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Hayabusa2 Mission Overview

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Abstract The *Hayabusa2* mission journeys to C-type near-Earth asteroid (162173) Ryugu (1999 JU_3) to observe and explore the 900 m-sized object, as well as return samples collected from the surface layer. The *Haybusa2* spacecraft developed by Japan Aerospace Exploration Agency (JAXA) was successfully launched on December 3, 2014 by an H-IIA launch vehicle and performed an Earth swing-by on December 3, 2015 to set it on a course toward its target Ryugu. *Hayabusa2* aims at increasing our knowledge of the early history and transfer processes of the solar system through deciphering memories recorded on Ryugu, especially about the origin of water and organic materials transferred to the Earth's region. *Hayabusa2* carries four remote-sensing instruments, a telescopic optical camera with seven colors (ONC-T), a laser altimeter (LIDAR), a near infrared spectrometer covering the 3-μm absorption band (NIRS3), and a thermal infrared imager (TIR). It also has three small rovers of MINERVA-II and a small lander MASCOT (Mobile Asteroid Surface Scout) developed by German Aerospace Center (DLR) in cooperation with French space agency CNES. MASCOT has a wide angle imager (MasCam), a 6-band thermal radiator (MARA), a 3-axis magnetometer (MasMag), and a hyperspectral infrared microscope (MicrOmega). Further, *Hayabusa2* has a sampling device (SMP), and impact experiment devices which consist of a small carry-on impactor (SCI) and a deployable camera (DCAM3). The interdisciplinary research using the data from these onboard and lander's instruments and the analyses of returned samples are the key to success of the mission.

Keywords Hayabusa2 · Ryugu · Near-Earth asteroid · Sample return mission · Formation of the solar system · Aqueous alteration

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1 Introduction

The *Hayabusa2* mission is a successor of the first asteroid sample return mission *Hayabusa* (2004–2010) by the Japan Aerospace Exploration Agency (JAXA). *Hayabusa* took surface particles from S-type near-Earth asteroid (25143) Itokawa (e.g., Fujiwara et al. 2006; Nakamura et al. 2011). The remote-sensing observations of *Hayabusa* revealed the rubble-pile structure of Itokawa, coexisting rough and smooth terrains with numerous boulders scattered (e.g., Saito et al. 2006), which had been unexpected on a 300 m-sized small asteroid. Though the intended sampling mechanism of the sampler on the *Hayabusa* spacecraft did not work, thousands of Itokawa particles have been collected from the container in the capsule returned to the Earth on June 13, 2010. These particles proved the direct linkage between S-type asteroids, the most common near-Earth asteroids (NEAs), and ordinary chondrites, the most frequently recovered meteorites on the Earth (Nakamura et al. 2011). The linkage had been unclear from comparison of reflectance spectra of asteroids with meteorites owing to the space weathering of asteroid's surface materials, the effect of which was also proved by analyses of surface rims of Itokawa particles (e.g., Noguchi et al. 2014). The most impressive features found on Itokawa particles are the records of surface processes in space such as impact micro-craters and adhered micro-particles (Nakamura et al. 2012).

After *Hayabusa*'s successful return to the Earth, JAXA planed another asteroid mission *Hayabusa2* to visit a carbonaceous-type (C-type) NEA and return surface samples of the asteroid to the Earth.

Science goals of *Hayabusa2* aim at understanding the origin and evolution of materials in the early solar nebula and in the asteroid parent body, as well as to constrain the physical properties of planetesimals during the planetary accretion processes. It is essential in the *Hayabsua2* mission to conduct the global-, local-, and micro-scale observations through the synergy of remote sensing from the spacecraft, *in situ* surface measurements by landers, and returned sample analysis.

The mission overview is the first of a series of articles describing science objectives, development, and performance of the scientific instruments and a lander onboard *Hayabusa2*. The subsequent papers describe the optical navigation camera telescope ONC-T (Kameda et al. 2017), the laser altimeter LIDAR (Mizuno et al. 2017; Yamada et al. 2017; Senshu et al. 2017), the near-infrared spectrometer NIRS3 (Iwata et al. 2017), the thermal infrared imager TIR (Okada et al. 2017; Arai et al. 2017; Takita et al. 2017), the sampler collecting asteroid's surface materials (Sawada et al. 2017b; Okazaki et al. 2017), and the small carry-on impactor SCI (Saiki et al. 2017; Arakawa et al. 2017) with the deployable camera DCAM3 for observing the SCI impact (Sawada et al. 2017a; Ogawa et al. 2017; Ishibashi et al. 2017). The articles also describe the lander MASCOT (Ho et al. 2017) and its instruments, the camera MasCam (Jaumann et al. 2017), the spectromicroscope MicrOmega (Bibring et al. 2017), the radiometer MARA (Grott et al. 2017), and the magnetometer MasMag (Herčík et al. 2017).

In the following sections, we give a brief overview of the background, the target asteroid, science objectives, observation, return sample analysis, and proximity operation of the *Hayabusa2* mission.

2 Background

In 2006 after occurring severe troubles on the *Hayabusa* spacecraft, a successor sample-return mission using the same type of *Hayabusa* spacecraft started to discuss in JAXA. In August 2008, the *Hayabusa2* proposal was selected for a JAXA pre-project. In addition to remote-sensing instruments and a sample acquisition system, a small carry-on impactor excavating an artificial crater and enabling to get subsurface samples was also designed. The project completed System Requirement Review in December 2009, System Definition Review and Preliminary Design Review in 2011, and Critical Design Review in 2012.

The external view of the *Hayabusa2* spacecraft is shown in Fig. 1. The 600-kg (wet) spacecraft based on the technological heritage of *Hayabusa* has four 10-mN-class Xe microwave discharge ion engines (where any three are operative at once), twelve 20-N bi-propellant hydrazine thrusters, two fixed-mount solar array paddles generating 2.6 kW and 1.4 kW of power at solar distances of 1.0 AU and 1.4 AU, respectively, a communication system for the X and Ka bands, an attitude and orbit control system (AOCS) with an optical navigation camera (ONC) system, laser altimeters (LIDAR and LRF), five target makers, four reaction wheels, two inertial reference systems, two star trackers, four coarse sun aspect sensors, and four accelerometers (Tsuda et al. 2013). Except for ONC and LIDAR, which also used for scientific observations, a near-infrared spectrometer (NIRS3) and thermal infrared imager (TIR) are onboard remote-sensing instruments.

Sampling surface material of the target asteroid is the most important and challenging task for the *Hayabusa2* mission. A sampler horn is extended beneath the spacecraft to conduct surface materials to a sample catcher inside the main body of *Hayabusa2*. The sampling will be performed within a few seconds during only the flexible sampler horn touches the asteroid's surface before firing of the thrusters for ascent (Sawada et al. 2017b). Exactly speaking, the sequence is not a landing but a touch-and-go, and we call it a "touchdown". In order to collect a sufficient amount of samples under a wide range of potential surface conditions, a projectile will be shot onto the asteroid's surface with a velocity of 300 m/s to produce impact ejecta from the surface at the instance of the touchdown. The ejecta will be collected into a chamber of the sample catcher through the sampler horn. Three projectiles are equipped for sampling at multiple surface locations of the asteroid, one of which will be used to obtain subsurface materials excavated by an artificial impact. The small carry-on impactor (SCI) is a 2-kg explosively formed copper impactor hitting the asteroid's surface at a velocity of ~2 km/s to dig an artificial crater (Saiki et al. 2017). Though this is a great opportunity for an asteroidal-scale micro-gravity impact experiment, the spacecraft cannot observe the impact because it has to move behind the asteroid to evacuate from the explosive debris and ejecta from the crater. Thus, the *Hayabusa2* project has developed a wide-angle deployable camera (DCAM3), which will be deployed on the way of the mothership evacuation to observe the impact ejecta curtain and identify the crater position (Sawada et al. 2017a; Ogawa et al. 2017; Ishibashi 2017). After all the sampling trials, the sample catcher is transferred into a sample container inside a re-entry capsule and sealed with an aluminum metal sealing system (Okazaki et al. 2017). The re-entry capsule is designed to deliver the asteroid sample to the Earth passing through the severe aerodynamic heating environment at an entry velocity of up to 12 km/s.

Hayabusa2 is equipped with one lander MASCOT (Mobile Asteroid Surface Scout) that has been developed by the German Aerospace Centre (DLR) in collaboration with Centre National d'Etudes Spatiales (CNES) (Ho et al. 2017), and three rovers (MINERVA-II) developed by JAXA and a consortium of universities in Japan.

The *Haybusa2* spacecraft successfully launched on December 3, 2014 by an H-IIA Launch Vehicle from Tanegashima Space Center in Japan. *Hayabusa2* performed an Earth swing-by on December 3, 2015, passing over the Pacific Ocean near the Hawaii islands at an altitude of ~3.1×10^3 km, to set it on a course toward the target asteroid. *Hayabusa2* is now travelling in very good conditions, successfully conducting health checks and calibrations of the scientific payloads. The round-trip trajectory design for *Hayabusa2* is shown in Fig. 2.

3 Target

The mission target is (162173) Ryugu (provisional designation 1999 JU_3), a C-type NEA discovered on May 10, 1999 by the Lincoln Near-Earth Asteroid Research (LINEAR) survey with a 1.0-m telescope located near Socorro, New Mexico, USA (Williams 1999). The semimajor axis, eccentricity, orbital inclination, and orbital period are 1.1896 AU, 0.19021, and 5.8836°, 473.89 days, respectively, at epoch 2457800.5 (February 16.0, 2017) in Barycentric Dynamical Time (TDB) based on the JPL Small-Body Database Browser. Ryugu is a potentially hazardous asteroid and the present orbit looks like a Hohmann transfer orbit from the Earth to Mars. Because the fraction of C-complex (C-type or the associated types of B, F, and G) asteroids among NEAs in the Asteroid Taxonomy Database are only ~10% (Kuroda et al. 2014), C-type low delta-V asteroid Ryugu is a very precious object for sample return missions aiming the quest for the origin of water and organics delivered to the Earth.

The physical properties of Ryugu have been determined by ground-based observations: the rotation period is about 7.63 h (Kim et al. 2013; Müller et al. 2017; Perna 2017), diameter is 865±15 m (Müller et al. 2017), geometric albedo is as low as 0.047±0.003 (Ishiguro et al. 2014; Müller et al. 2017), and thermal inertia is 150–300 J m^{-2} $s^{-1/2}$ K^{-1} (Müller et al. 2017). Its small size and relatively small thermal inertia indicate that Ryugu is probably a rubble-pile body formed after the destruction of a larger parent asteroid through the collisional cascade process in the main asteroid belt (Main Belt) (e.g., Bottke et al 2005).

The ground-based spectroscopic observations are controversial. Vilas (2008) reported the detection of ~0.7-μm absorption, indicating the presence of hydrated minerals, but others did not (e.g., Moskovitz et al. 2013; Lazzaro et al. 2013; Perna 2017), suggesting the surface chemical inhomogeneity (Vilas 2008; Lazzaro, 2013; Sugita et al. 2013). The spectra have flat to slightly red slopes in the visible to NIR parts and about 10% drop-off of the reflectance at the blue end (< 0.45 μm), like a CM carbonaceous chondrite (Perna 2017). Aqueous alteration probably proceeded in the parent icy planetesimals within the first 5 Myr after CAI formation, when the now-extinct short-lived radionuclide ^{26}Al was still alive. It should be noted that thermal metamorphism due to solar radiation during the near-Earth orbits, especially those with smaller perihelion distances, would affect the preservation of once-formed hydrated silicates (Michel and Delbo 2011).

Based on the far-infrared observations by the Herschel Space Observatory and re-analyses of previously published observations, Müller et al. (2017) combined radiometric and lightcurve inversion techniques to find the object's spin-axis orientation and its shape. The obtained best-fit solution leads to Ryugu having a retrograde rotation with a spin-axis orientation of ($\lambda = 325° \pm 15°$, $\beta = -40° \pm 15°$) in ecliptic coordinates, almost spherical shape, and very low surface roughness (r.m.s. of surface slopes < 0.1). Note that other formally possible pole orientations exists. Thus, we should prepare several proximity operation plans depending on the possible spin-axis orientations.

A plausible evolution scenario for Ryugu is that (a) it was a member of a low-albedo collisional family formed by collisional disruption of a parent asteroid in the inner Main Belt, (b) it migrated across the inner Main Belt from the collisional family via the Yarkovsky/YORP thermal forces/torques, (c) it reached the ν_6 secular resonance that took it into the terrestrial planet region (Campins et al. 2009), and (d) planetary encounters and resonances took it to its current orbit (Michel and Delbo 2011). The abundances of solar-cosmic-ray produced short-lived radionuclides with various half-lives (such as ^{10}Be, ^{26}Al, ^{41}Ca, ^{53}Mn, and ^{81}Kr) in returned samples are expected to constrain the timing of the formation and orbital change of Ryugu.

The source family of Ryugu has been investigated (e.g., Campins et al. 2009; Bottke et al. 2015), however, is as of yet unknown, because the migration timescale in the Main Belt via the Yarkovsky/YORP effect sensibly depends on the asteroid's density and shape to be determined by the *Hayabusa2* mission. Further, if the formation age of Ryugu by the collisional disruption is old enough, the collisional family once existed would merge into the background population and has become difficult to identify now. It should be note that a recent spectral observation of asteroids belonging to the Erigone collisional family, one of the possible source families of Ryugu, showed that 42% of the observed members are C-type asteroids and 86% of the C-types present hydration features at wavelengths around 0.7 μm (Morate et al. 2016). Anyway, reconstruction of the asteroid history through the remote-sensing observations and returned sample dating is crucial to determine the origin and evolution of Ryugu.

4 Science objectives

Through proximity observations, *in situ* measurement by the landers, returned sample analyses, and the impact experiment in space, the *Hayabusa2* mission pursues the following four science objectives. Each objective consists of a planetary science goal and the derived mission objective.

1. In order to characterize material mixing and transport operated within the early history of the solar system around the snow line, the project will describe how materials of different characteristics (such as hydrated silicates, organic matter, and etc.) are distributed and layered on the surface of Ryugu.

2. In order to characterize mineral-water-organic reactions on planetesimals, parent bodies of asteroids, the project will search for a variety of organic materials (functional groups or isotope anomalies) and coexisting key minerals representing aqueous alteration processes in the returned samples and map the corresponding absorptions by remote-sensing and *in situ* observations.

3. In order to figure out the material evolution in the early solar system, presolar environment, the protoplanetary disk, and planetesimals, the project will decipher the history of Ryugu by integrated chronology, preprocessing the later thermal alteration and space weathering that must have obscured some of the early memories.

4. In order to identify dynamical processes to which planetesimals were subject during the formation stage of the solar system, the project will characterize impact-related physical properties of Ryugu and reconstruct the collisional history.

Through these objectives we expect to clarify material delivery system, especially water and organics delivery system, from the Main Belt to the Earth. The exogenous delivery of organic materials by carbonaceous asteroids may have contributed to the organic inventory of the early Earth. The meteoritic organic materials consist of insoluble organic matter (IOM) and various soluble organic compounds, including key species that played important roles in the prebiotic chemical evolution on the early Earth (e.g., Cronin and Chang 1993; Cody and Alexander 2005).

Asteroids are a tracer of the evolution of the early solar system. Recent studies have highlighted on mixing and disruption of asteroid parent bodies through migration of giant planets such as the Nice model (Tsiganis et al. 2005; Gomes et al. 2005; Morbidelli et al. 2007; Levison et al. 2011) and the Grand Tack model (Walsh et al. 2011). These models predict the outer solar system origin of C-complex asteroids (including C-types and B-types), so that the origin of the parent body of Ryugu is a key to understand the ages of *Titanomachy* of the solar system.

Though Ryugu is just one example of a vast number of asteroids, the returned sample will provide a key evidence to make clear the relation between C-type asteroids and carbonaceous chondrites. The surface inhomogeneity of Ryugu will tell us how differentiation and diversification proceeded on the parent body. Further, collaboration with the *OSIRIS-REx* mission that will return a sample from the surface of B-type NEA Bennu (Lauretta 2015) will create a synergy effect. The comparative study of samples obtained in the two missions is crucial for better understanding of the common nature of C-complex asteroids as well as distinct difference between C-type and B-type asteroids.

5 Scientific observation and sample analysis

To pursue these scientific objectives, interdisciplinary collaboration between on-site observation and analysis of returned samples is essential. We will briefly summarize the scientific instruments onboard the spacecraft and collaboration between these instrumental observation and returned sample analysis.

The optical navigation camera (ONC) system comprises one telescope camera (T) with seven bandpass filters and two wide-angle cameras (W1, W2), controlled by an electronic package (Kameda et al. 2015, 2017). The scientific objectives of ONC-T are not only to construct terrain and shape models of the asteroid but to conduct multi-band surface mappings that enables us to know the spatial distributions of surface albedo, spectral slopes, and depth of absorption bands, especially the 0.7-μm absorption band that will indicate the presence of hydrated silicate minerals like Fe-rich serpentine (e.g., Hiroi and Zolensky 1999) and the drop-off of the reflectance at the blue end due to the presence of IOM.

Near infrared spectrometer (NIRS3) will observe the surface reflectivity at wavelengths from 1.8 to 3.2 μm with a spectral resolution of 18 nm using a linear-image sensor with indium arsenide (InAs) photo diodes (Iwata et al. 2017). The scientific objective of NIRS3 is to clarify the surface distribution of hydrated silicates from the 3-μm absorption band features and to estimate space weathering from spectral slopes at wavelengths ranging from 1.8 to 2.6 μm.

Thermal infrared imager (TIR) is a micro bolometer array taking thermal emission at wavelengths from 8 to 12 μm with a field of view of 16° × 12° and a spatial resolution of 0.05° per pixel (Okada et al. 2017). The performance is presented in Arai et al. (2017). The scientific objective of TIR is to determine the surface temperature distribution of the spinning asteroid and derive distribution of thermal inertia of the asteroid's surface (Okada et al. 2017; Takita et al. 2017). Comparison with topographic maps of the asteroid, one can estimate surface roughness and typical particle sizes at landing-site candidates prior to touchdowns.

The light detection and ranging (LIDAR) laser altimeter, having a dynamic range from 25 km to 30 m, is used not only for a navigation sensor but also for a scientific instrument to determine the asteroid's topography, global shape, gravity, surface roughness, and albedo (Mizuno et al. 2017; Yamada et al. 2017). LIDAR also has a dust detection mode that enable to observe dust grains around the asteroid in case of natural dust levitation or artificial impact ejection (Senshu et al. 2017).

The lander MASCOT has four scientific instruments, a multi-band wide-angle camera MasCam (Jaumann et al. 2017), a six-band thermal radiometer MARA (Grott et al. 2017), a three-axis fluxgate magnetometer MasMag (Herčík et al. 2017), and a hyperspectral microscope MicrOmega (Bibring et al. 2017). The lander will be deployed from the mothership at an altitude of < 100 m and land on Ryugu after a few bouncing. It can be operated up to 2 asteroid days (~16 h) and perform relocation via hopping on the asteroid's surface. MicrOmega has a field of view of 3.2 mm × 3.2 mm and covers wavelengths from 0.99 to 3.65 μm with a spatial sampling of ~25 μm, providing the ground truth for orbital observations as well as a reference for returned sample analyses (Bibring et al. 2017). MASCOT instruments may bridge remote-sensing observations from mothership with spatial resolution of say > 0.1 m and analyses of returned surface particles with diameters < 1 mm.

The sampler will collect at least 100 mg of surface materials including several mm-sized particles at most three landing points (Sawada et al. 2017b). Coarse grains with radius larger than ~100 μm collected from different locations will be preserved in a separate chamber in the catcher in order to enable comparative analysis of possible surface inhomogeneity. After all the sampling, the catcher will be transported into the re-entry capsule and sealed to preserve even volatile components (Okazaki et al. 2017).

Petrologic and mineralogical studies of mm-sized particles will provide constraints on the history of the asteroid and the early solar system (Tachibana et al. 2014). The morphology, micro-structure, and friability of particles will tell us the surface processes of a C-type asteroid, just like Itokawa particles told us those of an S-type asteroid (e.g., Nakamura et al. 2012). Integrated chronology using absolute and relative age determined by U–Pb, ^{40}K–^{40}Ar, ^{26}Al–^{26}Mg, and ^{53}Mn–^{53}Cr systems as well as orbital evolution models based on the precisely measured bulk density, shape, internal structure, and crater chronology of Ryugu will clarify the formation and evolution of not only the asteroid but its parent body. The analysis of fine grains will provide globally averaged surface features and geologic surface processes, such as space weathering, regolith formation due to micro-meteoroid impact (Nakamura et al. 2012), and thermal fatigue. Volatiles extracted from the container prior to opening will be the first extraterrestrial volatile sample to be returned, enabling us to investigate the origin and evolution of organic materials and water in the early solar system and the asteroid's parent planetesimal.

Less altered N- and O-rich organic materials are expected in returned samples from Ryugu. In some carbonaceous chondrites, positive correlations between the relative abundance of the amino acid isovaline and that of phyllosilicates, products of asteroidal aqueous alteration (Pizzarello et al., 2003), and between the L-enantiomer excess value of isovaline and the degree of aqueous alteration (Glavin and Dworkin, 2009) may indicate that mineral-water-organic reactions occurred on the parent body of these chondrites. A systematic study of hydrated silicates and soluble/insoluble organic materials in the Tagish Lake meteorite also suggested that aqueous alteration played an essential role in diversification of organic matter in the parent body (e.g., Herd et al., 2011). The analyses of the organic molecules and hydrated silicates present in the returned sample are essential to determine the physical and chemical conditions of hydrothermal processes within the parent planetesimal in the early solar system and potential prebiotic organic compounds available on the early Earth.

6 Asteroid proximity operation

Hayabusa2 will arrive at Ryugu in June or July 2018 and spend ~18 month around the asteroid (see Fig. 2). An example of the asteroid proximity operation scenario of *Hayabusa2* is shown in Fig. 3.

The spacecraft spends the first 2–3 months characterizing the surface and rotational environment of Ryugu by global mapping and observation, hovering around a home position (HP), ~20 km above the sub-Earth point of the asteroid's surface (Tsuda et al. 2013). The global mapping by ONC-T (2 km × 2 km field of view and 2 m/pix spatial resolution from HP) will reveal the spin-axis orientation, rotation period, shape, and topography of Ryugu. NIRS3 will observe surface reflectance spectra and make maps of absorption features in the 3-μm bands that may indicate the presence of hydrated silicate minerals. TIR will observe surface temperature distribution of the rotating asteroid and estimate the distribution of thermal inertia (Takita et al. 2017). Several descent operations (1–5 km) will be done for closer observation by remote-sensing instruments and for determination of the asteroid gravity by LIDAR and two-way Doppler measurements. These data are utilized not only for science purpose but for planning subsequent proximity operations, such as determination of the mission sequence, evaluation of sampling site candidates (landing-site selection: LSS) and lander/rovers deployment points, and an SCI target region.

Though the departure from Ryugu is scheduled in December 2019, the solar distance of Ryugu is so close in the last half year that the surface temperatures around the sub-Earth point, where the spacecraft is accessible from HP, will be possibly too high for the spacecraft to touchdown safely. Thus, we should perform touchdown trials up to three times within about one-year after arrival. Furthermore, the solar conjunction will occur in December 2018, which will shorten the available operation time by one month.

Sampling sites should be selected based on safety conditions of the spacecraft and scientific evaluation based on remote-sensing data. To clarify the inhomogeneity of the asteroid, we plan a total of three samplings, two for surface material at different geological sites and one for subsurface material excavated by the artificial impact of SCI. The scientific evaluation for LSS features primitiveness and surface conditions. The primitiveness can be estimated from the degree of aqueous alteration based on the shape/depth of the 3-μm absorption band and the presence of an absorption near 0.7 μm, and from volatile contents based on the difference of 0.39-μm and 0.55-μm absolute reflectances. The surface conditions can be evaluated by the degree of space weathering estimated from visible to NIR spectral slopes, depth of the 3-μm absorption band, and 0.39-μm absolute reflectance, and by particle sizes of the regolith estimated from the Hapke parameters and the thermal inertia.

Sequence of touchdown operation is as follows (Tsuda et al. 2013): The spacecraft descends from HP, using a ground/onboard-based hybrid navigation system with velocities at 0.1–1 m/s. Horizontal maneuvers are commanded to the spacecraft to keep along a predefined descent path, if the actual trajectory determined by a series of ONC imaging and LIDAR ranging differs from the planned path. When the spacecraft reaches an altitude of as low as 30 m, a laser range finder (LRF) system is turned on, a target marker (TM) is released, and the spacecraft moves autonomously above the landed TM. At an altitude of ~15 m, the LRF system determines the local surface orientation relative to the *Z*-axis of the spacecraft (see Fig. 2 for the body-fixed coordinate system of *Hayabusa2*), setting the attitude perpendicular to the local surface. As soon as a touchdown of the sampler horn is detected, a 5-g tantalum bullet of a sampling projector will be shot to the asteroid's surface within the sampler horn and some of the produced ejecta from the surface will be conducted into a chamber of the sample catcher. Thrusters will fire a few seconds after the touchdown detection and the spacecraft will lift off the asteroid's surface with the captured sample.

We also plan to excavate subsurface material of Ryugu by the impactor SCI (Saiki et al. 2017; Arakawa et al. 2017). It will be detached from the spacecraft ~500 m above and will be ~300 m above the asteroid's surface at the time of ignition. At ~40 minutes after the separation of SCI, when the spacecraft completes the evacuation behind the asteroid, explosive will be detonated to accelerate the impact head up to 2 km/s before colliding the asteroid's surface. The artificial impact will generate an ejecta curtain and leave a crater with a diameter of up to 10 m on the asteroid's surface. The detached camera DCAM3 having been deployed from the spacecraft along the way of the evacuation will take images of the ejecta curtain as well as SCI before the detonation (Sawada et al. 2017a; Ogawa et al. 2017; Ishibashi et al. 2017). After settling ejecta from the SCI impact, the mothership will come back to HP, try to discover the excavated crater using ONC-T and TIR, and observe the crater from an altitude of a few km. The purpose of the crater observation is not only to assess the safety of the forthcoming touchdown around the crater but to clarify properties of the surface material, subsurface structure, and the effect of microgravity on the cratering process. If the safety of the landing site is confirmed, the spacecraft will attempt to touch down near the crater for sampling fresh subsurface materials, using three TMs for the precise landing (see Fig. 3).

MINERVA-II and MASCOT are now planned to be deployed toward the asteroid's surface before the first touchdown operation. The range of latitudes at which the landers can be deployed is restricted around the sub-Earth latitude. MASCOT will attempt to take camera images of the asteroid already during descent and bouncing (Ho et al. 2017). The final resting position of MASCOT will be identified by ONC-T imaging from the mothership. After completion of science operation at the first location, which will take approximately one asteroid day (equal to ~7.6 h), MASCOT is planned to be relocated to another site by hopping.

Though the schedule of the proximity operation of *Hayabusa2* is very tight (see Fig. 3), making a rigid detailed plan before arrival is difficult because of uncertainties about the spin-axis orientation and shape of Ryugu. We should make an operational scenario with robust principles in a flexible pattern. In 2017 the project plans integrated dry runs of the proximity operation, especially the sequences of LSS and the touchdowns, to improve the skills of operation and decision as well as to circumvent the risks of real-time decision in some conceivable incidents or troubles during the actual operation.

7 Summary

Hayabusa2's visit at Ryugu offers the prospect to better understand the class of C-type asteroids and its position in small solar system bodies, in comparison with the results of the preceding missions like *Hayabusa* to Itokawa, *Rosetta* to comet 67P/Churyumov-Gerasimenko, and *Dawn* to Ceres, and in collaboration with ongoing mission *OSIRIS-REx* to Bennu and future Japan mission *MMX* (*Martian Moons Exploration*) to Phobos. Understanding the material delivery from the outer solar system beyond the snow line to the early Earth is one of the most important imprecations of the science of the *Hayabusa2* mission. It should be a great step in the progress of astrobiology and aqua planetology.

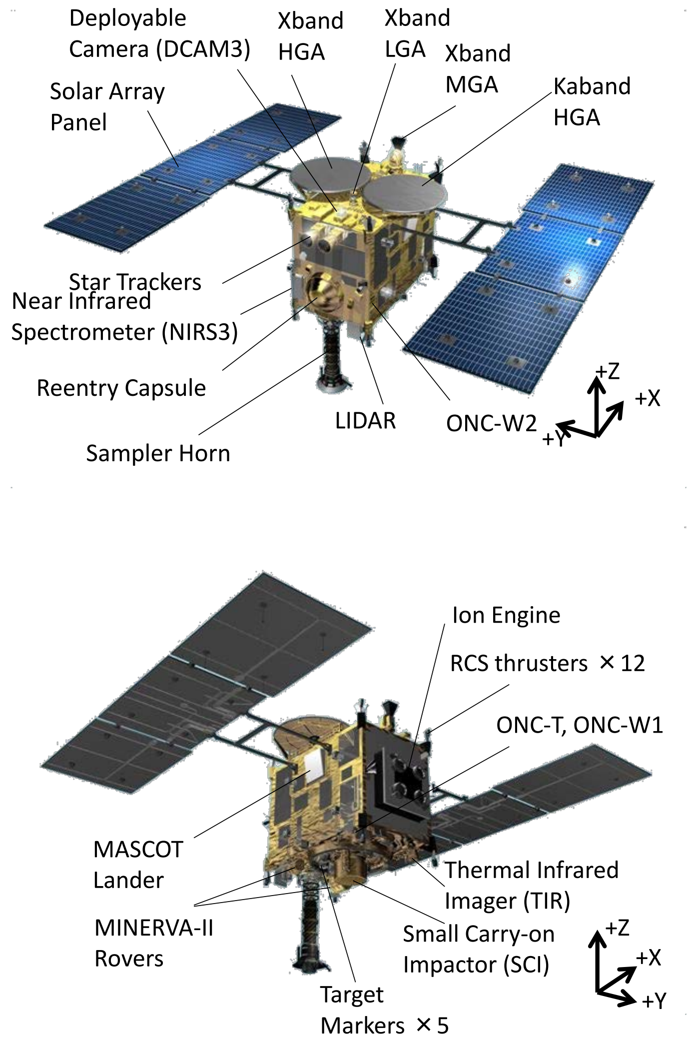

Fig. 1 External views of the *Hayabusa2* spacecraft and onboard instruments

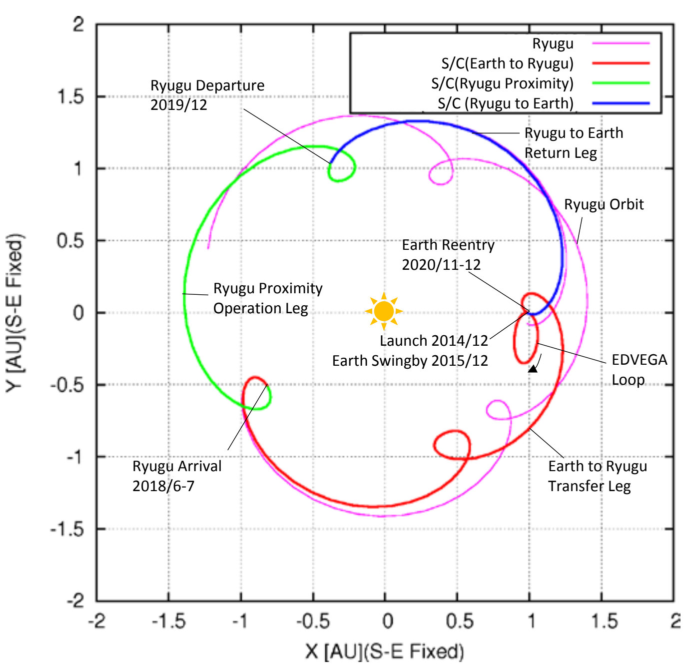

Fig. 2 Ryugu round-trip trajectory design for *Hayabusa2* on J2000EC Sun-Earth line-fixed coordinates (S/C: the *Hayabusa2* spacecraft, EDVEGA: Electric Delta-*V* Earth Gravity Assist)

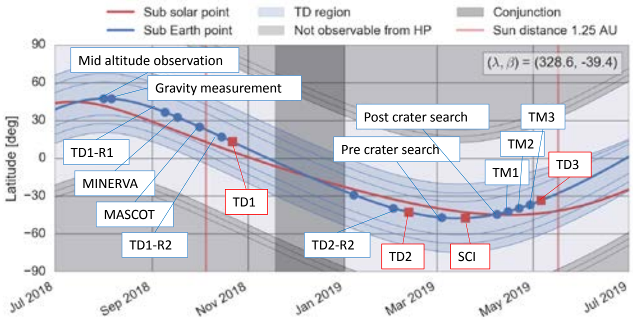

Fig. 3 An example of the asteroid proximity operation scenario of *Hayabusa2* for the nominal pole orientation (λ, β) = (328.6, -39.4) of Ryugu on time vs. latitude plane. The range of latitude that touchdown is possible at each time is shown by blue hatched region around the blue thick curve (trajectory of the sub-Earth point). The abbreviations are the following: TD: touchdown; HP: home position; TD*n*: *n*th touchdown operation; TD*n*-R*m*: *m*th rehearsal for TD*n*; MINERVA: the first MINERVA deployment; MASCOT: MASCOT deployment; SCI: SCI operation; TM*m*: *m*th rehearsal and target marker release for TD3

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