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Hayabusa2 mission status: Landing, roving and cratering on asteroid Ryugu

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ABSTRACT

Hayabusa2 arrived at the C-type asteroid Ryugu in June 2018. During one and a half year of the Ryugu-proximity operation, we succeeded in two rovers landing, one lander landing, two spacecraft touchdown/sample collection, one kinetic impact operation and two tiny reflective balls and one rover orbiting. Among the two successful touchdowns, the second one succeeded in collecting subsurface material exposed by the kinetic impact operation. This paper describes the asteroid proximity operation activity of the Hayabusa2 mission, and gives an overview of the achievements done so far. Some important engineering and scientific activities, which have been done in synchronous with the spacecraft operations to tackle with unexpected Ryugu environment, are also described.

1. Introduction

The Japan Aerospace Exploration Agency launched the asteroid sample return spacecraft Hayabusa2 [1] atop a Japanese H2A launch vehicle on December 3, 2014. Following the successful return of Hayabusa from asteroid 25143 Itokawa, Hayabusa2 aims at the round trip mission to asteroid 162173 Ryugu. Ryugu is a near-Earth C-type asteroid, which is believed to contain organic matter and hydrated minerals. Thus it is expected that successful sample return may provide fundamental information regarding the origin and evolution of terrestrial planets as well as the origin of water and organics delivered to the Earth.

Hayabusa2 successfully arrived at Ryugu on June 27, 2018 after 3.5 years of the ion engine assisted-interplanetary cruising, and began the asteroid-proximity operation phase.

This paper describes achievements of the asteroid proximity operation activity of the Hayabusa2 project, and gives an overview of the achievements done so far, which includes successful rovers/lander operation, touchdown and kinetic impact, as well as scientific and engineering assessment conducted synchronously with the spacecraft operations to tackle with unexpectedly harsh environment of Ryugu.

2. Asteroid proximity operation

2.1. Summary of asteroid-proximity activity

Hayabusa2 arrived at the "Home Position (HP)" on June 27, 2018, at which time the asteroid proximity phase began. The HP is defined as a position 20 km from the asteroid center toward asteroid-Earth (sub-Earth) line. The HP is always located on the day side of the asteroid, since the Sun-asteroid-Earth angle varies between 0 and 39 deg during 1.5 years of the asteroid proximity phase. The Sun-asteroid distance during the asteroid proximity phase varies between 0.96 and 1.4AU, and the Earth-asteroid distance varies between 2.0 and 2.4AU, which corresponds to the round trip light time of 33–40 min.

All the descent operations to lower altitude were defined as "critical operation" in the project, which were managed by a large operation team participated by 20–40 specifically-trained operators. Table 1 shows the list of the descent operations and the other important operations performed by Hayabusa2. Overall, the asteroid-proximity activity proceeded as planned despite the fact that the environment of Ryugu was found to be unexpectedly severe, and some operations were aborted (i.e. the spacecraft detected a failure and ascent back to HP while descending).

2.2. Initial Ryugu observation

On establishing the hovering state at HP, Hayabusa2 started initial observations of Ryugu using the remote science instruments, such as ONC-T (optical navigation camera-telescopic; multi-band imager, Fig. 1), ONC-W1 (optical navigation camera-wide), TIR (thermal infrared imager), NIRS3 (near-infrared spectrometer) and LIDAR (laser altimeter).

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Table 1
Asteroid proximity operation history.

Month/Date	Event	Status
2018		
Jun. 3	Approach Guidance Start (Dist. = 3100 km)	Complete
Jun. 27	Home Position Arrival (Alt. = 20 km)	Complete
Jul. 17-24	Box-C Descent Observation (Alt. = 6.5 km)	Complete
Jul. 31-Aug.2	[MID] Mid. Altitude Descent (Alt. = 5 km)	Complete
Aug. 5-7	[GRV] Gravity Measurement Descent (Alt. = 1 km)	Complete
Aug. 18-Sep. 7	Box-B Obs. (Alt. = 20 km, Dawn-Dusk Obs.)	Complete
Sep. 11-12	[TD1-R1] Touch Down Rehearsal (Alt. = 600 m)	Aborted
Sep 20–21	[MNRV1] MINERVA–II–1 Deployment (Alt. = 55 m)	Success
Oct. 2-5	[MSC] MASCOT Deployment (Alt. = 51 m)	Success
Oct. 14-15	[TD1-R1A] Touch Down Rehearsal (Alt. = 22 m)	Complete
Oct. 23-25	[TD1-R3] TD Rehearsal/TM Release (Alt. = 12 m)	Complete
Nov .23-Dec. 29	Conjunction Orbit Operation (Max Alt. = 110 km)	Complete
2019		
Feb. 20-22	[TD1-L08E1] Touch Down Operation 1	Success
Mar. 6-8	[DO-S01] TD Candidate Descent Observation (Alt. = 22 m)	Complete
Mar. 20-22	[CRA1] Pre-Impact Scan Observation (Alt = 1.6 km)	Complete
Apr. 3-6	[SCI] Kinetic Impact Operation (Alt. = 500 m)	Success
Apr. 23-25	[CRA2] Post-Impact Scan Observation (Alt = 1.6 km)	Complete
May 14–16	[PPTD-TM1] TM Release for PPTD (Alt. = 50 m)	Aborted
May 28–30	[PPTD-TM1A] TM Release Retrial (Alt. = 9 m)	Complete
Jun. 11-13	[PPTD-TM1B] Crater/PPTD Target Observation (Alt. = 9 m)	Complete
Jul. 8-11	[PPTD] Touch Down Operation 2	Success
Sep 12–22	[TM-ORB] TM Orbiting (Alt = 1.0 km)	Success
Sep 28-Oct 8	[MNRV-ORB] MINERVA–II–2 Orbiting (Alt = 1.0 km)	Success
Nov. 12-18	Leaving Home Position (Asteroid Departure)	Plan
Dec. 2	Return Ion Engine Cruise Start	Plan

*[ ] shows the codename of each critical descent operation.

The first two months of the proximity phase were dedicated to the "Landing Site Selection (LSS)" observation campaign. The objective of this campaign was to measure and understand the basic properties of Ryugu and to derive a set of landing sites for two MINERVA–II–1 rovers, one MASCOT lander, and a one spacecraft touchdown. The other sites (for the kinetic impact, second touchdown and MIENRVA-II2 rover) were to be decided in the next LSS activity in 2019.

Through these activities, it was revealed Ryugu has an oblate shape with an equatorial radius of 502 m and polar to equatorial axis ratio of 0.872. The asteroid spin state is upright and retrograde, having the obliquity of 171.64 deg with the period of 7.63262 h [2]. The spectral data obtained by ONC-T and NIRS3 indicate Ryugu is a Cb-type (carbon rich) asteroid with a very low geometric albedo of 4.5%, and was later shown to contain hydroxyl (OH)-bearing minerals all over the globe [3]. One of the extraordinary features of Ryugu is that the number density of boulders is uniformly high across the surface, twice as high as that of Itokawa for boulders having diameter larger than 20 m [4], which led to the primary difficulty that the Hayabusa2 mission faced for deriving feasible landing sites. The gravity of Ryugu was measured to be GM = 30.0 m^3/s^2 as the result of a free-fall operation conducted on August 5–7, 2018. This GM corresponds to the bulk density of 1.19 g/cm^3, showing that Ryugu is a rubble-pile.

Two critical operations were conducted during the LSS observation campaign phase. On July 31-August 2, "Mid-altitude descent observation" was conducted, in which the spacecraft descended down to 5 km and stayed there for 8 h to obtain high resolution observations for one rotational period. On August 5–7, "Gravity measurement descent" was conducted, in which the spacecraft descended down to 851 m above the

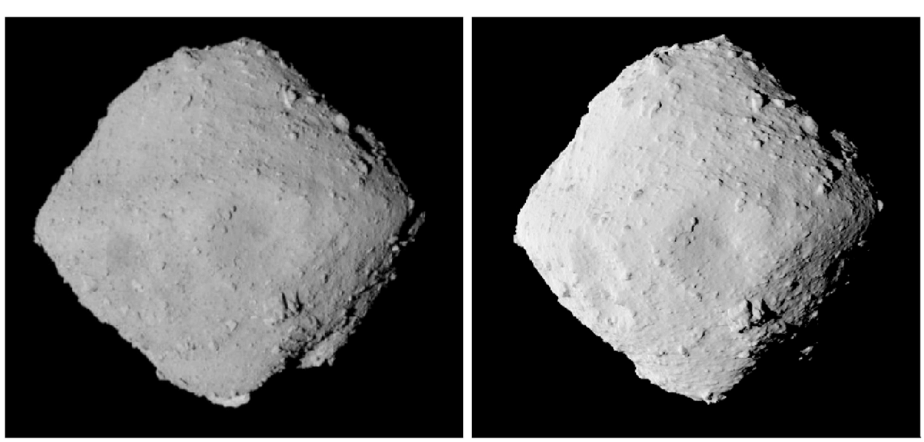

Fig. 1. (Left) An ONC-T image captured at HP on June 30, 2018 and (Right) Shape model generated in LSS activity (image credit: JAXA, U of Tokyo, Kochi U., Rikkyo U., Nagoya U., Chiba Tech, Meiji U., U. of Aizu, AIST, Kobe U.).

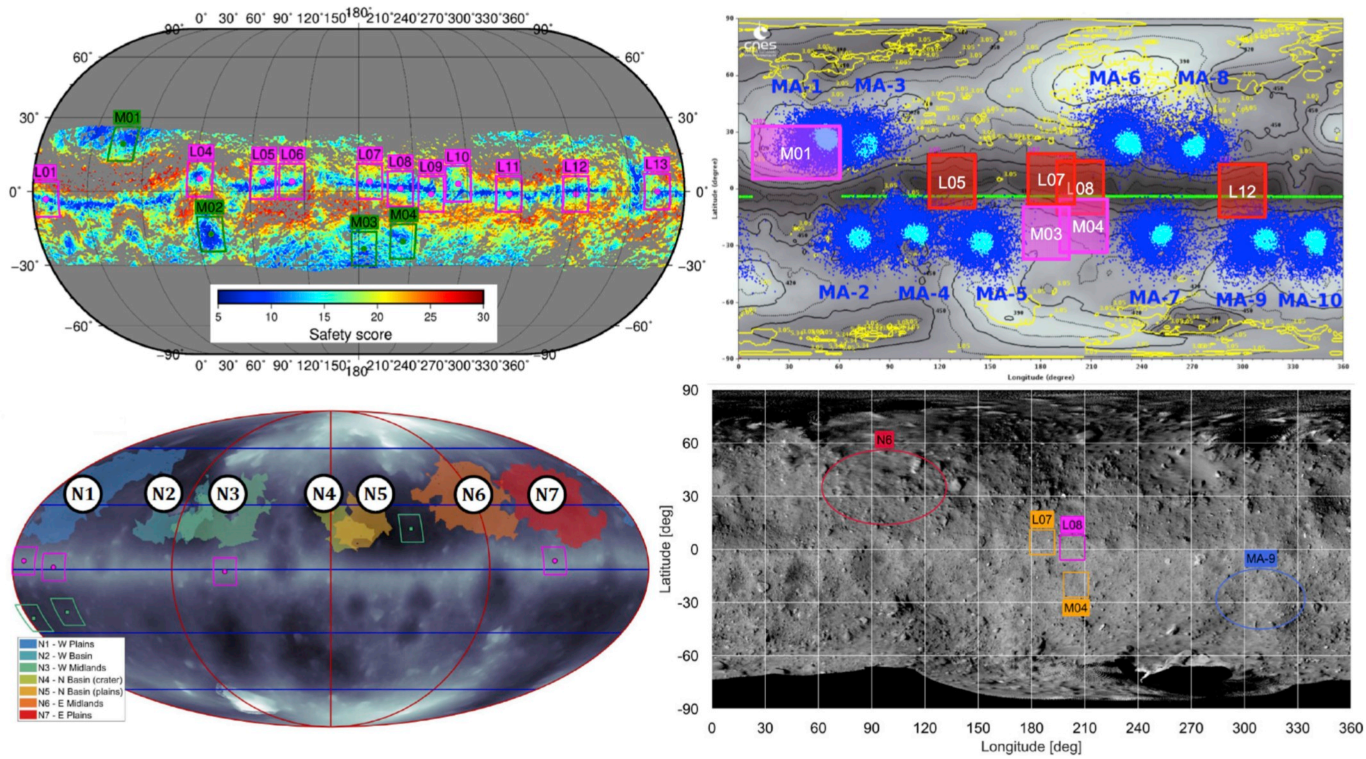

Fig. 2. (Top left) Landing site candidates of Hayabusa2 designated by L01 … L13 and M01 … M04. The size of each box is 100 m × 100 m (Top right) Landing site candidates of MASCOT, designated by MA-1 … MA-10, superimposed with some landing candidates of Hayabusa2 to check the interference. (Bottom Left) Landing site candidates of MINERVA–II–1, designated by N1⋯N7, superimposed with some landing candidates of Hayabusa2. (Bottom right) Finally selected landing candidates for Hayabusa2 (Primary: L08, Backup: L07, M04), MINERVA–II–1 (N6) and MASCOT (MA-6). (Image credit: JAXA, U. of Tokyo, DLR, CNES and collaborators).

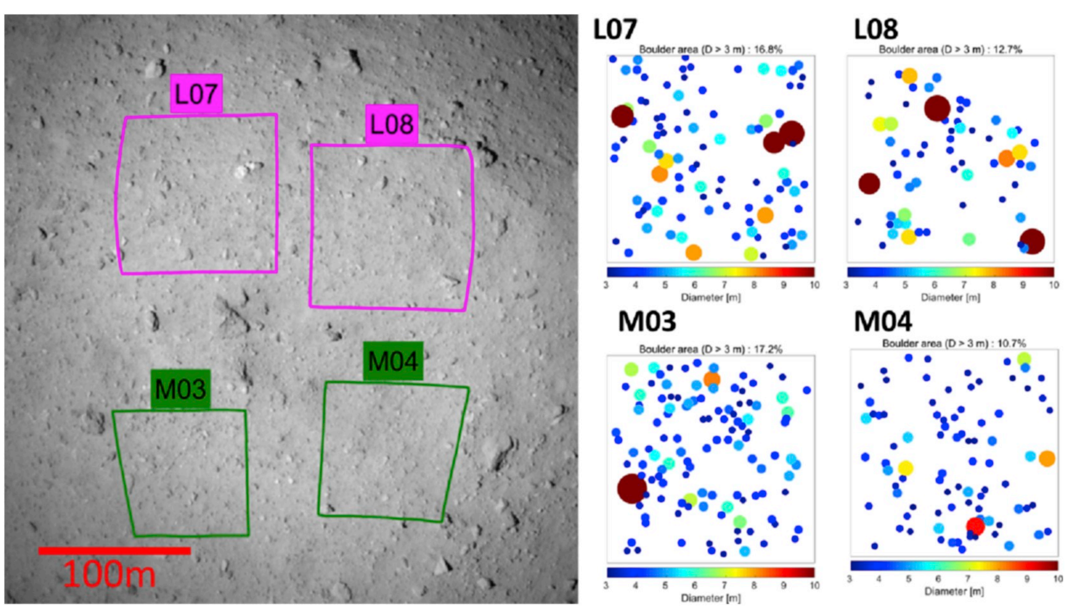

Fig. 3. (Left) An ONC-T image of the Hayabusa2 landing candidates L08, L07 and M04, captured at the altitude of 5 km, and (Right) Corresponding boulder size distributions.

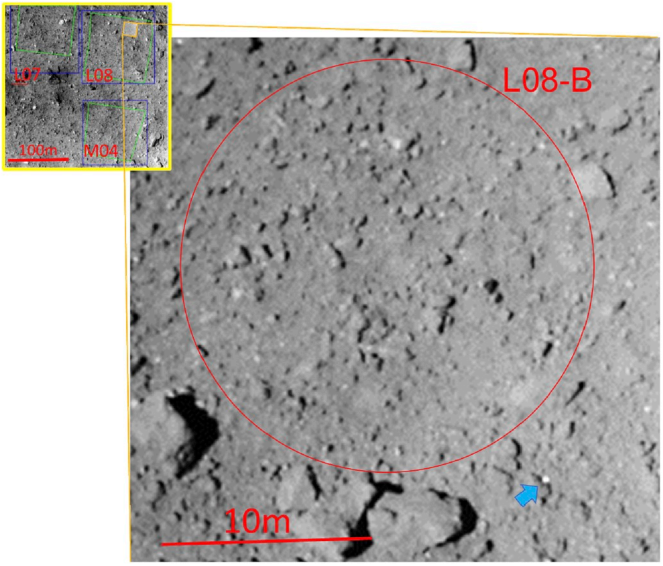

Fig. 4. Narrowed touchdown candidate site L08-B and the Target Marker (indicated by the arrow) dropped in the TD1-R3 operation.

Table 2
Scientific scores of the finalist spacecraft landing site candidates. Point 1 evaluates scientific values of expected sample using surface temperature, visible/near-infrared spectrum etc. Point 2 includes boulder density and surface roughness. Point 3 is evaluated from the viewpoint of surface particle size.

Candidate site	Point 1 surface properties	Point 2 safety	Point 3 Sample yield	Score
L5	22	29	12	63
L7	22	31	12	65
L8	22	31	12	65
L12	22	31	11	64
Ml	21	33	13	67
M3	21	30	13	64
M4	21	33	13	67

surface. The free-fall descent and free-ascent were conducted at an altitude below 5 km to measure the gravity. These two descent operations also enabled us to create a landmark database necessary for the subsequent lower altitude descents, and contributed as an in-situ operation practice of the terrain-relative precision guidance.

2.3. Landing Site Selection (LSS) activity

Selecting landing sites required a variety of high-level products of the asteroid properties. Many level-2 products, such as the shape model (Fig. 1), surface composition map, gravity potential model, temperature map and boulder distributions map were created by integrating and cross-evaluating the raw observation data (level-1 products) obtained through the LSS observation campaign.

Based on these level-2 products, level-3 maps which define candidate sites of the rover/lander/spacecraft landings were created. This level-3 maps were derived by integrating engineering feasibility, operation safety and scientific values.

Fig. 2 top-left shows 15 candidate sites for the spacecraft touchdown derived from engineering constraints. The spacecraft is to land on the surface along the sub-Earth line, and therefore the geometry with relative to the sub-Earth line is important. The sun angle, surface slope and terrain roughness with respect to the sub-Earth line have been evaluated based on the shape model of Ryugu. The pre-launch spacecraft design required 50 m (2.5σ) landing accuracy. Hence the 15 boxes shown in the top left of Fig. 2 all have the size of 100 m × 100 m.

Specifically for Ryugu, the major driver for deriving the spacecraft touchdown site candidates was engineering constraints (especially safety), reflecting the fact that the surface property of Ryugu is homogenous. Table 2 shows the scores evaluated by the science team for some of the candidate sites (the evaluation itself was done for all the candidate sites), showing that the scientific values of all the candidate sites are almost equal [5].

The landing site candidates for MINERVA–II–1 (Fig. 2 bottom-left) and MASCOT (Fig. 2 top-right) were derived by the Hayabusa2 spacecraft operation team and the DLR/CNES MASCOT team, respectively from the viewpoint of engineering constraints (c.f. Surface temperature, surface roughness, day-night ratio, landing dispersion) and scientific values.

The "LSS Decision Meeting" was held on August 17, 2018 to review all of the level-3 products and to derive a consistent set of landing sites for MINERVA–II–1, MASCOT and the spacecraft. The meeting was attended by 109 members including spacecraft engineers, science PIs and international scientists. Thanks to extensive training and dry-runs having been done before arrival [6], including a "simulated LSS decision meeting" held on September 5, 2017, the meeting reached a conclusion smoothly in one day with dense and constructive discussions. A set of landing site (MINERVA–II–1: N6, MASCOT: MA-9, Spacecraft: L08) with two backup spacecraft touchdown sites (L07 and M04) was selected such that these sites should not interfere with each other while maximizing the scientific value and success probability of the landings (see Fig. 2 bottom-right).

The conclusion included an important collateral condition for the spacecraft touchdown site: since none of the candidate sites perfectly fulfilled the touchdown safety due to the high boulder density, as shown in Fig. 3, the project was to search for a safer region within selected candidate sites by additional observations, and at the same time, to improve the landing accuracy to enable the use of narrower landing sites.

2.4. Post-LSS operations

Based on the LSS decision described in Sec.2.2, several critical operations have been conducted.

On September 11–12, the first touchdown rehearsal (TD1-R1) was conducted, targeting the center of the L08 site. This was the first attempt to descend to lower than 30 m to demonstrate the surface accessibility performance of Hayabusa2 and to determine the characteristics of LRF (laser range finder) which is a critical component for the autonomous operation of Hayabusa2 below 30 m. The operation was aborted at the altitude of 600 m and the spacecraft automatically ascended back to HP. The cause of it was an prematured LIDAR setting due to the very low reflectance surface of the asteroid, and the spacecraft failed to measure the altitude.

On September 20–21, the MINERVA–II–1 rovers release operation (MNV1) was conducted. This was followed by the MASCOT lander release operation (MSC) on October 2–5, both of which were successful (see Sec.3.1 and 3.2 for details).

At the time MSC operation completed, the project decided a new strategy toward realizing the spacecraft touchdown. Based on three descent operations completed in September–October 2018, the terrain relative guidance accuracy performance was evaluated to be approximately 15 m, which was far better than the original specification of 50 m. On the other hand. Due to the aborted TD1-R1 operation, the LRF

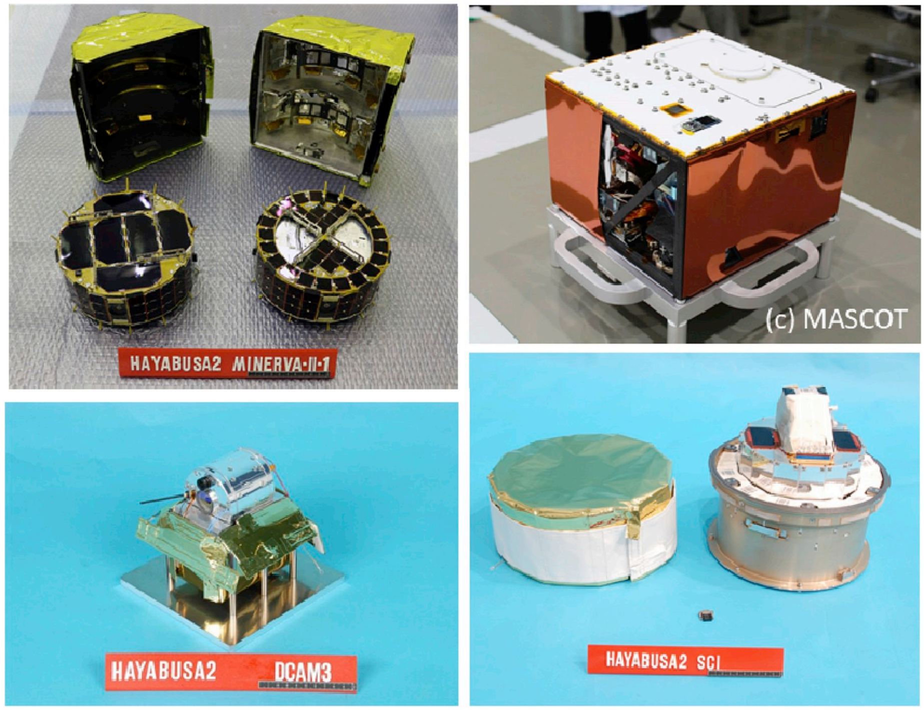

Fig. 5. (Top left) MINERVA–II–1 rovers, left: Rover-A "HIBOU", right: Rover-B "OWL", (Top right) MASCOT lander, (Bottom left) DCAM3 deployable camera, (Bottom right) Small Carry-on Impactor (SCI).

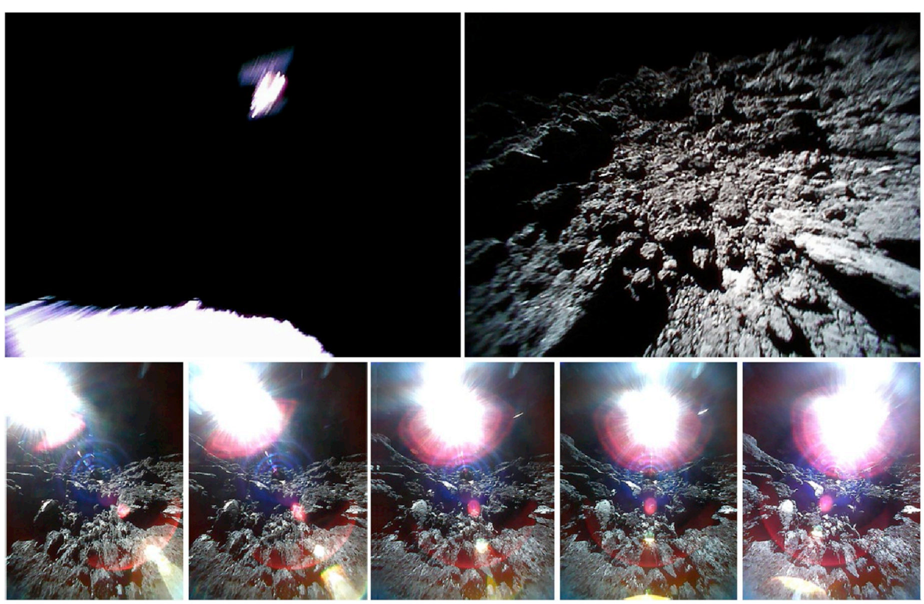

Fig. 6. (Top left) Image of Hayabusa2 taken by Rover-1A on September 21 at 4:08UT right after the separation. (Top right) Close-up image of Ryugu surface taken by Rover-1B on September 23 at 0:46UT. (Bottom) A series of images captured by Rover-1B on the Ryugu surface between 1:14–02:48UT on September 23.

performance had not been obtained. Thus the project decided to do two additional touchdown rehearsals (TD1-R1A and TD1-R3) before the actual touchdown operation. TD1-R1A was basically a retrial of TD1-R1 to acquire the LRF performance. TD1-R3 was to deploy the target marker (TM) on ground to precisely evaluate the our terrain relative guidance capability and the autonomous TM-tracking control performance of Hayabusa2. The TM is a 10 cm-diamter ball covered with a retro-reflective sheet. Hayabusa2 is equipped with a flash lamp (FLA). The combination of TM and FLA enables autonomous terrain relative control by a bright-spot tracking which is tolerant against highly uncertain surface conditions. The target site of these two operations was set at L08-B1, the diameter of which is 20 m. The location was selected because it is the flattest region in the L08 area.

We succeeded in conducting TD1-R1A on October 14–15 and TD1-

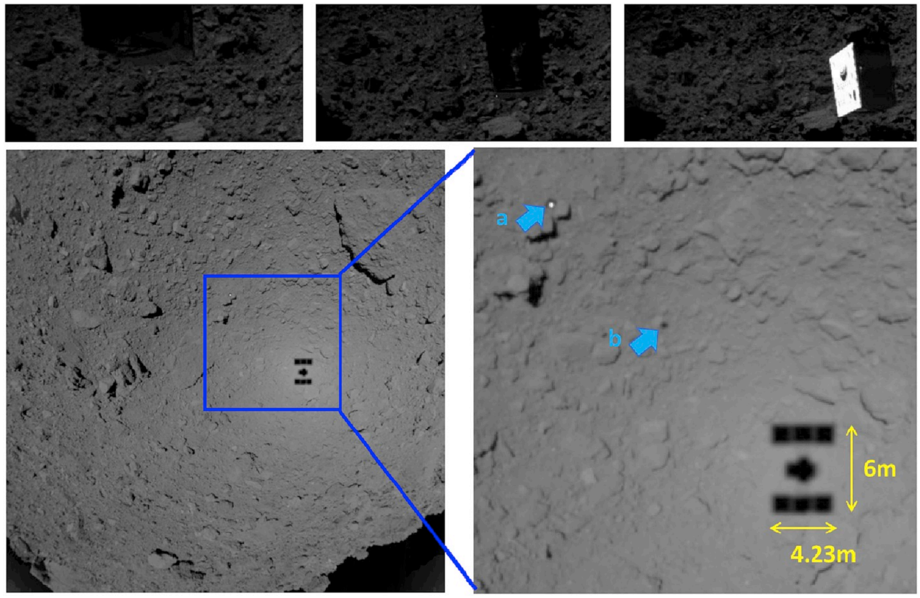

Fig. 7. (Top) Images taken by ONC-W2, attached on the side of the spacecraft, at the moment of MASCOT separation (October 3, 1:57:54–1:58:14UT). (Bottom) Falling MASCOT taken by ONC-W1 on October 3, 2018 at 1:59:40UT. MASCOT (arrow a) and its shadow (arrow b) are seen in the image.

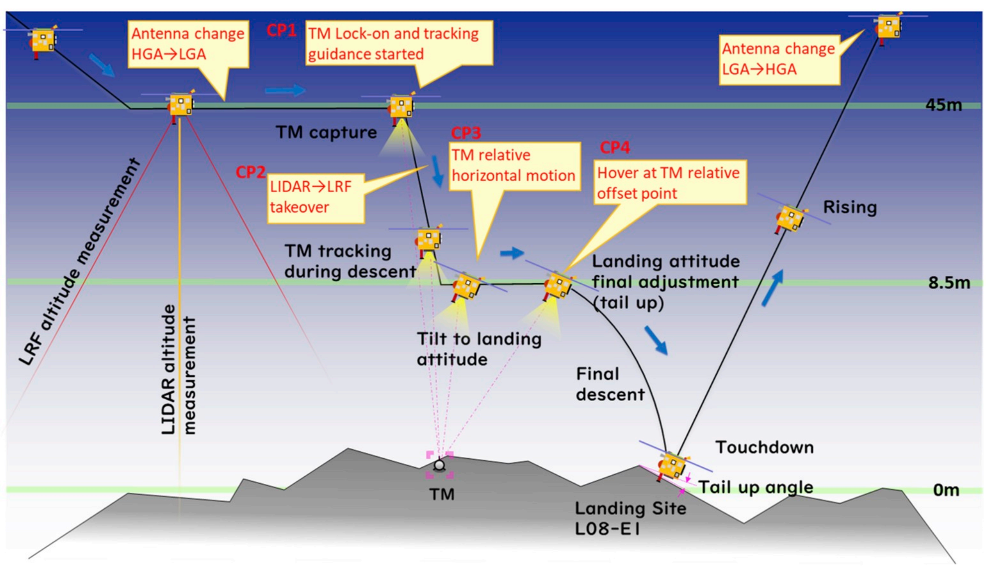

Fig. 8. Low altitude autonomous sequence of touchdown operation TD1-L08E1. CP indicates onboard autonomous "Check Points"; CP1: TM lock and start tracking, CP2: LIDAR to LRF takeover, CP3: 8.5 m arrival convergence, CP4: Final pre-free fall position and attitude convergence.

R3 on October 24–25. After TD1-R3 the TM was identified as settled on the surface, 15.4 m from the targeted center (Fig. 4). The success of TD1-R3 marked a critical milestone for the project for two reasons, (i) the dropped TM location indicates that our terrain-relative guidance is as good as around 15 m, and (ii) the autonomous TM tracking capability at very low altitude (~12 m) was confirmed to have ± 1 m TM-relative positioning accuracy in the Ryugu environment. These results opened a possibility toward a TM-relative pin-point touchdown which had not been planned originally, and is described in Sec.3.3.

3. Critical operation achievements

3.1. MINERVA–II–1 rover deployment operation

The two MINERVA–II–1 rovers (Rover-1A named "HIBOU" and Rover-1B named "OWL", Fig. 5 top-left) were deployed from the spacecraft at an altitude of 55 m on September 21 at 4:06UT. A horizontal ΔV of 0.2 m/s was executed right before the separation to compensate for the fast ejection velocity of the rovers, thereby ensuring that the rovers would not exceed the escape velocity of Ryugu. The terrain-relative guidance accuracy at the time of release was 3.3 m.

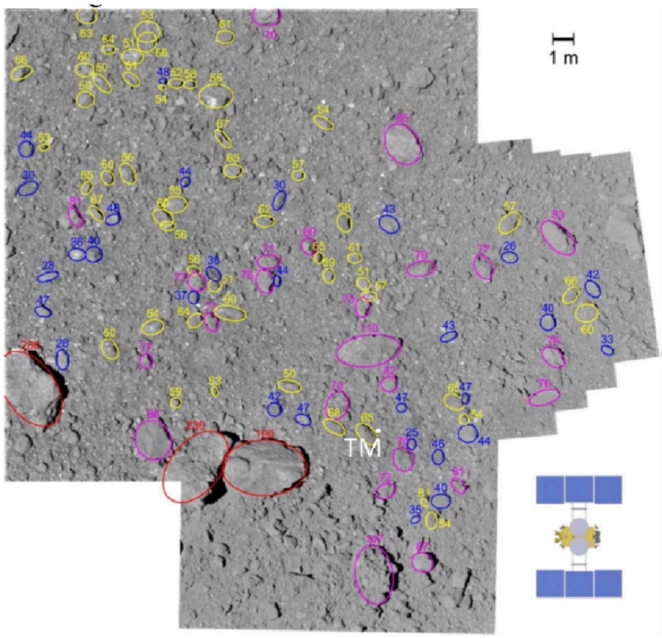

Fig. 9. Boulder distributions around the dropped TM. The ellipses indicate identified big boulders with the numbers indicating their estimated height in centimeter.

The two rovers were confirmed active immediately after deployment, and some images captured by the rover onboard cameras were received by Hayabusa2. Two rovers are designed to do hopping-observation cycles autonomously on the asteroid surface for unlimited duration, powered by body-mounted solar cells, On Sol 4 (i.e., fourth asteroid rotation), Rover-1A was confirmed doing some autonomous hops, and Rover-1B as well on Sol 7. The final decodable telemetry was received on Sol 114 for Rover-1A and Sol 10 for Rover-1B. The carrier signal of Rover-1B was successfully received again on August 2, 2019 for about 10 min at rather distant location from the original landing point, which indicates that the rover has acted on the Ryugu surface for more than 10 months.

Over the time of the entire MINERVA–II–1 operation, a few hundreds of images, including movies and stereo images, as well as surface temperature were obtained (Fig. 6). The two rovers became the world's first mobile landers to be successfully operated on a small body. Landing site N6 was nicknamed "Tritonis" by the MINERVA–II–1 team.

3.2. MASCOT lander deployment operation

The MASCOT lander (Fig. 5 top-right), developed by DLR and CNES was successfully deployed from the spacecraft at the altitude of 51 m on October 3 at 1:57UT. Separation was later confirmed by the Hayabusa2 onboard cameras ONC-W2 and ONC-W1 (Fig. 7). No horizontal compensation was executed for this release, as the MASCOT separation mechanism deploys the lander very slowly (~5 cm/s). The terrain-relative guidance accuracy at the time of release was 30 m.

Different from MINERVA-II rovers, MASCOT is driven by a primary battery and can be active for 17 h from the time of separation (i.e. 3-4 Sols). The project team prepared the biggest operation organization for this operation. The operation center for the MASCOT was placed in Cologne, Germany, and was connected online to the Sagamihara Space Operation Center (SSOC; operation center for Hayabusa2 in Japan). A 24 h continuous coverage was prepared to cover the entire life time of MASCOT using ground stations of JAXA Usuda Deep Space Center, NASA Deep Space Network, and the ESA (ESTRACK) Malargue station. The MASCOT telemetry and command operations were performed through the rover communication component (OME-E) which enabled simultaneous two-way communication with MASCOT and all the MINERVA-II rovers.

MASCOT was confirmed active immediately after release, and landed in the MA-6 region a few minutes later after some bouncing. On Sol 1, the lander was found to be sitting on the surface with inappropriate orientation. Hence the MASCOT team decided to command a "hop" on Sol 2, which was successful. Thereafter, extensive scientific observations were performed on Sol 2–3. On Sol 3 a small relocation hop was commanded by the MASCOT team to do some additional observations at a different attitude, and this was also successful. The last telemetry was received in the dawn of Sol 3, and the battery was estimated to have been depleted after 17 h of the successful surface activity [7–9]. The landing site MA-6 was nicknamed "Alice's Wonderland" by the MASCOT team.

3.3. First touchdown and sampling operation

The original touchdown sequence used the Target Marker (TM) to eliminate the terrain-relative velocity at the final phase of landing.

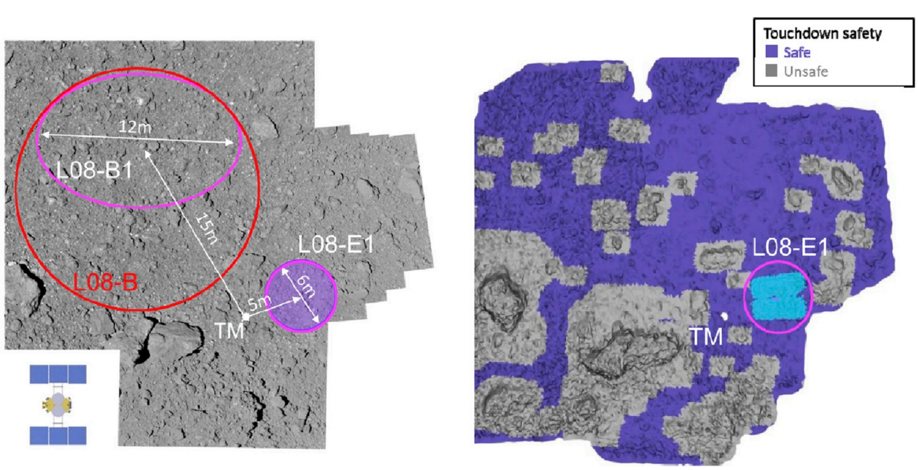

Fig. 10. (Left) Two final candidates for touchdown site L08-B1 and L08-E1. (Right) A Monte-Carlo simulation result based on finalized touchdown sequence of Hayabusa2 for TD1-L08E1 operation.

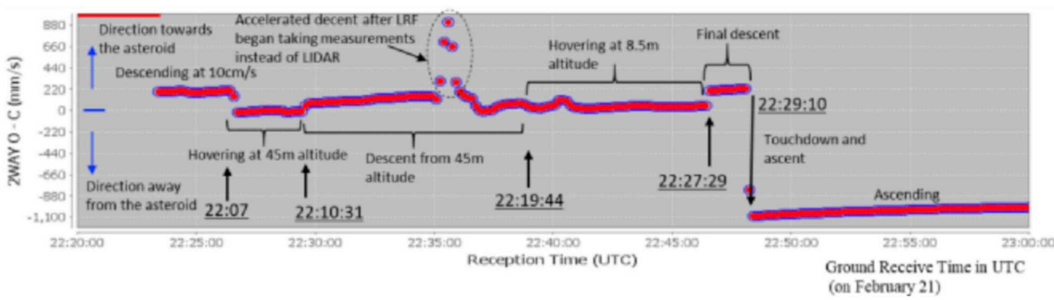

Fig. 11. The Doppler signal observed on ground at the moment of touchdown in TD1-L08E1 operation. The vertical axis is “2-way O–C”, which is twice the value of the line-of-sight velocity of the spacecraft, relative to the asteroid.

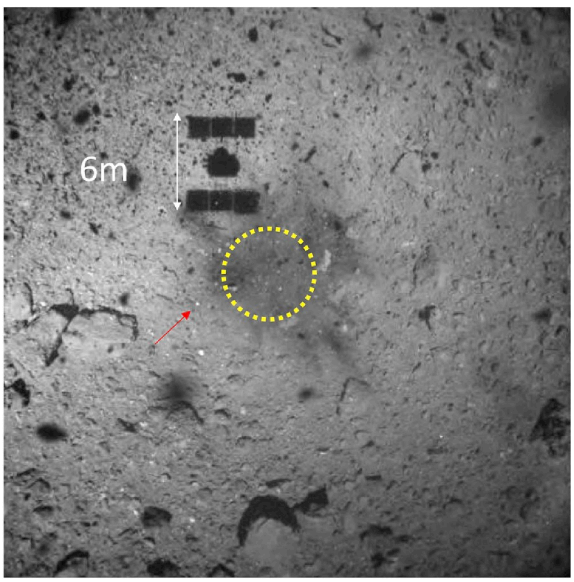

Fig. 12. ONC-W1 image captured after touchdown at February 21, 22:30UT at the altitude of approximately 25 m. Boulder distributions around the dropped TM. The circle indicates the 6 m circle of the landing target L08-E1, and a bright dot at the arrow tip is the Target Marker.

From the result of TD1-R3, as described in Sec.2.4, however, the project team acquired great confidence in the TM-tracking capability of Hayabusa2, and decided to re-configure the onboard guidance program such that the final landing sequence should use the TM for terrain-relative position control in addition to the velocity compensation.

This technique had been prepared for the crater landing and is called “pin-point touchdown”, which would have been planned to be used after the kinetic impact operation, which is described in Sec.3.4. With this original pin-point touchdown as a basis, some modifications appropriate for the L08-E1 landing were applied. For example, four “check points” (Fig. 8) were implemented onboard for the autonomous sequence below 45 m such that, if the pre-programmed status conditions were not fulfilled, the spacecraft is to automatically abort and the ascent-back ΔV is to be triggered. The second example is a “tail-up” attitude (Fig. 8) adopted for the final touchdown attitude so as to minimize the risk for any part of the spacecraft body other than the sampler horn hitting the terrain. By tilting up the attitude by 10° from the locally horizontal attitude, an additional 10 cm margin was gained for the minimum distance between the local terrain and spacecraft body.

In terms of our terrain knowledge, high resolution images obtained in a series of low altitude operations (i.e., MNV, MSC, TD1-R1A and TD1-R3) enabled us to create a precise boulder distribution map (Fig. 9) and a digital elevation map (Fig. 10 right) with a few centimetre accuracy, which was good enough for a sub-meter level safety evaluation. Using on these maps, two new landing candidate sites were found within the L08 area, L08-B1 and L08-E1 (Fig. 10 left). L08-B1 is located 15 m from the already-dropped TM, and spans about 12 m. L08-E1 is located 4.2 m from the TM, and spans about 6 m.

Combining these two progresses (i.e. improvements in touchdown accuracy and terrain knowledge), the project team decided to choose L08-E1 for the first touchdown target. L08-E1 is a narrower region but closer to the TM than L08-B1, and was found to be the only feasible region that Hayabusa2 can target using the updated landing accuracy (Fig. 10 right).

Touchdown operation 1 (TD1-L08E1) was conducted on February 19–22, 2019. Due to a miss-configuration in the pre-descent activity, the start of descent was delayed by 5 h, which was recovered by adopting a faster descent rate trajectory to catch up with the original descent path at around the altitude of 6.5 km. The spacecraft was sent the “Go” command for autonomous landing on February 21 at 21:10UT while at an altitude of approximately 500 m, and reached the altitude of 45 m at 22:07UT. Then the spacecraft successfully captured and locked the TM, and started TM-tracking descent to 8.5 m. At 8.5 m, a horizontal maneuver was triggered, and the spacecraft moved about 4 m toward northeast. On converging the horizontal motion, the final free-fall descent was triggered autonomously, and the spacecraft touched the surface at 22:29:10UT. One of four touch down detection sources (i.e., attitude rate limit) was triggered, when a projectile was ejected and an ascent-back ΔV was executed 0.1sec later as planned. Four 20 N thrusters on the bottom of the spacecraft were activated for 4.7 s to attain the total ascend-back ΔV of 0.64 m/s. The autonomous activity below 45 m was done with non-Earth pointing attitude, limiting the communication link to Earth only using a low gain antenna. Therefore, the low altitude onboard activity was monitored on ground solely by the carrier signal receive power and the Doppler signals (Fig. 11).

The successful touchdown was soon confirmed through the playback telemetry of rising temperature of the fired projector at the touchdown, and also of the sequence progressing normally as pre-programmed. There are three container rooms in the Hayabusa2 sampling system. As we confirmed the touchdown, the sampler room A was commanded “Close” on February 22 at 2:20UT, and the sample collected in the TD1-L08E1 operation was secured.

The moment of touchdown was recorded by the ONC-W1 (Fig. 12)

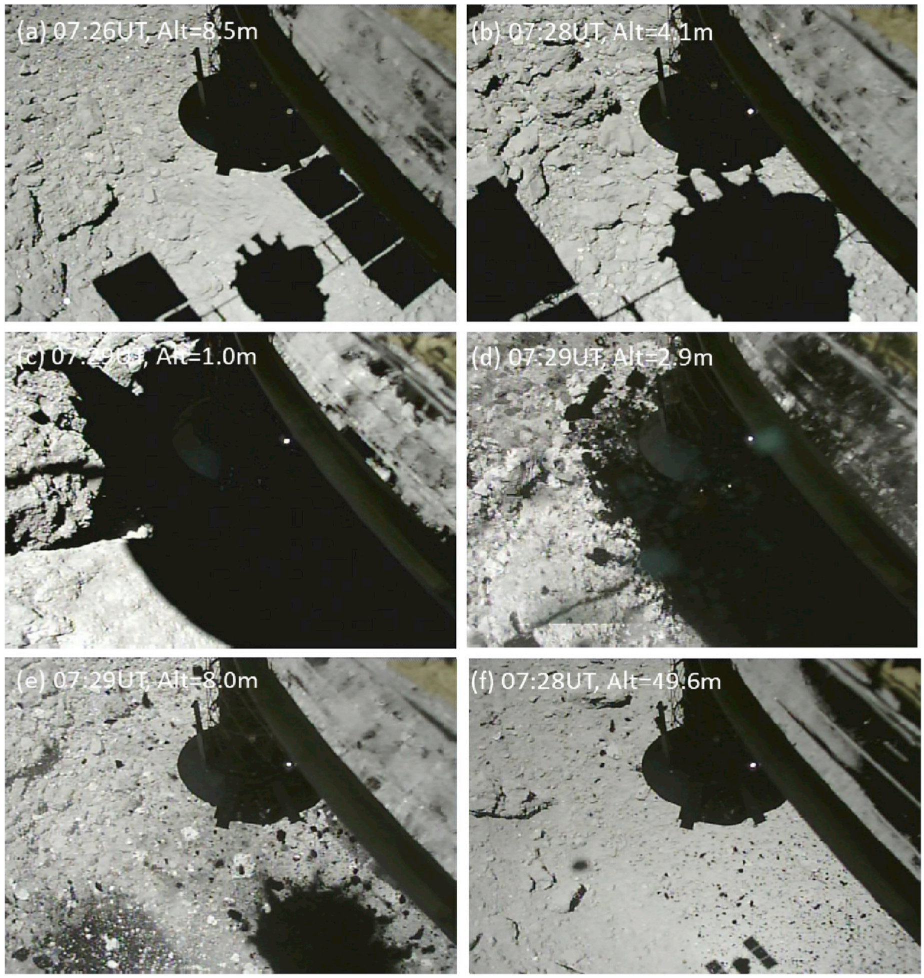

Fig. 13. A series of images captured by CAM-H before (a–c) and after (d–f) the touchdown.

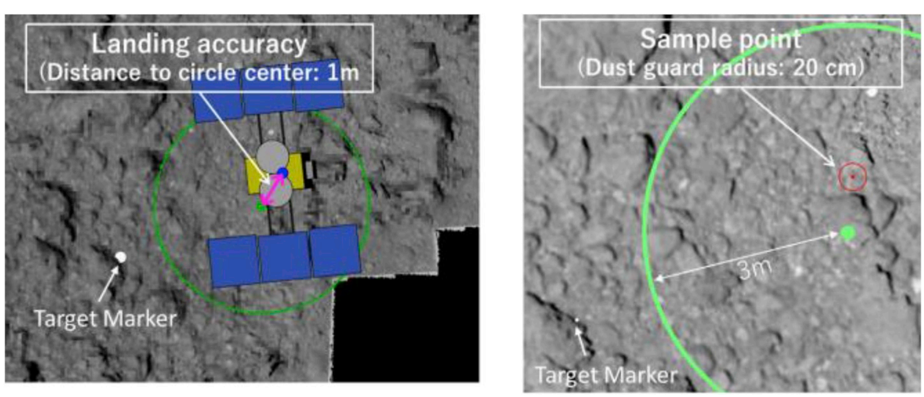

Fig. 14. Post analysis result of the touchdown accuracy (left), and the sample point (right) for TD1-L08E1 operation.

and CAM-H (a sampler-horn monitor camera, Fig. 13). As observed in these images, many fragments were seen to be ejected as the reaction of to shooting the projectile and the ascend-back ΔV. Processing images from these cameras revealed that the resulting landing accuracy was 1 m, which was within the L08-E1 requirement accuracy of 3 m. The sampling location was also resolved precisely, which was 20 cm off from the center of L08-E1 (Fig. 14).

Landing site L08-E1 was then nicknamed “Tamatebako” (meaning

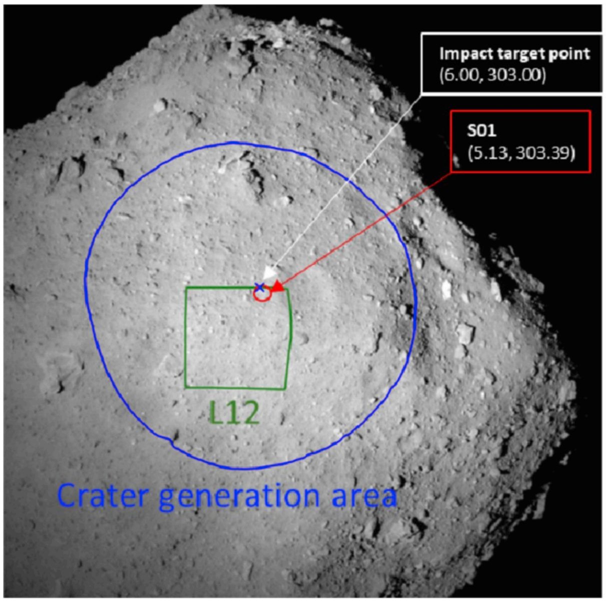

Fig. 15. Impact target for SCI kinetic impact operation with 200 m dispersion radius.

"Treasure Box") by the Hayabusa2 project team.

At this moment, as we had spent 4 months longer than the original plan to achieve the first touchdown, a decision was made to cancel the second touchdown, which had been performed after the first touchdown, and to directly move on to the kinetic impact operation.

3.4. Kinetic impact operation

The kinetic impact was to be done using "Small Carry-on Impactor (SCI)" (Fig. 5 bottom-right). It weighs 15 kg and was mounted on the bottom of the spacecraft. SCI is to be ignited by an onboard timer, and the 2 kg copper bullet is to be ejected at the speed of 2 km/s. For the operation planning purpose, the targeting accuracy from the nominal stand-off distance of 500 m was set to be as conservative as 200 m (3σ), which included the accuracy of SCI acceleration itself as well as the spacecraft attitude and guidance errors. Because of this relatively large dispersion, SCI was planned to be released exactly on the Sub-Earth line, leading to a constraint that the center of the impact target should be on the equatorial ridge of Ryugu.

The target point of the kinetic impact was called "S01" region, which is located on the equatorial ridge of Ryugu, apart longitude-wise from the L08 landing site (Fig. 15). There are two requirements on the kinetic impact target site; (i) maximizing the possibility to create a large crater detectable by the post-impact observations by the onboard instruments, and (ii) maximizing the landability in terms of terrain condition (for safety). S01 was found through the global survey activity which had been done in parallel with the first touchdown activity. Due to the highly homogeneous surface property of Ryugu, the main driver for selecting the impact site was (ii) rather than (i). S01 was found to maximize (but not to fulfil due to the very large impact dispersion) the landability condition.

Prior to the SCI operation, two critical operations were performed. One is the S01 low altitude descent observation (DO-S01, March 6–8, 2019), another is a pre-impact crater search operation (CRA1, March 19–22, 2019). These two operations provided the original (pre-impact) terrain information around the SCI target. After the SCI operation, a post-impact crater search operation (CRA2) was conducted, which enabled us to compare images before and after the impact.

The SCI operation was conducted on April 14–16. The spacecraft reached the bottom altitude of approximately 500 m and released the SCI on April 5 at 1:56UT. The spacecraft autonomy worked perfectly as planned and followed the pre-programmed path to the backside of the asteroid from the impact point to avoid the ejecta and debris of the SCI ignition and impact. On its way of escaping, the Hayabusa2 released a deployable camera called "DCAM3" (Fig. 5 bottom-left) at 2:14UT, which successfully observed the impact event (Fig. 16). The impact occurred at 2:37UT.

As the result of the CRA2 operation conducted on April 13–16, the artificial crater generated by SCI was found (Fig. 17). The diameter of the crater was measured to be 13 m, and was located approximately 25 m off from the aim point, which is far better targeting accuracy than anticipated. The SCI crater was then nicknamed "Omusubi-Kororin (meaning "rolling rice ball" from a Japanese fairly tail).

3.5. Second touchdown and sampling operation

The objective of the second touchdown (codenamed as PPTD) was to sample subsurface material exposed by the kinetic impact. By evaluating images from the CRA2 operation, and by applying the same landability condition as the TD1-L08E1 operation, as many as 11 touchdown candidate sites with wider than 6m-diameter flat terrain were found within 30 m from the crater. On the other hand, a scientific evaluation revealed that the ejecta deposit distribution was thick in the North of the crater and very faint in the South (Fig. 18). Hence the project chose C01-Cb site which is closest among the sites located North to the crater. C01-Cb spans 7 m in diameter and is located 20 m distant from the center of the SCI crater.

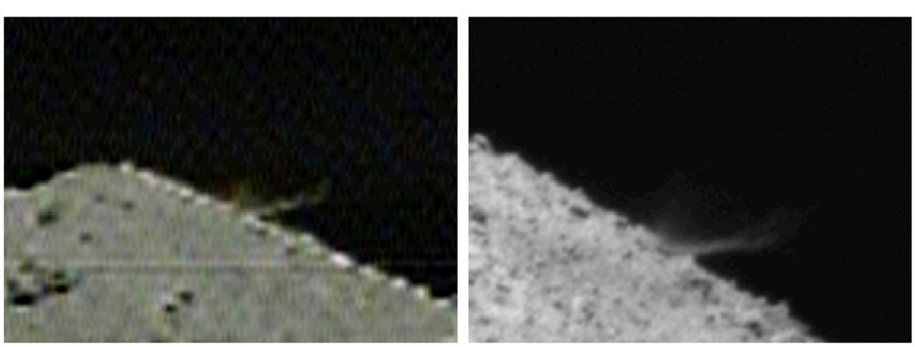

Fig. 16. Impact event captured by two cameras equipped on DCAM3, (left) DCAM3-A (640 × 480 pixels analog camera), 2 s after impact, (right) DCAM3-D (2000 × 2000 pixels digital camera), 3 s after impact.

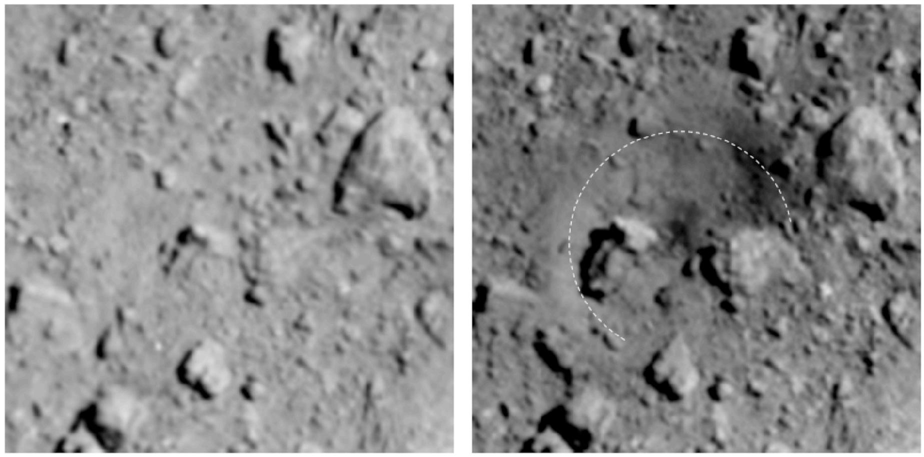

Fig. 17. Terrain change by kinetic impact operation, (left) impact point observed before the SCI impact in CRA1 operation, (right) after the SCI impact observed in CRA2 operation. The white dashed line shows the crater diameter of 13 m.

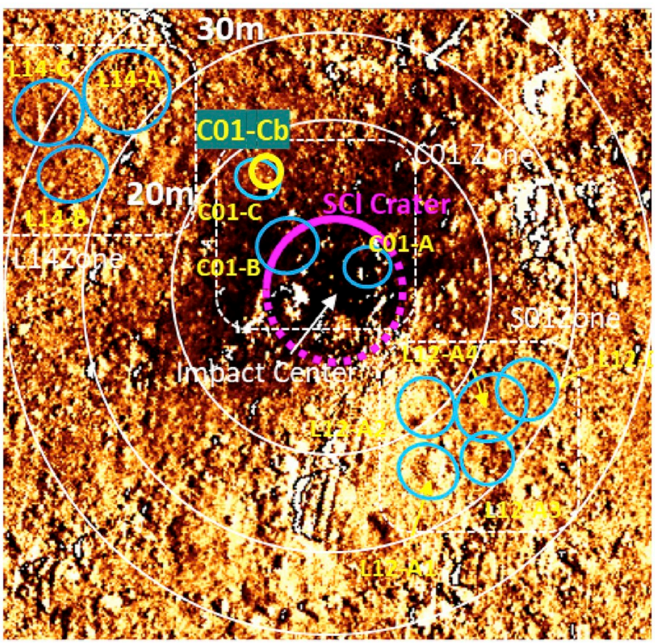

Fig. 18. Map of ONC-T v-band reflectance factor difference between before and after the SCI impact around the SCI crater. Dark region corresponds to thick ejecta deposit. Blue ellipsoids indicate identified touchdown candidate sites. C01-Cb is the decided touchdown target for PPTD. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Prior to PPTD, three rehearsal descents were conducted for the purpose of landing site survey and operation practice. In the second rehearsal descent (designated as PPTD-TM1A), a TM was dropped in the C01-Cb site. The operation was successful, and the TM was placed within the C01-Cb region, just 2.6 m off from the center (Fig. 19). The project team decided to use this TM for PPTD, and to aim at the center of C01-Cb for landing.

The spacecraft suffered degradation in two optical instruments ONC-W1 and LRF in the TD1-L08E1 operation. These two instruments play critical role in the low altitude autonomous touchdown sequence. Due to a dynamic reaction from the surface soil in the TD1-L08E1 operation (as seen in Fig. 13), optical lenses were covered by dust and the sensitivity was reduced to approximately 70%. To compensate for this optical degradation, the altitude for entering the full-autonomous mode was lowered to 30 m from the original 45 m. This required better guidance accuracy above 30 m to appropriately “lock” the TM by the onboard camera with narrower FOV coverage, and also finer altitude control precision below 30 m to guarantee collision-safe maneuver against closer terrain.

The spacecraft left HP at the descent rate of 0.4 m/s on July 10, 2019. The descent rate was reduced to 0.1 m/s at the altitude of 5 km a half day later. The project gave “Go” for the full-autonomous mode at July 11, 00:12UT. The spacecraft reached 30 m at 00:41UT and successfully locked the TM with ONC-W1. The all the autonomous sequence proceeded perfectly as planned, and the touchdown to the ground occurred at July 11, 01:06:18UT. The sample container room C was used in PPTD, which was closed after we confirmed the successful touchdown at 5:10UT on July 11, 2019.

The post-operation analysis revealed that the landing accuracy for PPTD was 0.6 m (Fig. 20). The landing site C01-Cb was then nicknamed “Uchideno-kozuchi” (meaning “Treasure Hummer”) by the Hayabusa2 project team.

3.6. Target Markers/MINERVA–II–2 orbiting operation

Two more semi-critical operations were conducted after PPTD. One is the Target Markers (TMs) orbiting operation (TM-ORB), in which the two TMs were released from the spacecraft at the terrain altitude of 1 km with fine-tuned velocity. The TM-ORB operation was planned to provide an additional contribution to the gravity science, and was also prepared as a rehearsal for the following MINERVA–II–2 orbiting operation. The first TM was inserted onto an equatorial orbit at 16:17:40UT, September 16, 2019, and the second TM was inserted onto a polar orbit at 16:24:20UT on the same day. The TMs were then observed from the spacecraft holding at 20 km sub-solar point using ONC-T camera from the separation until September 23 successfully.

The last semi-critical operation was the MINERVA–II–2 orbiting operation (MNRV-ORB), in which the MINERVA–II–2 rover, developed by Tohoku University and the Japanese University Consortium, was released from the spacecraft at the terrain altitude of 1 km onto an equatorial orbit. The main computer of the MINERVA–II–2 rover had

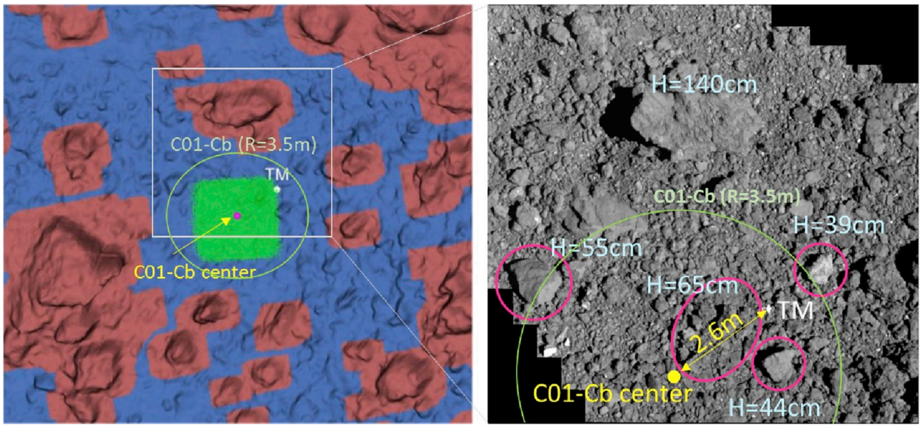

Fig. 19. (Left) Landing dispersion analysis. Green dots indicate the landing dispersion obtained by a Monte-Carlo simulation. Blue region indicates safe for landing, and red region indicates unsafe. (Right) High resolution image taken in PPTD-TM1B operation. Red ellipsoids indicate boulders marked for special safety caution with their estimated height. "TM" indicates the location of the target maker dropped in PPTD-TM1A operation, and "C01-Cb" indicates the landing target of the PPTD operation.

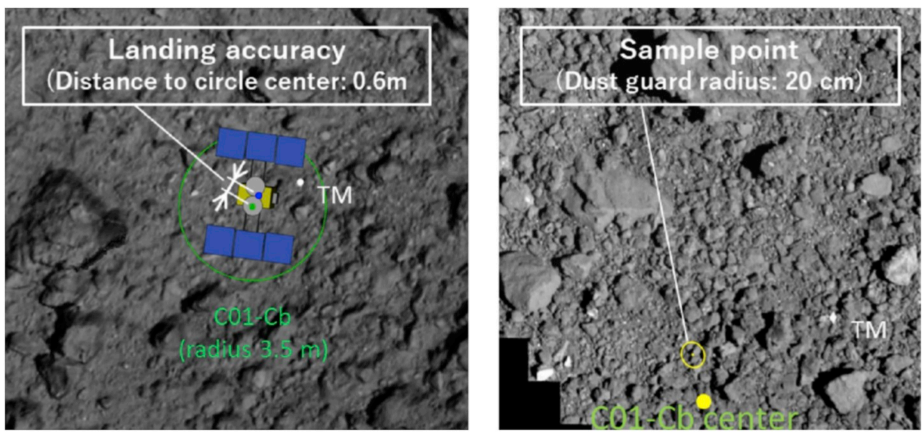

Fig. 20. Post analysis result of the touchdown accuracy (left), and the sample point (right) for PPTD operation.

been found to be unfunctional, and therefore the objective of the mission was changed to more focus on the behaviour of the rover from separation until landing rather than post-landing activity. The separation occurred at 15:57:20UT on October 2, 2019 and the orbiting MINERVA–II–2 rover was observed from the spacecraft's ONC-T/ONC-W1 camera at the altitude of 8–10 km from the separation until October 8. The radio link between Hayabusa2 and MINERVA–II–2 was also confirmed. These measurements are to be also used for the gravity science.

4. Conclusions

Hayabusa2 arrived at an unexplored C-type asteroid Ryugu, and conducted all the planned missions successfully. Fundamental scientific questions about Ryugu have been answered through successful scientific activities, and more fundamental questions have been raised. From the engineering point of view, during one and a half year of the Ryugu-proximity phase, Hayabusa2 has achieved seven "world's firsts", that are (1) mobile activity of rovers on small body, (2) multiple rovers deployment on small body, (3) 60 cm-accuracy landing and sampling, (4) artificial crater forming and detailed observation of impact process, (5) multiple landing on extra-terrestrial planet, (6) subsurface material sampling, (7) Smallest-object constellation around extra-terrestrial planet. Hayabusa2 left Ryugu on November 13, 2019, and is scheduled to return to Earth in November–December 2020.

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References

[1] Y. Tsuda, M. Yoshikawa, M. Abe, H. Minamino, S. Nakazawa, System design of the Hayabusa 2 – asteroid sample return mission to 1999 JU3, ActaAstronautica 90 (2013) 356–362, https://doi.org/10.1016/j.actaastro.2013.06.028.

[2] Watanabe, S., Tsuda, Y., et al., Hayabusa2 Arrives at the Carbonaceous Asteroid 162173 Ryugu—A Spinning Top–Shaped Rubble Pile, Science, Published online 2019/3/19, DOI:10.1126/science.aav8032.

[3] Kitazato, K., et al., The Surface Composition of Asteroid 162173 Ryugu from Hayabusa2 Near-Infrared Spectroscopy, Science, Published online 2019/3/19, DOI: 10.1126/science.aav7432.

[4] Sugita, S., et al., The Geomorphology, Color, and Thermal Properties of Ryugu: Implications for Parent-Body Processes, Science, Published online 2019/3/19, DOI: 10.1126/science.aaw0422.

[5] Yabuta, et al., Landing site selection for Hayabusa2: scientific evaluation of the candidate sites on asteroid (162173) Ryugu, The 50th Lunar and Planetary Science Conference, Houston, USA, No.2304, 2019.

[6] Y. Yamaguchi, T. Saiki, Y. Takei, T. Okada, T. Takahashi, Y. Tsuda, Hayabusa2-Ryugu proximity operation planning and landing site selection, Acta Astronaut. 151 (2018) 217–227.

[7] M. Grott, et al., In-situ determination of thermal inertial of near Earth asteroid (162173) Ryugu using MARA – the MASCOT radiometer, The 50th Lunar and Planetary Science Conference, Houston, USA, No.1267, 2019.

[8] S.E. Schroder, et al., Ryugu as seen up Close by the MASCOT camera, The 50th Lunar and Planetary Science Conference, Houston, USA, No.2450, 2019.

[9] R. Jaumann, et al., Images from the surface of asteroid Ryugu show rocks similar to carbonaceous chondrite meteorites, Science 365 (2019) 817–820.