Initial Achievements of Hayabusa2 in Asteroid Proximity Phase*

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Hayabusa2 arrived at the asteroid Ryugu in June 2018, and as of April 2019, the mission succeeded in conducting two rovers landing, one lander landing, one spacecraft touchdown/sample collection and one kinetic impact operation. This paper describes the initial nine months of the asteroid proximity operation activity of the Hayabusa2 mission, and gives an overview of the achievements thus far. Some important engineering and scientific activities conducted synchronously with spacecraft operations in order to complete all planned operations in time against unexpectedly harsh environment of Ryugu are also described.

Key Words:  Solar System Exploration, Sample Return, Asteroid Mission, Rover and Lander, Kinetic Impact

1. Introduction

The Japan Aerospace Exploration Agency launched the asteroid sample return spacecraft Hayabusa21) atop a Japanese H2A launch vehicle on December 3, 2014. Following the successful return of Hayabusa from asteroid 25143 Itokawa, the aim for Hayabusa2 is a 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 a successful sample return may provide fundamental information regarding the origin and evolution of terrestrial planets, as well as the origin of water and organic matter delivered to the Earth.

Hayabusa2 successfully arrived at Ryugu on June 27, 2018 after 3.5 years of ion engine-assisted interplanetary cruising, and began the asteroid-proximity operation phase. This paper describes the initial nine months of the asteroid proximity operation activity of the Hayabusa2 project, and gives an overview of the achievements thus far. The achievements include successful rover/lander operations, touchdown and kinetic impact, as well as scientific and engineering activities conducted synchronously with spacecraft operations in order to complete all planned operations in time against unexpectedly harsh environment of Ryugu.

2. Asteroid Proximity Operation

2.1. Initial Ryugu observations

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 towards the 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 0.96–1.4 AU, and the Earth-asteroid distance varies between 2.0–2.4 AU, which corresponds to the round-trip light time of 33–40 min.

Hayabusa2 established a hovering state at HP and started initial observations of Ryugu using remote science instruments, such as a multiband optical navigation camera-telescopic (ONC-T) imager (image in Fig. 1), an optical navigation camera-wide (ONC-W1) imager, a thermal infrared (TIR) imager, a near-infrared spectrometer (NIRS3) and a laser altimeter (LIDAR).

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-II1 rovers, one MASCOT lander, and one spacecraft touchdown. The other sites (for the kinetic impact, second touchdown and MINERVA-II2 rover) were to be derived in the next LSS activity in 2019.

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*Received 10 July 2019; final revision received 21 November 2019; accepted for publication 12 December 2019.
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Fig. 1. (Left) An ONC-T image captured at HP on June 30, 2018. (Right) Shape model generated during LSS activity. (Image credit: JAXA, Univ. of Tokyo, Kochi Univ., Rikkyo Univ., Nagoya Univ., Chiba Tech., Meiji Univ., Univ. of Aizu, AIST, Kobe Univ.)
Through these activities, it was revealed Ryugu has an oblate body 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 a period of 7.63262 hr. The spectral data obtained by the ONC-T and NIRS3 indicate Ryugu is a carbon-rich (Cb)-type asteroid with a very low geometric albedo of 4.5%, and was later proved to contain hydroxyl (OH)-bearing minerals all over the globe. 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 diameters larger than 20 m, which led to the primary difficulty that the Hayabusa2 mission faced for deriving feasible landing sites. The gravity of Ryugu was measured to be $GM = 30:0 \text{m}^3/\text{s}^2$ as the result of a free-fall operation conducted on August 5–7, 2018 and some other free-drift operations. This GM corresponds to the bulk density of 1.19 g/cm$^3$, suggesting that Ryugu is a rubble pile.

We categorize a descent operation from the HP using a landmark tracking guidance system called Ground Control Point Navigation (GCP-NAV) as the “critical operation.” Two critical operations were conducted during the LSS observation camping phase. On July 31–August 2, a “mid-altitude descent observation” was conducted, in which the spacecraft descended to 5 km and stayed there for 8 hr to obtain high-resolution observations for one rotational period. On August 5–7, a “gravity measurement descent” was conducted, in which the spacecraft descended to 851 m above the 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 creation of the landmark database necessary for upcoming lower-altitude descents, and worked as an in-situ operation practice of the terrain-relative guidance technique.

2.2. LSS activities

Selecting landing sites required a variety of high-level products of the asteroid property. 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 observation data (level-1 products) obtained through the LSS observation campaign.

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

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

The scientific value of each landing site was evaluated using a pre-agreed measure for scoring based on (1) diversity of topographic features and geology of Ryugu, (2) distributions of hydrous minerals, (3) carbon contents, and (4) secondary topographic features and geology of Ryugu, (2) distributions ining a pre-agreed measure for scoring based on (1) diversity of surface particle size.

Table 1. 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    |
| M1             | 21                        | 33             | 13                  | 67    |
| M3             | 21                        | 30             | 13                  | 64    |
| M4             | 21                        | 33             | 13                  | 67    |

The scientifi of the project, it is the higher the better for (1) and the lower the better for (4). Table 1 shows the scores evaluated by the science team for some of the candidate sites (i.e., the evaluation itself was done for all of the candidate sites) showing that the scientific values for all of the candidate sites are almost equal; reflecting the fact that the surface property of Ryugu is highly homogenous.5 Thus, specifically for Ryugu, the major driver for deriving the spacecraft touchdown site candidates was engineering constraints.

The landing site candidates for MINERVA-II1 (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-II1, 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 after thorough and constructive discussions. A set of landing sites (MINERVA-II1: N6, MASCOT: MA-9, Spacecraft: L08) with two backup spacecraft touchdown sites (L07 and M04) was selected such that the sites should not interfere with each other while maximizing the 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 fulfill 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 following additional observations, and at the same time, to improve the landing accuracy to enable the use of narrower landing sites.

2.3. Post-LSS operations

Based on the LSS decision described in Sec. 2.2, several critical operations were 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 the laser range finder (LRF), 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 the aborted flight was a premature LIDAR setting due to the very-dark (low reflectance) surface of the asteroid, and the spacecraft failed to measure the altitude.

On September 20–21, the MINERVA-II1 rover 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. 3.2 and 3.3 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, 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 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 a target marker (TM) on ground to precisely evaluate the terrain relative guidance performance and the autonomous TM-tracking control performance of Hayabusa2. The TM is a 10-cm-diameter 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 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. This location was selected because it is the flattest region in the L08 area.

We succeeded conducting TD1-R1A on October 14–15 and TD1-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: (1) the dropped TM location indicated that the our terrain-relative guidance is as good as around 15 m, and (2) 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.

2.4. Hovering operation around asteroid

In the normal operation (except the critical operation periods), the spacecraft maintains its position near the HP using a technique called Home Position Navigation (HP-NAV). HP-NAV uses the asteroid centroid position in the ONC-W1 images combined with the Earth-to-spacecraft range measurement for navigation. One ΔV is performed every one–two days to maintain hovering at HP. Three virtual boxes around HP are defined (i.e., BOX-A, -B and -C) to cover a variety of observation purposes (Fig. 5). BOX-A is a 1–5 km right rectangular region around HP. BOX-B is a horizontally-spread rectangular region (20 km × 20 km × 1 km) around HP to cover dusk-dawn observation. BOX-C is a vertically-spread rectangular region (1 km × 1 km horizontally, covering the altitude of 5–20 km). As of April 18, 2019, Hayabusa2 has spent 168 days in BOX-A, 37 days in BOX-B, 17 days in BOX-C, and 34 days conducting critical operations.

The spacecraft experienced a conjunction (i.e., spacecraft and asteroid are located behind the Sun as viewed from Earth) from November 23 to December 29, 2018. During this period, the Sun-spacecraft-Earth angle was less than 3.5 deg and no communication was expected due to solar interference. Hence, for the sake of safety, the spacecraft temporarily left HP and was put into an auto-return trajectory with a maximum distance to the asteroid of 108 km (Fig. 6). The natural elliptical three-body restricted dynamics together with the solar radiation pressure brought the spacecraft back to HP on December 29, fine-guided by two trim maneuvers on November 30 and December 25. The total ΔV of 29 cm/s was used for the conjunction operation.

3. Critical Operation Achievements

3.1. MINERVA-II1 rover deployment operation

The two MINERVA-II1 rovers (i.e., Rover-1A named “HIBOU” and Rover-1B named “OWL”, Fig. 7 top-left) were deployed from the spacecraft at an altitude of 55 m on September 21 at 4:06 UT. A horizontal ΔV of 0.2 m/s was executed right before 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.

The two rovers were confirmed active immediately after deployment, and some images captured by the rover onboard cameras were received by Hayabusa2. On Sol 4 (i.e., fourth asteroid rotation, 1 sol = 7.6 hr), Rover-1A was confirmed doing some autonomous hopping, 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 power signal continued to be received after that time, indicating that two rovers may have remained active for a while.

Over the time of the entire MINERVA-II1 operation, a few hundreds of images, including movies and stereo images, as well as surface temperature were obtained (Fig. 8). The two rovers became the world’s first mobile landers successfully operated on a small body. Landing site N6 was nicknamed “Tritonis” by the MINERVA-II1 team.

Fig. 7. (Top left) MINERVA-II1 rovers: Left, Rover-A “HIBOU,” and right, Rover-B “OWL.” (Top right) MASCOT lander. (Bottom left) DCAM3 deployable camera. (Bottom right) Small carry-on impactor (SCI).

3.2. MASCOT lander deployment operation

The MASCOT lander (Fig. 7 top-right), developed by DLR and CNES, was successfully deployed from the spacecraft at the altitude of 51 m on October 3 at 1:57 UT. Separation was later confirmed by the Hayabusa2 onboard cameras ONC-W2 and ONC-W1 (Fig. 9). No horizontal compensation was executed for this release, as the MASCOT separation mechanism deployed 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 hr 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, and was connected online to the Sagamihara Space Operation Center (SSOC, operation center for Hayabusa2). A 24-hr continuous coverage was prepared to cover the entire lifetime of MASCOT using the 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 the two MINERVA-II rovers.

MASCOT was confirmed active immediately after release, and landed in the MA-9 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 at the dawn of Sol 3, and the battery was estimated to have been depleted after 17 hr of successful surface activity.7,8 The landing site MA-9 was nicknamed “Alice’s Wonderland” by the MASCOT team.
3.3. Touchdown and sampling operation

The original touchdown sequence used the TM to eliminate the terrain-relative velocity at the final phase of landing. From the results of TD1-R3, as described in Sec. 2.3, however, the project team acquired great confidence in the TM-tracking capability of Hayabusa2, and decided to reconfigure 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 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. 10) were implemented onboard for the autonomous sequence below 45 m such that, if the pre-programmed status conditions were not fulfilled, the spacecraft automatically aborts and the ascent-back/C1V is triggered. The second example is a “tail-up” attitude (Fig. 10) 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 deg 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 more precise boulder distribution map (Fig. 11) and a digital elevation map (Fig. 12 right) with <10 cm accuracy, which is good enough for a sub-meter level safety evaluation. Using these maps, two new landing candidate sites were found within the L08 area, L08-B1 and L08-E1 (Fig. 12 left). L08-B1 is located 15 m from the TM, and spans about 12 m. L08-E1 is located 4.2 m from the TM, and spans about 6 m.

Combining these two progressions (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 is found to be the only feasible region that Ha-
yabusa2 can target using the updated landing accuracy (Fig. 12 right).

Touchdown operation 1 (TD1) 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 hr, 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 21:10 UT while at an altitude of approximately 500 m, and reached the altitude of 45 m at 22:07 UT. Then the spacecraft successfully captured and locked in on 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 UT. One of four touchdown detection sources (i.e., attitude rate limit) was triggered when a projectile was ejected and an ascend-back $\Delta V$ was executed 0.1 s 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 $\Delta V$ of 0.64 m/s. The autonomous activity below 45 m was done with non-Earth pointing attitude, limiting the communication link to Earth using only a low-gain antenna. Therefore, the low-altitude onboard activity was monitored on the ground control center solely by the carrier power and Doppler signals (Fig. 13).

The successful touchdown was soon confirmed by the rising temperature of the projector, and also by confirming that all of the sequences had performed nominally. There are three container rooms in the Hayabusa2 sampling system. As we confirmed the touchdown, sampler room A was commanded to “Close” on February 22 at 2:20 UT, and the sample collected during TD1-L08E1 operation was secured.

The moment of touchdown was recorded by the ONC-W1 (Fig. 14) and CAM-H (i.e., sampler-horn monitor camera, Fig. 15). As observed in these images, many fragments were seen to be ejected as the reaction to shooting the projectile and the ascend-back $\Delta V$. 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. 16).

Landing site L08-E1 was then nicknamed “Tamatebako”
At this moment, as we had spent four months longer than originally planned to realize the first touchdown, the decision was made to cancel the second touchdown, which was to be performed after the first touchdown, and directly move on to the kinetic impact operation.

3.4. Kinetic impact operation

The kinetic impact was performed using the SCI (Fig. 7 bottom-right). It weighs 15 kg and was separated from the bottom of the spacecraft. It was ignited using an SCI-onboard timer, at which time a 2 kg copper mass was ejected at the speed of 2 km/s. For the operation planning purpose, the targeted accuracy from a nominal stand-off distance of 500 m was set to be as conservative as 200 m (3σ), which included the accuracy of the SCI itself as well as the spacecraft attitude and guidance errors. Because of this relatively large dispersion, the 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 almost on the equator.

The target point of the kinetic impact was called the “S01 region,” which is located on the equatorial ridge of Ryugu, apart longitude-wise from the L08 landing site (Fig. 17). There were two requirements for the kinetic impact target site: (1) Maximizing the possibility to create a large crater detectable by the onboard instrument, thereby enabling post-impact observations; and (2) maximizing the ability to land in terms of terrain conditions (i.e., for safety). S01 was found through the global survey activity conducted 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 (2) rather than (1). S01 was found to maximize, but not to fulfill due to the very large impact dispersion, the conditions for landing.

Prior to the SCI operation, two critical operations were performed. One was S01 low-altitude descent observation (DO-S01, March 6–8, 2019), and the other was 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. A post-impact crater search operation (CRA2) was planned to follow DO-S01. By comparing the images obtained during CRA1 and CRA2, the artificial crater generated by the SCI was expected to be detected.

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 1:56 UT. 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 escape route, Hayabusa2 released a deployable camera called “DCAM3” (Fig. 7 bottom-left) at 2:14 UT, which successfully observed the impact event (Fig. 18). The impact occurred on April 5 at 2:37 UT.

In the follow-on descent operation conducted on April 23–25 (CRA2), the crater formed by the kinetic impact was successfully identified (Fig. 19).
4. Conclusion

Hayabusa2 arrived at Ryugu on June 27, 2018. As of April 2019, the mission has succeeded in two rovers landing, one lander landing, one spacecraft touchdown/sample collection and one kinetic impact operation. Drastic modifications were applied to the touchdown operation to cope with the severe environment of Ryugu, and finally, a precision landing with the accuracy of 1 m was achieved. There are still several critical operations planned in the asteroid proximity phase. Hayabusa2 will leave the asteroid in November or December 2019, and will return to the Earth in November or December 2020.

Acknowledgments

The authors are grateful for the entire Hayabusa2 team for their effort to achieve the operations as described, and for supplying the operation products used in this paper.

References

1) Tsuda, Y., Yoshikawa, M., Abe, M., Minamino, H., and Nakazawa, S.: System Design of the Hayabusa 2—Asteroid Sample Return Mission to 1999 JU3, Acta Astronautica, 90 (2013), pp. 356–362. DOI: 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.aav0422
5) Yabuta, H., 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) Yamaguchi, Y., Saiki, T., Takei, Y., Okada, T., Takahashi, T., and Tsuda, Y.: Hayabusa2-Ryugu Proximity Operation Planning and Landing Site Selection, Acta Astronautica, 151 (2018), pp. 217–227.
7) Grott, M., 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) Schroder, S. E., et al.: Ryugu as Seen Up Close by the MASCOT Camera, The 50th Lunar and Planetary Science Conference, Houston, USA, No. 2450, 2019.