.

The parts were first cleaned carefully before bringing into a clean room at the ISAS Curation Facility by wiping with ultrapure water and/or organic solvents. The parts were then cleaned ultrasonically (40 kHz) for 20 minutes with ultrapure 2-propanol and a 1:1 mixture of dichloromethane and methanol to dissolve organic contaminants, followed by the ultrasonic cleaning with ultrapure water to remove ions and particles. The ultrasonic cleaning with ultrapure water (40 kHz) was also made for 30-40 minutes with overflowing the water from the ultrasonic bath (overflow cleaning). After the series of ultrasonic cleaning procedures, all the cleaned parts were dried in a desktop clean booth.

6 On-Orbit Statue of Sampler

Hayabusa2 was launched on December 3rd, 2014. In the first visible pass from the Usuda ground station, at Nagano, Japan, a deployment operation of the sampler horn was conducted. We confirmed that the sampler horn was deployed correctly by releasing a launch lock mechanism by the HK telemetry. We then took an on-orbit picture of the sampler horn with a small camera head (CAM-H) (Fig. 32).

7 Summary

The Hayabusa2 sampling system was developed based on the 1st Hayabusa sampling system (Bouvier and Wadhwa 2010) with improvements to satisfy the scientific requirement of collection of a minimum of 100 mg of surface samples including several mm-sized particles at several different surface locations of the C-type asteroid, Ryugu, without any severe terrestrial contamination.

The main sampling operation is the projectile shooting through the sampler horn that is the same as 1st Hayabusa. The sample catcher for the storage of samples was improved to have three chambers instead of two chambers for the 1st Hayabusa sample catcher.

Table 1 Summary of contamination monitor operation

No.	Location	Start date	Location 2	Start date 2	Location 3	Start date 3	Location 4	Start date 4	Location 5	Start date 5	Location 6	Start date 6	Location 7	Start date 7	Location 8	Start date 8	Location 9	Start date 9	End date	Remarks
1	JAXA ISAS C Building Clean Room near Sampling Mechanism	11/29/2013	C Building Chamber Room	5/21/2014	C Building CR	6/18/2014				change location several times					TNSC SFA2 in Fairing	11/17/2014	TNSC VAB in Fairing	11/21/2014	12/2/2014	used for total period
2	JAXA ISAS C Building Clean Room near Sampling Mechanism	11/29/2013																	2/10/2014	
3	JAXA ISAS C Building Clean Room near Hayabusa2 Main Body	3/27/2014	C Building Chamber Room	5/21/2014															6/18/2014	recovered after thermal vacuum test
4	JAXA ISAS C Building Clean Room near Hayabusa2 Main Body	6/18/2014	Tsukuba SC SITE	7/9/2014	C Building CR	7/13/2014	C Building Vibration Test room	7/14/2014	C Building CR	7/18/2014	C Building Vibration Test room	7/24/2014	C Building CR	8/8/2014	C Building Vibration Test room	9/2/2014	C Building CR	9/2/2014	9/5/2014	recovered after removing sampler horn form Hayabusa2
5	JAXA ISAS C Building Clean Room near Hayabusa2 Main Body	9/4/2014	ISAS → TNSC in Transport Container	9/19/2014	TNSC STA1 CR	9/23/2014													9/24/2014	recovered after transportation to TNSC 9/24/2014 ~ stored at TNSC
6	Tanegashima Space Center STA1 Building Clean Room near Hayabusa2 Main	9/24/2014	in Transport Container	10/29/2014	TNSC SFA2 PAR nera HY2	10/31/2014	TNSC SFA2 in Fairing	11/17/2014	TNSC VAB in Fairing	11/21/2014									12/2/2014	9/24/2014 ~ set at TNSC No. 6 was used for total period of TNSC operation
7	Tanegashima Space Center STA1 Building Clean Room near Hayabusa2 Main	9/24/2014	in Transport Container	10/29/2014	TNSC SFA2 PAR nera HY2	10/31/2014													10/31/2014	
8	Tanegashima Space Center STA1 Building Clean Room near Hayabusa2 Main	9/24/2014																	10/17/2014	
9	Tanegashima Space Center STA1 Building Clean Room near Hayabusa2 Main	10/17/2014	in Transport Container	10/29/2014	TNSC SFA2 PAR nera HY2	10/31/2014													10/31/2014	
10	Tanegashima Space Center SFA1 Building Clean Room near Hayabusa2 Main	10/31/2014																	11/17/2014	
11	Tanegashima Space Center SFA1 Building Clean Room near Hayabusa2 Main	10/31/2014																	11/17/2014	
12	Tanegashima Space Center in Fairing of Launch Vehicle	11/17/2014	TNSC VAB in Fairing	11/21/2014															12/2/2014	12/02/2014 17:00 recovered
13	Tanegashima Space Center in Fairing of Launch Vehicle	11/17/2014	TNSC VAB in Fairing	11/21/2014															12/2/2014	12/02/2014 17:00 recovered

Table 2 Comparison of Hayabusa2 and 1st Hayabusa sampler design

	1st Hayabusa	Hayabusa2	Note
Dimension	Almost same		
Weight	Almost same		
Sampling method	Same (projectile method)		
Number of projector	Same (3 projectors)		
Projectile	Same (tantalum, 08 mm, 5 g)		
Sealing method	Double O-ring sealing	All metal sealing	Improvement
Volume for sample storage	Almost same		
Number of chamber	2	3	Improvement
Back-up sampler	N/A	Scoop-up part on the tip of sampler horn	Improvement
Witness plate	1	2	Improvement
Additional function		Volatile gas extraction I/F	Improvement

We also improved the sampler horn to have a redundant sampling method to collect millimeter-sized surface sample with a scoop-up part at the tip of the sampler horn even without the projectile shooting.

The most remarkable improvement of the Hayabusa2 sampler is the aluminum metal sealing of the sample container to prevent the incorporation of the terrestrial air after the return to the Earth, while the Hayabusa sample container with double O-ring sealing had a leakage of air. Furthermore, the Hayabusa2 sample container allows being extracted volatile species from the sample container immediately after the return to the Earth.

Table 2 shows a summary of improvement and same points of the Hayabusa2 sampler compare to that of 1st Hayabusa.

The development of the flight model of the Hayabusa2 sampler system was completed at the end of 2013 and several integrated tests and the end-to-end test were conducted to check the function of the sampler.

Hayabusa2 was launched on Dec. 3, 2014 and the sampler horn was successfully deployed on the same day. We believe that the newly improved Hayabusa2 sampler will collect enough amounts of samples for the analysis on the ground and show its reliability and applicability to future sample return missions.

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