Orbit insertion strategy of Hayabusa2's rover with large release uncertainty around the asteroid Ryugu

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ABSTRACT

This paper describes the orbit design of the deployable payload Rover 2 of MINERVA-II, installed on the Hayabusa2 spacecraft. Because Rover 2 did not have surface exploration capabilities, the operation team decided to experiment with a new strategy for its deployment to the surface. The rover was ejected at a high altitude and made a semi-hard landing on the surface of the asteroid Ryugu after several orbits. Based on the orbital analysis around Ryugu, the expected collision speed was tolerable for the rover to function post-impact. Because the rover could not control its position, its motion was entirely governed by the initial conditions. Thus, the largest challenge was to insert the rover into a stable orbit (despite its large release uncertainty), and avoid its escape from Ryugu due to an environment strongly perturbed by solar radiation pressure and gravitational irregularities. This study investigates the solution space of the orbit around Ryugu and evaluates the orbit's robustness by utilizing Monte Carlo simulations to determine the orbit insertion policy. Upon analyzing the flight data of the rover operation, we verified that the rover orbited Ryugu for more than one period and established the possibility of a novel method for estimating the gravity of an asteroid.

KEYWORDS

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1 Introduction

The exploration of asteroids is receiving much attention among space agencies around the world, given the potential for elucidating how the solar system was created and evolved. Japan Aerospace Exploration Agency (JAXA)'s deep space exploration probe Hayabusa2 was launched in December 2014 and rendezvoused with its target asteroid, Ryugu, in June 2018. After Hayabusa2 conducted a global mapping and estimated the gravity

model of Ryugu, it successfully made two touchdowns and sample collections on the surface of Ryugu, in February and July, 2019. Hayabusa2 remained in proximity to Ryugu, conducting operations related to touchdown and the rover release operation. This paper describes the orbital analyses with respect to the planning and results of one rover operation.

Hayabusa2 has several rovers, one of which is called "Rover 2 of MINERVA II-2" [1, 2]. Figure 1 shows the appearance of the MINERVA II-2 system. We

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Nomenclature

$\mathbf{r} = [x, y, z]$	position vector and its elements in cartesian coordinates
$\mathbf{a}_G = [a_{Gx}, a_{Gy}, a_{Gz}]$	normalized gravitational acceleration
e_r	eccentricity of asteroid's orbit
a_r	semi-major axis of asteroid's orbit (m)
f_r	true anomaly of asteroid's orbit (rad)
U	normalized gravity potential associated with asteroid harmonics
d	distance between the Sun and asteroid
LU	distance unit
TU	time unit
β	normalized acceleration by solar radiation pressure
a_{SRP}	unnormalized acceleration by solar radiation pressure (m/s^2)
γ	reflectivity
p_0	solar flux constant ($\text{kg} \cdot \text{m/s}^2$)
m	mass of the rover (kg)
A	projected area of the rover (m^2)
μ_S	gravitational parameter of the Sun (m^3/s^2)
μ	gravitational parameter of the asteroid (m^3/s^2)
P	legendre polynomial
l, m	order and degree of harmonics taken into account
C_{lm}, S_{lm}	stocks coefficients
ϕ	latitude in asteroid fixed frame (rad)
λ	longitude (rad)
n	mean motion (rad/s)
C_J	Jacobi integral (m^2/s^2)
v_c	critical velocity (m/s)
v_o	circular orbit velocity in two-body problem (m/s)
v_m	velocity margin (m/s)
a	semi-major axis of spacecraft's orbit (m)
e	eccentricity of spacecraft's orbit
I	inclination of spacecraft's orbit
W	longitude of the ascending node of spacecraft's orbit
w	augment of periapsis of spacecraft's orbit
f	true anomaly of spacecraft's orbit

Fig. 1 MINERVA II-2 system.

determined that Rover 2 encountered some trouble after Hayabusa2 was launched. Its onboard computer did not function correctly due to hardware and software faults. Although it could emit radio waves when its communication equipment was powered on, if the rover was released to the surface of Ryugu, according to nominal

operation, it would not be able to obtain surface data and send it to the mother spacecraft. Therefore, we planned to insert the rover into orbit and make a semi-hard landing on the surface after several orbits. Based on a basic orbital analysis around Ryugu, if Rover 2 was deployed at an altitude of 1.0 km above the surface, its impact with Ryugu would be slower than 25 cm/s. This expected collision speed was tolerable for the rover to function after impact.

The greatest scientific significance of orbiting the rover around Ryugu was its contribution to the construction of Ryugu's gravity model via determining the rover's orbit; this was achieved using an optical camera mounted on the mother spacecraft. By using the rover's orbit to accurately estimate the gravity field, we established the possibility of a novel method for estimating the gravity of asteroids via the orbit of a small probe.

The rover must avoid escaping from Ryugu and ultimately land on the surface. However, as the design of Rover 2 did not account for orbit around Ryugu, inserting it into orbit entailed some difficulties. Primarily, the rover had a large release velocity uncertainty. The rover's release velocity was estimated to be between 5.4 and 25.4 cm/s. Moreover, there were guidance and control errors regarding the mother spacecraft's position and velocity. Hence, to overcome these difficulties, this study investigated stable orbits around Ryugu, notwithstanding large errors regarding the initial conditions.

This study first defines the coordinate systems used for both orbit design and spacecraft operation. It then demonstrates the equations of motion, including Ryugu's gravity and shape model. The main part of this paper describes how the rover's insertion policy was determined based on both an analytical perspective, such as the Jacobi integral, and the numerical solution space. Some trade-offs, such as whether a polar or equatorial orbit were more appropriate, are considered from the standpoints of stability and operational safety. Finally, this paper describes the results of the actual Rover 2 operation. The actual rover orbit was estimated based on flight data from several images taken by Hayabusa2's optical camera. We analyzed the rover's operation flight data, verified that the rover rotated around Ryugu for more than one period, and established the possibility of a novel method for estimating the gravity of an asteroid.

2 Coordinate system

This section defines the three main coordinate systems used in this study. The Hill coordinate system was typically used to express dynamics around Ryugu. As shown in Fig. 2(a), the origin was the center of Ryugu. The x -axis was defined along the anti-solar line and the z -axis was taken as normal to Ryugu's orbital plane. The y -axis was defined to complete the right-handed coordinate system.

The Hayabusa2 spacecraft was predominantly operated

at a hovering point where it was on a sub-Earth line at an altitude of 20 km. Hence, the spacecraft's operation was easy to describe, given the special coordinates for Hayabusa2; i.e., the home position (HP) coordinate system. Figure 2(b) shows the HP coordinate system. The origin was the center of Ryugu and the z -axis was defined along the sub-Earth line. The x -axis was defined so that the first quadrant of the X - Z plane included the sub-solar line and the y -axis was defined to complete the right-handed coordinate system.

The asteroid body fixed coordinate system was convenient for calculating the gravitational acceleration. The origin was the center of Ryugu and the z -axis was defined along the rotation axis. In this study, the rover insertion conditions were expressed in the HP coordinate system, the equations of motion were predominantly expressed in the Hill coordinate system, and the gravitational acceleration was calculated in the asteroid body fixed coordinate system; this coordinate system required proper transformation [3].

3 Dynamics

3.1 Augmented elliptic Hill three-body problem (AEH3BP)

The equations of motion are given in this section. The orbit was numerically propagated in an augmented elliptic Hill three-body problem (AEH3BP) according to the equations below. These equations were derived by extending the Hill three-body problem from the previous study [4].

$$x'' - 2y' = \frac{a_{Gx} + \beta + 3x}{1 + e_r \cos f_r} \quad (1)$$

$$y'' + 2x' = \frac{a_{Gy}}{1 + e_r \cos f_r} \quad (2)$$

$$z'' + z = \frac{a_{Gz}}{1 + e_r \cos f_r} \quad (3)$$

where the orbital angular velocity is normalized as unity, “'” denotes the true anomaly derivative and $\mathbf{a}_G = [a_{Gx}, a_{Gy}, a_{Gz}]$ is normalized gravitational acceleration.

Fig. 2 Hill coordinate system and HP coordinate system.

These equations are normalized by both the distance (LU) and time unit. Both units were derived using the distance between the Sun and Ryugu as shown in Eq. (4), and are expressed by Eqs. (5) and (6), respectively.

$$d = \frac{a_r(1 - e_r^2)}{1 + e_r \cos f_r} \quad (4)$$

$$\text{LU} = d \left(\frac{\mu}{\mu_S} \right)^{\frac{1}{3}} \quad (5)$$

$$\text{TU} = \sqrt{\frac{d^3}{\mu_S(1 + e_r \cos f_r)}} \quad (6)$$

where d denotes distance between the Sun and asteroid, a_r , e_r , and f_r denote semi-major axis, eccentricity, and true anomaly of asteroid's orbit, respectively, and μ_S and μ denote gravitational parameters of the Sun and asteroid. The equations of motion also include the normalized acceleration of solar radiation pressure (SRP) as β , expressed by Eq. (7). The β value is zero when the rover is in Ryugu's shadow.

$$\beta = \begin{cases} \frac{(1+\gamma)p_0}{(m/A)\mu_S^{2/3}\mu^{1/3}} & (\text{the rover is exposed to the Sun}) \\ 0 & (\text{the rover is in the asteroid's shadow}) \end{cases} \quad (7)$$

where γ denotes reflectivity, $p_0 = 1.0197 \text{ kg}\cdot\text{m/s}^2$ denotes solar flux, m denotes mass of the rover, and A denotes projected area of the rover. The normalized gravity potential, U is the gravity potential associated with the asteroid harmonics and indicated by the following equation, using the Legendre polynomial P_{lm} and Stokes coefficients C_{lm} and S_{lm} .

$$U(r, \phi, \lambda) = \frac{1}{r} \sum_{l=0}^{\infty} \sum_{m=0}^l \left(\frac{R}{r} \right)^l P_{lm}(\sin \phi) (C_{lm} \cos m\lambda + S_{lm} \sin m\lambda) \quad (8)$$

where R is the reference radius and ϕ and λ are the latitude and longitude, respectively. ϕ and λ are defined in the asteroid body fixed coordinate system. The reference radius R is the normalized value of 526 m, from Eq. (5). The gravitational acceleration is calculated from the gravity potential as follows:

$$\overline{\mathbf{a}}_G = \frac{\partial U}{\partial \mathbf{r}} \quad (9)$$

where $\overline{\mathbf{a}}_G$ and $\mathbf{r}$ are the gravitational acceleration and position vector expressed in the asteroid body

fixed coordinate system, respectively. The gravitational acceleration in the Hill coordinate system, $\mathbf{a}_G$, can be obtained by transforming the coordinate system of $\overline{\mathbf{a}}_G$. Tables 1 and 2 list the physical parameters of Rover 2 and Ryugu. These parameters are used in Eqs. (1)–(8).

Table 1 MINERVA II-2 parameters

Item	Symbol	Value
Mass	m	0.877 kg
Projected area	A	0.02175 m ²
Reflectivity	γ	0.35

Table 2 Ryugu parameters

Item	Value
Gravitational constant	30 m ³ /s ²
Eccentricity	0.190
Equatorial radius	503 m
Polar radius	443 m
Pole direction	[179.3, −87.44] deg
Obliquity	171.64 deg
Rotational period	7.6326 h

3.2 Asteroid's gravity and shape model

This section describes the gravity and shape models of Ryugu used in this study. The Hayabusa2 mission team constructed a polygonal asteroid shape model before touchdown, as shown in Fig. 3(b). The previous study developed the gravitational acceleration, computed using the homogeneous density polyhedron model [5]. In addition, the Stokes coefficients C_{lm} and S_{lm} have already been directly converged using the polyhedron gravity model [6]. These two gravity models have advantages and disadvantages. Although the calculation accuracy using the polyhedron gravity model is high, the calculation cost is also high. Conversely, the calculation cost of using the spherical harmonics model is lower than that of the polyhedron model. However, the accuracy usually reduces when the probe is close to the surface. Therefore, this study used both gravity models. After the spherical harmonics gravity model was used for searching the solution space, the polyhedron gravity model was used for validating the orbit candidate selected by the grid search.

Figure 3 shows the two shape models of Ryugu in the Hill coordinate system at 16:00:00 on 2 October 2019, when we planned to release the rover. The magenta lines indicate the rotation axes. As shown in Fig. 3, the rotation axis was almost perpendicular to the X – Y

Fig. 3 Asteroid models.

plane. Note that the obliquity was 171.64 deg, according to Table 2, which is almost a completely retrograde rotation; when the obliquity is 180 deg, the rotation direction is retrograde. When the spherical harmonics gravity model was used, the shape was set to be two cones, as shown in Fig. 3(a). The shape models were used to determine whether the rover collides with the surface. Note that 8×8 spherical harmonics gravity is taken into account and the Stokes coefficients are listed in Table 3. Table 3 clarifies the strong oblateness of Ryugu as C_{20} is of order 10^{-2} , which is much larger than the other terms.

3.3 Rover 2 deployment

Rover 2 was ejected in the $-y_{SC}$ direction, in spacecraft body fixed coordinates. This nominal release direction was the same as the $-y_{HP}$ direction in the HP coordinates because the x_{SC} and y_{SC} axes corresponded to x_{HP} and y_{HP} when the spacecraft maintained constant attitude; this occurred during the release of MINERVA II-2 to guarantee both communication with Earth and power generation. As shown in Fig. 4, the nominal release direction was inclined 5 deg in the direction of $-z_{SC}$ to avoid impact with the spacecraft. Most significantly, this release velocity had a large uncertainty of ± 10 cm/s. The next section describes how this initial deployment error was overcome and the rover was inserted into a stable orbit around Ryugu.

4 Orbit design

4.1 Critical velocity

We first investigated the zero velocity curve around Ryugu to approximately determine the orbit insertion

Table 3 Unnormalized gravity coefficients

l	m	C_{lm}	S_{lm}
0	0	1.000000000e+00	0.000000000e+00
1	0	-2.599033996e-16	0.000000000e+00
1	1	1.062577084e-16	3.494929332e-16
2	0	-3.898812629e-02	0.000000000e+00
2	1	-9.356634314e-05	-5.918281151e-04
2	2	-1.579451669e-03	-1.099248649e-03
3	0	1.808135634e-03	0.000000000e+00
3	1	2.903207922e-03	3.092943141e-03
3	2	5.316500199e-04	-1.296893281e-03
3	3	1.380156630e-04	-2.853838179e-04
4	0	2.235039289e-02	0.000000000e+00
4	1	2.174354306e-03	9.805267670e-04
4	2	-7.205712007e-05	3.969527686e-05
4	3	-7.624624543e-06	-9.146659147e-06
4	4	-1.216141238e-05	-1.639308253e-06
5	0	1.679282696e-04	0.000000000e+00
5	1	3.656499615e-04	2.584972684e-04
5	2	6.123689211e-06	9.739625836e-05
5	3	-1.515033208e-05	2.531872788e-06
5	4	-1.539966499e-06	-2.295906186e-06
5	5	1.914132501e-08	-2.029363817e-07
6	0	-7.777325445e-03	0.000000000e+00
6	1	-7.138750680e-04	3.514570437e-04
6	2	-4.676504321e-05	-1.542343672e-05
6	3	-2.590314773e-06	6.287585904e-06
6	4	-6.060159865e-08	6.403054172e-08
6	5	3.780898045e-08	4.947584575e-08
6	6	7.137350504e-08	3.878680629e-08
7	0	-4.164003942e-04	0.000000000e+00
7	1	1.446753633e-04	3.337757330e-04
7	2	1.963966097e-05	-3.371212653e-05
7	3	4.651910495e-07	-2.334143802e-06
7	4	-1.617124235e-07	-1.377487760e-07
7	5	-6.548581422e-08	2.379569051e-08
7	6	1.755518584e-09	4.088822413e-10
7	7	-6.728838670e-10	2.736666545e-09
8	0	3.729550481e-03	0.000000000e+00
8	1	1.605378972e-04	2.789848182e-05
8	2	-5.411124027e-06	2.791469736e-06
8	3	2.341238678e-07	-1.061777400e-06
8	4	-6.925824555e-08	2.885921386e-08
8	5	1.354088745e-08	-1.175582598e-08
8	6	-3.672817326e-09	-3.176220530e-09
8	7	3.819611085e-10	-5.905042470e-10
8	8	1.894731930e-11	-2.034058704e-10

Fig. 4 MINERVA II-2 deployment.

policy. Since the zero velocity curve cannot be defined as a time-invariant parameter in the EH3BP, we introduced the quasi-elliptic Hill three-body problem (QEH3BP), which is the modified equations of EH3BP developed by the previous study [7]. The Jacobi integral can be defined in QEH3BP as the QEH3BP equations are the autonomous equations of motion. The normalized QEH3BP equations are expressed as follows:

$$\ddot{x} - 2\tilde{n}\dot{y} = -\frac{x}{r^3} + \beta - \frac{3}{1 + e_r \cos f_r} \tilde{n}x \quad (10)$$

$$\ddot{y} + 2\tilde{n}\dot{x} = -\frac{y}{r^3} \quad (11)$$

$$\ddot{z} = -\frac{z}{r^3} - \tilde{n}^2 z \quad (12)$$

where the gravity is approximated by a point mass. $\tilde{n}$ is indicated by Eq. (13).

$$\tilde{n} = \frac{(1 + e_r \cos f_r)^2}{(1 - e^2)^{\frac{3}{2}}} \quad (13)$$

The conserved quantity (i.e., Jacobi integral) can be calculated in QEH3BP as follows:

$$C_J = \frac{v^2}{2} + \bar{U} \quad (14)$$

$$\bar{U} = -\frac{1}{2}\tilde{n}^2 \left(\frac{3x^2}{1 + e_r \cos f_r} - z^2 \right) - \frac{1}{r} - \beta x$$

Figure 5 shows the unnormalized zero velocity curve obtained by substituting $v = 0$ into Eq. (14). The epoch was set to be 2 October 2019, at 16:00:00. There is one Lagrange point (L2) because the L1 point disappears due to SRP force. Since the bold line in Fig. 5 indicates the closed region of C_J , proximity to Ryugu was not

Fig. 5 Zero velocity curve.

guaranteed outside of the bold line. Thus, the rover required release inside this closed region. The critical velocity (v_c) that guaranteed the rover's proximity to Ryugu can be defined as follows:

$$v_c = \sqrt{2(C_J^* - \bar{U})} \quad (15)$$

C_J^* corresponds to the bold line in Fig. 5. The sum of the rover's orbital velocity, v_o , release velocity error must be smaller than v_c . Therefore, the velocity margin (v_m) that guarantees not escaping from Ryugu could be obtained in the cases where the rover was inserted in the tangential and normal direction to the orbit.

$$v_m = \begin{cases} v_c - v_o & (\text{tangential}) \\ \sqrt{v_c^2 - v_o^2} & (\text{normal}) \end{cases} \quad (16)$$

When the spacecraft was on the sub-Earth line and v_o was calculated as the circular orbital velocity in the two-body problem and expressed by $v_o = \sqrt{\mu/r}$, the relation of v_m and orbital radius is shown in Fig. 6. Obviously, the rover requires release in the normal direction to the orbit as the velocity margin of the normal direction is more than twice as large as that of the tangential direction. In addition, Fig. 6 indicates that an orbit radius smaller than 1.5 km should be chosen because the rover release velocity has ± 0.1 m/s error.

4.2 Terminator orbit and equatorial orbit

In this study, there were two candidate orbits into which the rover could be inserted: a terminator orbit and equatorial orbit. This subsection compares the

Fig. 6 Velocity margin.

initially circular terminator orbit and the initially circular equatorial orbit. The terminator orbit is a well-known

stable frozen orbit around a small body in an environment strongly perturbed by the SRP force. Many previous papers have investigated the characteristics and stability of the terminator orbit; in addition to being stable inside the surrounding linearized region, there is a broad solution space that avoids both escape and impact, even if the orbits are outside the linearized region [8, 9].

Two initially circular terminator orbits with radial distances of 1.0 and 1.5 km, respectively, were propagated over 20 days according to Eqs. (1)–(3), as shown in Fig. 7. These orbits are displayed in the Hill coordinate system. The nominal orbits, shown as blue lines, indicate initially circular terminator orbits. Other orbits include initial velocity errors of ± 10 cm/s due to the release

Fig. 7 Terminator orbits.

velocity of 15.4 ± 10 cm/s. The initial position was set to be $[x_{\text{Hill}}, y_{\text{Hill}}, z_{\text{Hill}}] = [0, 0, 1.0 \text{ or } 1.5 \text{ km}]$ and the velocity errors were given to v_x . Figure 7 shows that the terminator orbits with large velocity uncertainties were stable over more than 20 days, even if perturbations due to higher order gravity and SRP were included in the dynamics around Ryugu. Figure 8 shows the history of the eccentricity of the terminator orbits. Despite the eccentricities oscillating in the case of ± 10 cm/s, the

rover avoids impacting with the surface.

An alternative candidate is the near-equatorial orbit around Ryugu. It is known that there are stable equatorial orbits when the J_2 terms of gravity and SRP are dominant in the vicinity of Ryugu. These are frozen orbits, sometimes called heliotropic orbits by previous studies [10, 11]. Since Ryugu also has large oblateness, the eccentricity of the equatorial orbits around Ryugu tend towards stability. Figure 9 shows the initially

Fig. 8 Eccentricity of terminator orbits.

Fig. 9 Equatorial orbits.

circular orbits as the nominal orbits in the two cases where the radial distance is equivalent to 1.0 and 1.5 km in Hill coordinates. These were propagated for 20 days. The initial position was set to be $[x_{\text{Hill}}, y_{\text{Hill}}, z_{\text{Hill}}] = [-1.0$ or $-1.5, 0, 0$ km] and the velocity errors were given to v_z as 10 cm/s. Although the rover finally impacts with the surface, except for the nominal case of $r = 1.0$ km, it does not escape from Ryugu; even if the initial velocities include an error of 10 cm/s. The eccentricities are shown in Fig. 10 and the minimum duration is 5 days. These results indicate that the equatorial orbit is also a valid candidate for the orbit owing to its relative stability, considering the gravitational irregularity.

In this section, we compare the orbits from the standpoint of Rover 2 insertion operability. Figure 11 shows a comparison of insertion into the terminator orbit and equatorial orbit. In both orbits, the spacecraft must decrease its altitude to insert Rover 2. If the equatorial orbit is chosen, after the spacecraft descends along the sub-Earth line the spacecraft should give the rover's orbit velocity and correction maneuver in the

$-z_{\text{Hill}}$ direction because the release direction is $+z_{\text{Hill}}$. Since this operation can ensure release direction normal to the orbital velocity, the orbit becomes robust against release velocity error. Conversely, if the terminator orbit is chosen, the spacecraft must move to the polar position and insert the rover so that the release direction corresponds to the direction normal to the orbital velocity, without any change in attitude. This extremely unusual operation is more difficult than that of the equatorial orbit as the spacecraft must be very far from the sub-Earth line. Therefore, from the standpoint of operational safety the equatorial orbit is better than the terminator orbit for the Hayabusa2 spacecraft.

4.3 Solution space

To determine the best initial conditions for inserting Rover 2 into equatorial orbit, we conducted a grid search of the orbits' solution space around Ryugu. Initial velocities were given in HP coordinates and $v_{x\text{HP}}$ and $v_{y\text{HP}}$ were chosen as grid search parameters. $v_{z\text{HP}}$ was set to 0. Initial positions were on the sub-Earth

Fig. 10 Eccentricity of equatorial orbits.

Fig. 11 Comparison of MINERVA II-2's insertion operation.

line and the radial distances were varied from 1.0 to 3.0 km. Figures 12 and 13 show the solution space of duration and number of periods, respectively. The white areas indicate that the rover escapes from Ryugu and the areas surrounded by red lines indicate that the rover impacts with the surface without any revolutions. Note that the areas where v_{yHP} is close to zero correspond to the equatorial orbits because the y_{HP} direction corresponds to the z_{Hill} direction. These figures show that the larger the orbit becomes, the smaller the solution space becomes. Moreover, v_{yHP} should be chosen as zeros because the solution spaces are symmetric about v_{yHP} . It is important that v_{yHP} has a 10 cm/s velocity margin in the valid solution area that avoids both escape and impact without revolution.

These figures reveal that with the exception of (d) $r = 3.0$ km, the solution case satisfies the 10 cm/s v_{yHP} margin and as the orbit becomes smaller the v_{yHP} margin becomes accordingly larger. Although $r = 1.0$ km is optimal in terms of orbit robustness against velocity error, it is a high risk operation; $r = 1.0$ km indicates the spacecraft altitude is less than 500 m. Hence, we chose a value of $r = 1.5$ km, accounting for both velocity margin and operational safety.

Another topic of interest concerns which orbit direction is optimal. There are two areas where the v_{yHP} margins are more than 10 cm/s and v_{xHP} is from -14 to -10 cm/s and from 10 to 14 cm/s on the left and right sides of Fig. 12, respectively. Each area corresponds to the prograde and retrograde orbits.

Fig. 12 Duration map with several radial distances.

Fig. 13 Number of periods map with several radial distances.

Note that “prograde” and “retrograde” are defined in Hill coordinates. Figure 14 shows enlarged maps of Fig. 12(b). Interestingly, these figures are very different. Prograde orbits have a broad yellow area, indicating a stable and long duration, whereas retrograde orbits have a mottled pattern that indicates an orbit family sensitive to errors. For instance, Fig. 15 shows the case of $[v_{xHP}, v_{yHP}] = [-0.113, 0]$ m/s and $[v_{xHP}, v_{yHP}] = [0.113, 0]$ m/s. This prograde orbit is very stable and has a duration of more than 90 days, whereas the retrograde orbit has a duration of less than 12 days. It is assumed that the reason for this derives from gravitational irregularity having a stronger effect on retrograde orbits than on prograde orbits as Ryugu’s rotation is retrograde and in the same direction as the

retrograde orbit. When an orbit direction opposing Ryugu’s rotation is chosen, the perturbation averages out and the orbit tends towards stability. If the rover is not inserted into orbit but the spacecraft is, the orbit direction should oppose Ryugu’s direction of rotation to ensure maximum stability. However, in this study the rover was required to finally land on the surface without an excessively long orbit duration, as mentioned in Section 1. Therefore, the somewhat unstable retrograde orbit was a more suitable choice for Rover 2’s orbit.

4.4 Monte Carlo simulation

The previous subsection revealed that v_{xHP} should be a positive value for the retrograde orbit. We subsequently conducted a Monte Carlo simulation to

Fig. 14 Close-up of duration map for the case $r = 1.5$ km.

Fig. 15 Comparison of prograde orbit and retrograde orbit.

precisely determine the initial v_{xHP} by considering various errors in using the spherical harmonics gravity model. Although the previous sections only consider the release velocity error, the actual orbit insertion has various associated errors, such as release angle error, reflectivity error, and spacecraft guidance and control error. Table 4 lists the insertion errors used in the Monte Carlo simulation. In addition to spacecraft and rover errors, dynamic uncertainty was also taken into account in the form of errors regarding higher order gravity. We conducted 500 Monte Carlo simulations for each initial condition. Figure 16 and Table 5 show the results. Figure 16 shows the orbits' periods ratio and duration ratio in four initial velocity cases ($v_{xHP} = 0.125, 0.130, 0.135, 0.140$ m/s). Significantly, the rover must avoid escape and an excessively long duration to the greatest possible extent. Table 5 lists the ratios of escape and long duration orbits. Although these results show there were no cases where both escape and long duration orbits were 0%, we determined that $v_{xHP} = 0.13$ m/s was the best initial velocity because the escape ratio was less than 1% and the long duration ratio was also sufficiently low. Therefore, the case of $v_{xHP} = 0.13$ m/s was chosen as the nominal orbit and propagated in both the spherical harmonics and polyhedron gravity model, as shown in Fig. 17. Figure 18 shows each orbital element. The orbit duration of the spherical harmonics gravity model was 5.2180 days, whereas that of the polyhedron gravity model was

4.7933 days. Although the duration difference of about 0.4 days was caused by gravity and the differences in the surface model, the histories of the orbital element shown in Figs. 18(a) and 18(b) are approximately the same. Hence, propagation using the spherical harmonics gravity model was validated by the polyhedron gravity model.

Therefore, the nominal initial velocity was designed to be $\mathbf{v}_{HP} = [0.13, 0, 0]$ m/s. Since the rover was ejected in the $-y_{SC}$ direction and the release velocity was not zero, the spacecraft gave both the orbital velocity of the rover and the compensation maneuver, where $\mathbf{v}_{HP} = [0.13, 0.1534, 0.0134]$ m/s when the rover was released.

5 Flight results

The MINERVA II-2 operation was performed between 28 September and 8 October 2019. Hayabusa2 started its descent along the sub-Earth line on 28 September. We repeated orbit determination and trajectory correction of the spacecraft daily so that the spacecraft arrived at the point where Rover 2 of MINERVA II-2 was deployed at 15:57:20 on 2 October. After releasing the rover, the spacecraft proceeded to the observation point, as shown in Fig. 19. The observation point was located at $\mathbf{r}_{HP} = [2, 0, 8]$ km in HP coordinate and the spacecraft aligned its attitude with the observation attitude. This is so the optical navigation camera (ONC-T) could image the area where

Table 4 Given errors in Monte Carlo simulation

Error type	Value	Random type
Rover 2, release velocity error	from 5.4 to 25.4 cm/s	Uniform random
Rover 2, release angle error	$3\sigma = 5$ deg	Gaussian random
Rover 2, reflectivity error, γ	from 0.2 to 0.5	Uniform random
Spacecraft guidance and control error, x_{HP}	$1\sigma = 80$ m	Gaussian random
Spacecraft guidance and control error, y_{HP}	$1\sigma = 80$ m	Gaussian random
Spacecraft guidance and control error, z_{HP}	$1\sigma = 20$ m	Gaussian random
Spacecraft guidance and control error, v_{xHP}	$1\sigma = 8.21$ mm/s	Gaussian random
Spacecraft guidance and control error, v_{yHP}	$1\sigma = 8.19$ mm/s	Gaussian random
Spacecraft guidance and control error, v_{zHP}	$1\sigma = 8.93$ mm/s	Gaussian random
Gravity higher order, C_{lm} ($l \neq 0 \vee m \neq 0$)	from -3% to 3%	Uniform random

Table 5 Escape and long duration ratios

v_{xHP}	Escape	Long duration (more than 40 days)
0.125 m/s	0%	10.6%
0.130 m/s	0.4%	4.2%
0.135 m/s	1.0%	3.0%
0.140 m/s	2.4%	0.8%

Fig. 16 Monte Carlo simulation results.

Fig. 17 Nominal orbit.

Fig. 18 Nominal orbital element.

Fig. 19 Observation point and ONC-T coordinate $\mathbf{r}_{\text{cam}}$.

the rover was likely to pass, despite the release condition including the various errors mentioned above, and ONC-T would not image Ryugu. Since ONC-T images of Ryugu were too bright, the rover could not be imaged if Ryugu was in the field of view (FOV) of ONC-T. After the spacecraft rotated 25 deg around the y_{sc} axis, it rotated -10 deg around the z_{sc} axis, aligning its

HP attitude with the observation attitude. Here, the ONC-T coordinates are defined as the spacecraft fixed coordinates during the observation. The rover's position ($\mathbf{r}_{\text{cam}}$) in ONC-T coordinates can be expressed as shown in Eq. (17).

$$\mathbf{r}_{\text{cam}} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \phi & \sin \phi & 0 \\ -\sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{pmatrix} \mathbf{r}_{\text{HP}} \quad (17)$$

where $\theta = 25$ deg and $\phi = -10$ deg. When the spacecraft fixed coordinates matched the HP coordinates, the x -axis of the ONC-T coordinates opposed that of the HP coordinates. After the spacecraft moved to the observation point, it continued to take pictures with ONC-T until 8 October 2019.

We obtained 14 pictures showing bright spots that indicate Rover 2 in orbit. Figure 20 shows the 14 pictures. These pictures were taken every 10 min from 08:20:17 to 10:23:15 on 3 October. We can see that the rover appears on the left side of the first picture and moves to the right side of the picture frame. Although

Fig. 20 Pictures taken by ONC-T.

we planned to image the rover over several periods in case the rover was inserted into the nominal orbit, we were able to image one arc.

This study then approximately estimated the rover's release condition using these observation results. As a result of the orbit determination of Hayabusa2, when it descended we obtained the position of the rover's release as $\mathbf{r}_{\text{HP}} = [11.56, -22.07, 1503.78]$ m at 15:57:20 on 2 October 2019 [12]. The rover's release velocity was estimated using least-squares estimation to minimize the objective function, as expressed below.

$$J = \sum_i (x_{\text{obs},i} - x_{\text{cal},i})^2 + (y_{\text{obs},i} - y_{\text{cal},i})^2 \quad (18)$$

where $x_{\text{obs},i}$ and $y_{\text{obs},i}$ denote the observed position of the rover in ONC-T coordinates, $x_{\text{cal},i}$ and $y_{\text{cal},i}$ denote the estimated position in ONC-T coordinates, and i denotes the numbering of the pictures. The optimization problem was solved to minimize J under the condition that the rover's initial velocity was set as the input parameters. This study did not estimate the gravity coefficients and fix them as nominal constant parameters. Table 6 lists the results of estimated initial velocity. Comparing the reference and estimated values, we found that the error in $v_{x\text{HP}}$ was within 3σ of the guidance and control error represented in Table 4. In addition, the release velocity magnitude, relative to the spacecraft, could be calculated as 0.1924 m/s by $v_{y\text{HP}}$ and $v_{z\text{HP}}$ of the rover's estimated initial velocity and the spacecraft's compensation maneuver. The release velocity magnitude was also within the assumed error. However, the error of $v_{z\text{HP}}$ was much larger than expected. Figure 21 shows the estimated position (calculation) and observed position (observation) in ONC-T coordinates. The O-C residual was found to converge and the estimated initial condition was valid. The estimated initial condition resulted in the orbit illustrated in HP coordinates, as shown in Fig. 22. The blue line indicates the rover's orbit, the green bold line indicates the arc taken by ONC-T, and the

Fig. 21 Calculation and observation of MINERVA II-2's position in ONC-T's FOV.

Fig. 22 Estimated MINERVA II-2 orbit with ONC-T's field of view.

Table 6 Comparison of the released rover's initial state

	Reference	Estimation
x_{HP} (m)	0	11.56
y_{HP} (m)	0	-22.07
z_{HP} (m)	1500	1503.78
$v_{x\text{HP}}$ (m/s)	0.13	0.1120
$v_{y\text{HP}}$ (m/s)	0	-0.0128
$v_{z\text{HP}}$ (m/s)	0	-0.0836

four pink lines indicate the four corners of ONC-T's FOV. This figure indicates that after the rover orbited Ryugu for one and a quarter periods, it landed on the surface. The duration was 0.9372 days. The duration of all orbits in the Monte Carlo simulation, except for the cases of escape, were more than 3 days, as shown in Fig. 16(b-2). Nevertheless, the duration was much less than 3 days as the error in $v_{z\text{HP}}$ was greater than expected. The actual release angle could be estimated based on the estimated initial velocity, as shown in Fig. 23. Although the angle between

Fig. 23 Estimated MINERVA II-2's release angle.

the release direction and the y_{sc} axis was assumed to be 5 deg, it could be estimated as 30 deg. This corresponded with the analysis based on images taken by the other optical camera, in the seconds immediately following the rover's release. The MINERVA II-2 team concluded that the error in the release direction was attributed to inaccurate maintenance of the tightening torque of the screw used to close the rover's cover.

Thus, the MINERVA II-2 operation achieved orbiting of Ryugu and landing on the surface, although the periods were fewer and the duration shorter than planned. Even though SRP and gravitational irregularity strongly perturbed the dynamics around Ryugu and the rover had a large insertion velocity uncertainty, we successfully achieved Japan's first orbit around a small body for more than one period and established the possibility of a new method for gravity estimation.

6 Conclusions

This paper presented the design of the orbit of Ryugu by Rover 2 of MINERVA II-2, installed on the Hayabusa2 spacecraft. The rover required insertion into an orbit that would avoid escape from Ryugu and ultimately allow the rover to land on the surface. It was important to design a robust orbit satisfying these requirements under the severe conditions of the rover's large release uncertainty and the strongly perturbed dynamics around Ryugu by SRP and gravitational irregularity. Our analyses of the solution space revealed that the retrograde equatorial orbit was most appropriate as it satisfied operational safety and stability by taking

advantage of the high obliquity of Ryugu. Moreover, the retrograde orbit offered a higher possibility of landing the rover than the prograde orbit. In addition, this study showed that Hayabusa2 mission accomplished not only orbiting of Ryugu but also landing on the surface via orbit determination, using the flight data of several images taken by ONC-T.

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