# The Flight Dynamics Contribution to the Selection of MASCOT Landing Site on the Surface of the Asteroid Ryugu

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## Abstract

The Mobile Asteroid Surface SCOuT (MASCOT) is a German-French lander carried by the Japanese space probe Hayabusa2 [1] toward the near Earth asteroid Ryugu (162173). Arrived in the vicinity of Ryugu at the end of June 2018, the Japan Aerospace Exploration Agency (JAXA) space probe has acquired crucial data about the asteroid. In the frame of the collaboration between the German Aerospace Centre (DLR) and the French Space Agency (CNES) [2], the CNES Flight Dynamics Team was responsible for using these unprecedented data in order to define a preliminary list of possible landing sites for MASCOT [3], compatible with technical constraints and scientific objectives. After an exhaustive and iterative analysis of the reachable zones on Ryugu's surface, the resulting list of possible candidates was proposed for approval and ranking to MASCOT engineering and science teams. The final landing site was chosen in the ranked list in agreement with JAXA and successfully reached by MASCOT on the 3rd of October 2018.

**Keywords:** Lander, Bounce, Trajectory, Asteroid, Landing Site Selection

## Introduction

2018 was a crucial year for the Japanese space probe Hayabusa2 since it reached its final destination after a 4-year cruise in our Solar System: the carbonaceous asteroid Ryugu, whose exploration will give unprecedented information about the birth of the solar system. In its journey across space, Hayabusa2 (HY2) carried the small German-French Lander called Mobile Asteroid Surface SCOuT (MASCOT), with the objective to release it to Ryugu's surface. In the very impressive operational schedule of Hayabusa2 that includes three touchdown operations during which the probe will gather some samples and the release of 3 small Japanese rovers called MINERVA, a slot of three days has been reserved for MASCOT's delivery. The date of MASCOT's release has been fixed in early October 2018, just after the two first MINERVA releases and before the sampling operations. This place in the operational scenario allowed MASCOT to be safely released before the hazardous touchdowns and to fully play its role of a scout by gathering useful data about the environment that will be found by Hayabusa2 at the surface. After a ballistic descent, the small shoe-box shaped lander was expected to bounce several times at the surface. Once stabilized, the on-board autonomy software realizes an up-righting of MASCOT, to ensure that the instruments point toward the ground and then it has to start an operational sequence consisting of chained activations of science instruments. Powered by a primary battery without any recharging capability giving roughly 15 hours of on-asteroid operations, MASCOT was supposed to explore at least two different locations in Ryugu, using its hopping mechanism to move from its first rest position to a second one. In the challenging mission to make MASCOT safely land on this new world, and in the frame of the collaboration between the German Aerospace Centre (DLR) and the French Space Agency (CNES), the

MASCOT CNES Flight Dynamics Team (MASCOT FD Team) had a primary role to play, since it was responsible for the activities related to Mascot landing trajectory prediction and optimization. In the exploration of Ryugu, the selection of the landing site for MASCOT is an essential step, not only to ensure that the lander will find conditions adapted to nominal operation, but also to guarantee that MASCOT operations will not interfere with Hayabusa2 touchdown and sampling operations, which are major objectives of the mission. In the present paper, the contribution of the CNES Flight Dynamics Team to the selection of MASCOT landing site will be discussed. In the first part, the challenges of the MASCOT trajectories prediction will be presented. Then, an overview of the process followed in August 2018 to select MASCOT landing site will be given. The information learned about Ryugu will be described focusing on their impact from flight dynamics point of view. Finally, the process set up by the CNES Flight Dynamics Team will be detailed and the main steps of its actual progress will be commented, before concluding about the main lessons learned from such an extraordinary experience.

## MASCOT trajectories computation

The selection of the landing site for MASCOT requires to be able to give an estimation of the trajectory followed by the lander once separated from the mother spacecraft. MASCOT is not equipped with thrusters or attitude control and all trajectories are purely ballistic. The trajectory can be separated into two different phases. The first phase is the descent toward the surface; it is the most deterministic phase depending only on the time and position at which the release is commanded and on gravitational acceleration created by Ryugu. The second phase starts as soon as MASCOT hits the surface: since the lander has no stabilizing nor anchoring mechanisms, it is expected to bounce several times at the surface. The contact with the surface modifies MASCOT energy in a way which depends on many parameters for which only assumptions can be made beforehand. Since the nature of Ryugu's surface remains very poorly known until it has been explored, it is necessary to envisage a wide range of possible assumptions if one wants to cover all possible scenarios. That's why this second phase introduces a lot of dispersion in the predictions.

### Uncertainties and degrees of freedom for MASCOT's descent toward Ryugu

The descent trajectory is defined as the path followed by MASCOT between its separation from Hayabusa2 spacecraft and the first contact with Ryugu's surface called Contact Point 1 or CP1. The starting point of the descent phase is defined by the conditions of the separation from Hayabusa2. The present section will focus on the parameters of the separation that can be tuned in order to reach a given CP1.

For MASCOT separation, Hayabusa2 descends from its Home Position (HP) at 20 km above Ryugu's surface along the Earth-Asteroid line with a controlled velocity. The detection by Hayabusa2 LIDAR (LIght Detecting And Ranging) of an altitude of 60 m above the surface triggers a deceleration manoeuvre reducing Hayabusa2 vertical velocity to -0.03m/s. From this point, Hayabusa2 starts to fall freely toward Ryugu's surface. After 140s of free fall, which correspond to the time needed to stabilize the probe attitude after the deceleration manoeuvre, MASCOT is released from the mother spacecraft with a pre-defined non-tuneable separation velocity (in the order of 5 cm/s).

At this point, it has to be noted that the attitude of Hayabusa2 at MASCOT's release is pre-defined and cannot be changed. Let's define the Home Position frame, or HP frame, using the following axes:

- $Z_{HP}$ axis is aligned with Asteroid-Earth line, pointing towards the Earth,

- $X_{HP}$ axis is perpendicular to $Z_{HP}$ and in the plane generated by the Earth and the Sun direction, facing the Sun,
- $Y_{HP}$ completes the positively oriented system.

During the descent performed by Hayabusa2 in order to release Mascot, the attitude of the mother spacecraft is always controlled such that the Hayabusa2 frame coincides with the HP frame. As shown in Fig. 1, the nominal separation direction for Mascot is thus in the $Y_{HP}Z_{HP}$ plane, in the $-Y_{HP}$ axis direction and forming an angle of -15 degrees with this axis. As a consequence, the separation direction will thus always be oriented in the same way with respect to the asteroid's surface and cannot be changed.

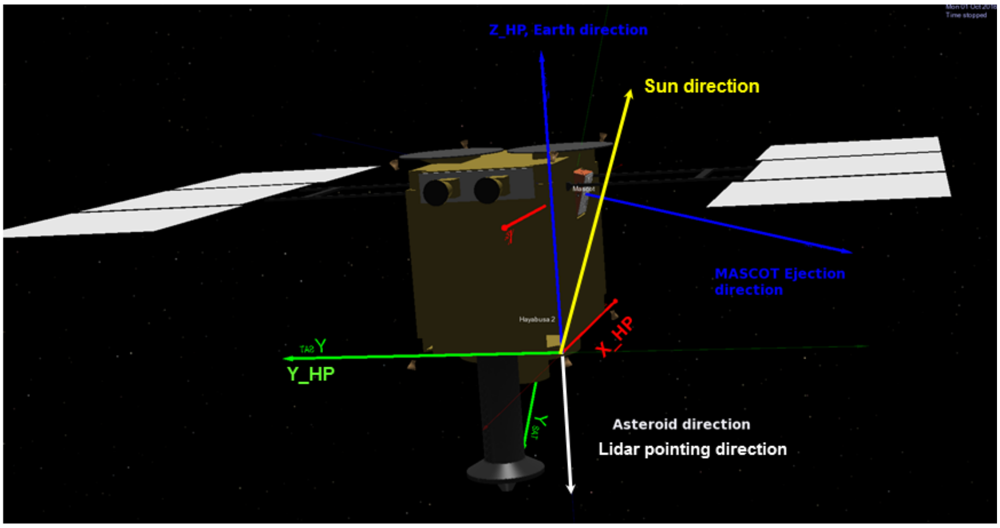


*Fig. 1 MASCOT release geometry*

Even if the release position is mainly fixed by the nominal Hayabusa2 descent operations, a degree of freedom has been given by JAXA to increase the number of possible landing sites for MASCOT. At the instant of MASCOT's separation, the mother spacecraft position can be shifted in the plane perpendicular to the $Z_{HP}$ axis by a distance d shorter than or equal to 200 m to the Earth to asteroid line. The maximum distance d is imposed by Hayabusa2 technical and operational constraints. If one defines the position of Hayabusa2 in the allowed release disk with a distance d and an angle a as shown in Fig. 2, the pair (d, a) will be part of the parameters that can be used to optimize the Mascot separation and to target a specific landing area. It will mainly help to gain a possible range in latitude.
As far as landing longitude is concerned, it mainly depends on the chosen time of separation that can also be tuned within the pre-selected epoch range in order to target a given point on Ryugu's surface. Since Hayabusa2 starts its descent from the fixed Home Position with Ryugu's surface rotating below this point, the time of separation directly allows to choose CP1's longitude, as shown in Fig. 3. As for the latitude, it is imposed by the Earth to asteroid line, and by the fixed release orientation delivered by the separation mechanism, and can be fine-tuned within the limits of 200 m fixed for the distance d defined in Fig. 2.

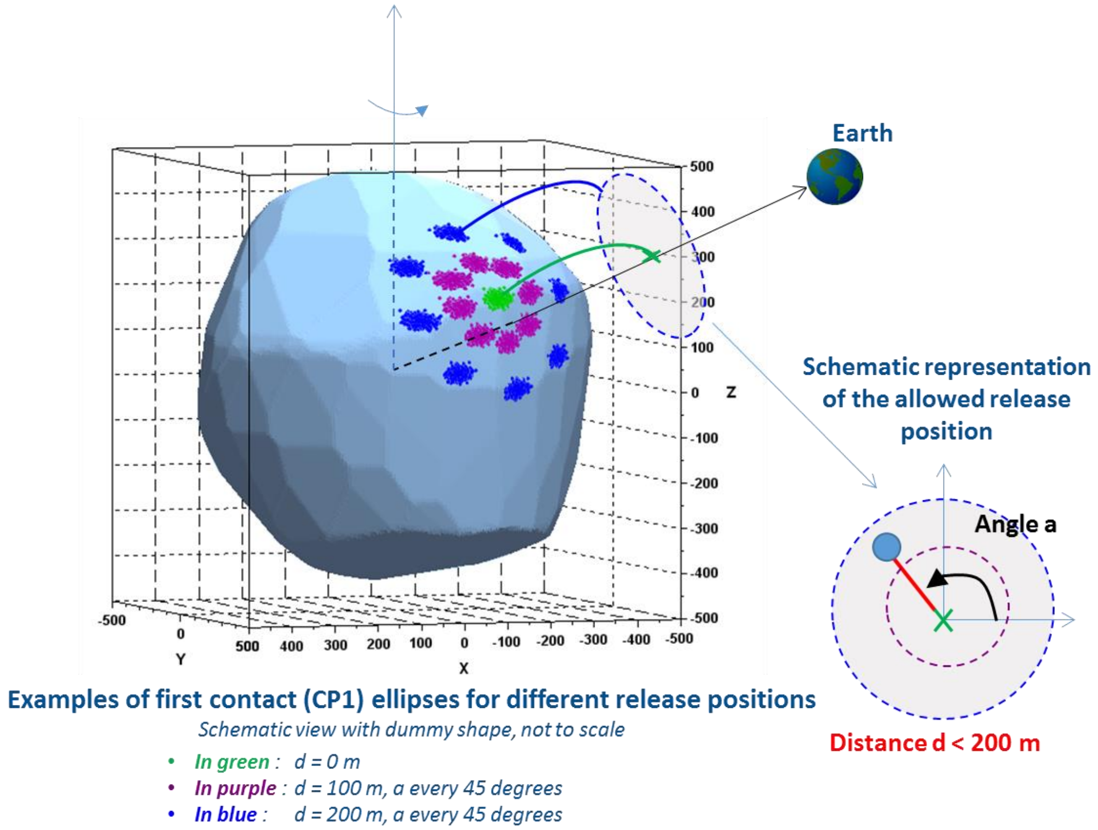


*Fig. 2 Scheme showing the impact of release conditions on the CP1 location*

Once the nominal release position and epoch have been selected, the following uncertainties shall be taken into account for computing the ellipse of first contact point:

- Uncertainty on Ryugu's GM,
- Uncertainty on separation time, resulting from vertical navigation errors,
- Uncertainty on Hayabusa2 position and velocity at release, resulting of navigation errors, altitude detection error and deceleration manoeuvre realisation errors,
- Uncertainty on Hayabusa2 attitude, resulting of attitude control error,
- Uncertainty on separation manoeuvre magnitude and direction, resulting of inaccuracy in separation mechanism operation.

All these uncertainties are taken into account in the descent trajectory Monte-Carlo analyses, leading to CP1 ellipses as shown on examples in Fig. 3.

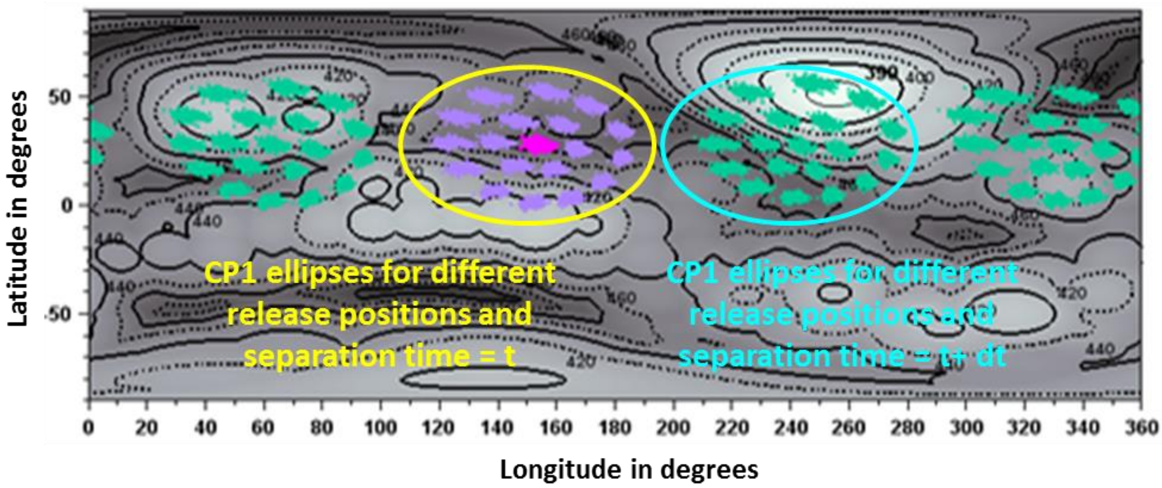


*Fig. 3 Illustration of the shift in longitude with respect to the time of separation. The green, purple and pink spots are ellipses representing CP1 positions.*

**The bouncing phase: rolling a dice on an unknown surface**

As soon as CP1 has been reached, MASCOT trajectories have to account for the contact with the asteroid surface which will define the bounces. In the following lines, the final position reached by MASCOT after the bounces is called final settlement point. The areas at the surface of Ryugu covered by all the possible final settlement points resulting of Monte-Carlo simulation are called final settlement areas or zones.

The accurate physical modelling of such contact requires very complex and time-consuming algorithms which are not compatible with Monte-Carlo analyses. Moreover, most of the input parameters, as the mechanical properties of the ground, the exact local normal at contact point or the MASCOT attitude, are unknown. An important work was thus done by CNES Flight Dynamics Team in order to design a simplified but suitable modelling of the contacts allowing to run performant Monte-Carlo analyses. The accurate description of the bouncing model is not in the scope of this paper and only a global overview of the implementation is given in the following lines.

The simplification consists in using a statistical approach based on parameters and statistical properties derived from analytical simulations of bouncing trajectories. The statistical approach allows to have time performance compliant with operational constraints and to easily take into account all the uncertainties encountered on the asteroid.

The exact nature of the ground being barely known, results coming from two different types of analytical simulations have been considered in order to integrate into the statistical models two main types of contacts:

- Hard contact simulating bounces on rocky / hard surface have been modelled using results obtained with the simulator developed by the University of Boulder - Colorado and described in Ref. 5 and Ref. 6,
- Softer contact with granular surface simulating bounces on regolith have been modelled using results from a simulator developed by the Observatoire de la Côte d'Azur and described in Ref. 7.

Since the simulations had to be performed before the actual arrival at the asteroid, they were run with realistic assumptions for the shape of the asteroid and its gravity, commonly endorsed by all the community working on Ryugu as the reference model.

The statistical approach simplifies the computations because all the complexity is supported by the numerical simulations from which the statistical laws are determined. It allows to take statistically into account MASCOT's cubic shape and attitude, the exchange between kinetic energy and rotational energy and the roughness of the terrain, since all these features are simulated in the analytical simulators. The results of analytical simulations have been processed to deduce Cumulative Density Functions (CDF) for each of the main parameters ruling the contacts with the ground, that is:

- The tilt angle of the local normal for the hard contact, namely the deviation due to the presence of rocks,
- The effective coefficient of restitution called $e_{tot}$ defined as the ratio between outgoing velocity magnitude and incoming velocity magnitude, for each kind of contact.

The implemented algorithm follows several steps described here after and illustrated in Fig. 4:

1. Randomization of the surface material properties: depending on the location of the contact at the surface of the asteroid, one determines by a random shooting if the material is considered as regolith (soft contact) or rock (hard contact). This is done with the help of a probability map to fall on regolith or rock. The probability map may be established from asteroid observations to take into account areas covered by regolith or on the contrary very rocky areas. For the actual operations, and taking into account the important quantity of rocks quasi-homogeneously covering the surface, it has been considered that MASCOT had 75% of chances to fall on rocks everywhere on the surface.
2. Randomization of the local normal: the expected shape model resolution is a few meters. In order to represent lower size rocks, a random local normal tilt model is applied following CDF derived from Ref. 5.
3. Bounce modeling: depending on the material drawn at step 1, the outgoing velocity is computed differently:
   - The magnitude of the velocity is computed thanks to the coefficient $e_{tot}$ applied to the magnitude of the incoming velocity:
     - For hard contact (i.e. rocks), $e_{tot}$ is derived from the distribution of coefficients obtained with the simulator described in Ref. 6. This simulator was configured with a coefficient of restitution equal to 0.6 (deduced from DLR studies described in Ref. 8) and a coefficient of friction equal to 0.5. The distribution has been found different for the first bounce and for the following ones.
     - For smooth contact (i.e. regolith), the applied $e_{tot}$ is derived from the distribution of coefficients obtained with the simulator described in Ref. 7. It depends on the impact angle, defined as the angle between incoming velocity and the local normal.
   - For both kinds of material, the outgoing direction is drawn in a range defined in such a way that it is consistent with the expected coefficient of friction.
4. If the norm of the outgoing velocity is lower than a fixed threshold, the trajectory ends. Otherwise, the trajectory is propagated until the next contact with the ground.

The validity of statistical implementation was verified by comparing the final settlement areas obtained with the analytical model used to define the CDF and the ones obtained with the statistical model. After some adjustments in the statistical model parameters, a good matching has been reached, confirming that the implemented model can be used for trajectory predictions.

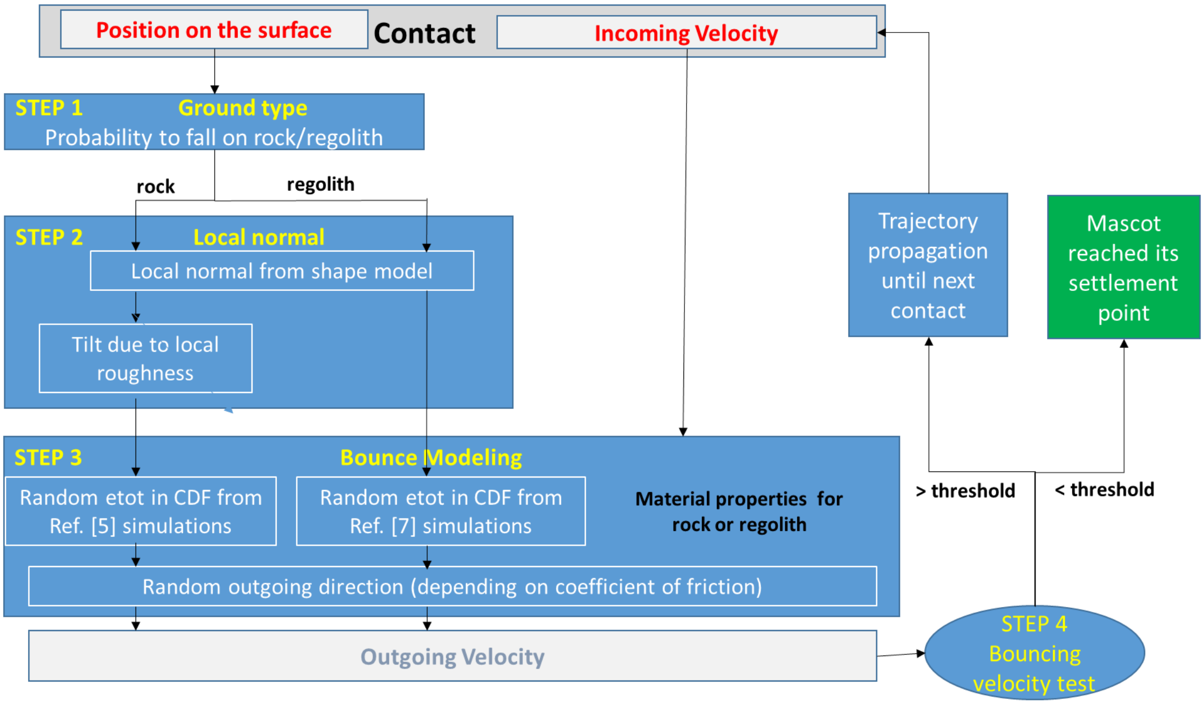


*Fig. 4 Schematic representation of the bouncing model*

**Example of full trajectory predictions**

In order to illustrate the trajectory predictions, a plot showing the results of the Monte-Carlo simulations is shown in Fig. 5. These are the results of a 10 000 draws Monte-Carlo simulation for a given set of separations conditions (epoch, position). The set of cyan points are the points where MASCOT is released, with dispersions due to uncertainty on release conditions. This area represents a Gaussian distribution. The set of green points shows where all the trajectories propagated from the cyan points are hitting the ground for the first contact. This is the image of a propagated Gaussian distribution. The set of dark blue points shows the final points of all the green trajectories propagated taking into account the bounces and its uncertainties as described in the previous section. This set is not Gaussian any longer, since the different dispersion sources introduced by the bouncing model are not Gaussian. The local topography, as depression or hills is also shaping the landing as bouncing trajectories may descend the slopes. One can clearly see that the main source of uncertainty for the final settlement point is the unknown character of the contact with the ground, imposing to take into account a wide range of possible scenarios and thus spreading the trajectories in all directions. This example of simulation was run with the latest data delivered by JAXA and considering that MASCOT has a significant probability to fall on a rock each time it touches the surface. Assumptions considering more regolith would lead to a much smaller final settlement area, very close to the first contact point area in green.

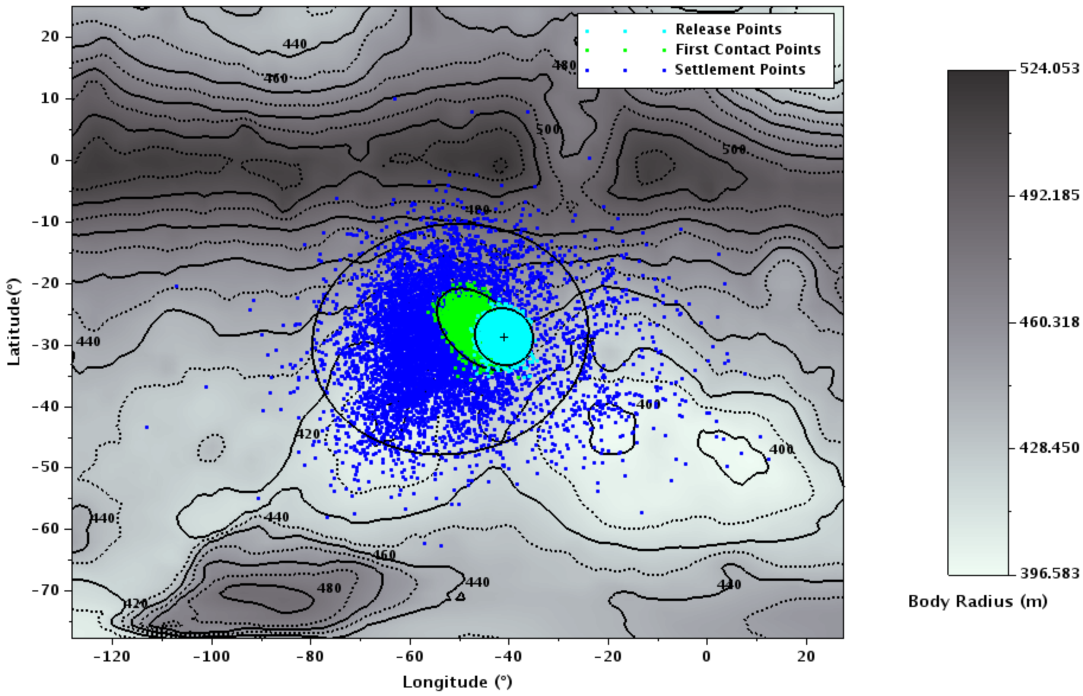


*Fig. 5 Release, first contact point and final settlement points areas for a given set of release conditions. The example was computed for the landing site selected for MASCOT. In cyan: dispersed positions at release projected on the asteroid surface, with corresponding 3-sigma ellipse in black. In green: dispersed positions at first contact with asteroid surface, with corresponding 3-sigma ellipse in black. In dark blue: dispersed final settlement positions, with corresponding 2-sigma ellipse in black*

## Ryugu unveiled

The target body for the Hayabusa2 mission is the near Earth asteroid 162173 called Ryugu. This carbonaceous asteroid is an Apollo type asteroid with a diameter of circa 1 km. Until the arrival of Hayabusa2 in the vicinity of Ryugu, this privileged witness of the birth of Solar System was only known through observation campaigns performed from Earth. The reference model of Ryugu used for the preliminary analyses is described in Ref. 4.
Only one month after Hayabusa2's arrival at its home position near Ryugu, sets of data giving a much more accurate description of Ryugu were delivered by JAXA to MASCOT's team. Before starting to analyse possible landing sites for the lander, the MASCOT FD team studied the actual shape, spin axis and gravity of the asteroid to assess the similarities and differences with the reference model issued from ground observations used so far for the trajectories analysis and their impact on the computations.

### Ryugu's shape

As Hayabusa2 was approaching its target, one discovered a spinning top shaped asteroid, with a relatively prominent protrusion at the equator, dividing the small body into two clear reachable zones. The shape is not very different from a sphere and thus relatively close to the one used in the preliminary computations. Its effective radius, being the radius of a volume equivalent sphere, is about 448 m, very close to the 440 m value considered in the reference model. Nevertheless, it appeared quite quickly that landing in the equatorial zone would be quite problematic, since it is one of the steepest region. Projections of the polyhedron shape model used for Flight Dynamics computations are shown in Fig. 6.

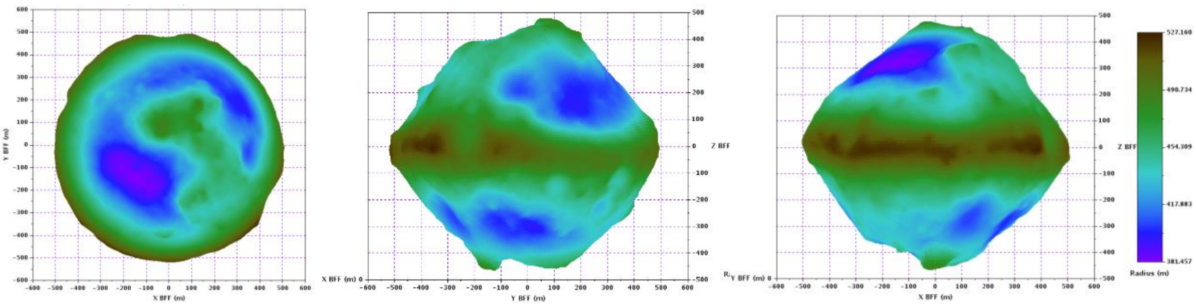

*Fig. 6: Three dimensional visualisation of the polyhedron model used in Flight Dynamics computation (~50 000 faces) – Left: view along Body Fixed Frame (BFF) Z axis, Centre: view along BFF X axis, Right : view along BFF Y axis*

On can note that the polyhedron shape does not show any large concavity. The (latitude, longitude) map of the asteroid's radius is shown in Fig. 7. This representation allows to spot four main blue zones corresponding to large depressions on both sides of the equatorial ridge.

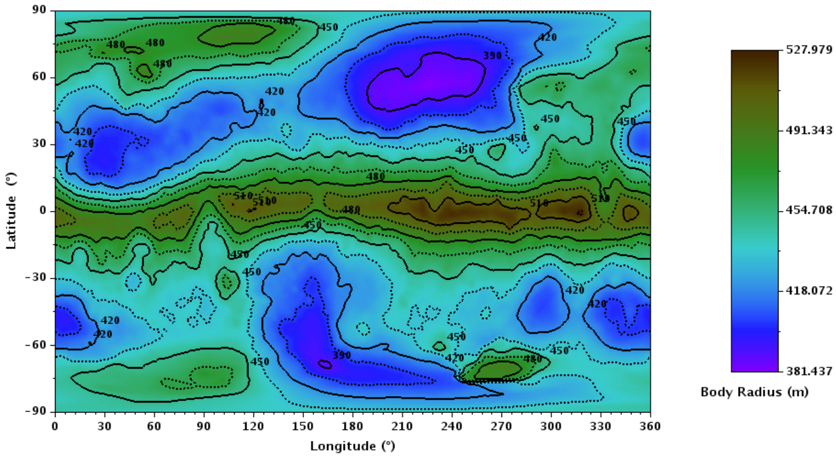


*Fig. 7: Radius of Ryugu as a function of latitude and longitude*

**Ryugu's rotation**

While Ryugu's rotation period was already relatively well known from ground observations, about 7.63 h, its spin axis was very uncertain until Hayabusa2 arrived at the small body. It eventually proved to be nearly perpendicular to the ecliptic plane which allowed to rapidly draw the following conclusions. It has to be noted that the rotation was steady enough to be properly defined with a fixed rotation axis and a constant rotation period.
The first consequence of the quasi-orthogonality between the spin axis and the orbital plane is the fact that Ryugu's shape could be fully observed from Hayabusa2 Home Position very early in the mission, drastically reducing the uncertainty on position of Ryugu's centre of mass and gravity field modelling (cf. next section)
The second consequence concerns the ratio between day duration and night duration. With such an axis, this ratio is very close to 50% over the whole surface as shown on Fig. 8.
The third consequence has to do with Hayabusa2 operations schedule. As noted in the first section of this paper, operational activities of Hayabusa2 includes three different touchdown operations, separated by a few months all along the mission duration. Hayabusa2 always starts its descent for the Home Position located at 20 km above Ryugu's surface along the Earth-Asteroid line. The geometrical configuration between the Earth, Ryugu and the asteroid's spin axis defines a range of altitude reachable for the touchdown. With a spin axis inclined compared to the normal to ecliptic plane, this range of latitude varies with the position of the asteroid on its heliocentric trajectory. Since the spin axis is nearly perpendicular to the ecliptic plane, this seasonal variation is negligible, which means that the same range of latitude should host the

three sampling zones of Hayabusa2 and the area left for MASCOT operations will thus be very limited in this range.

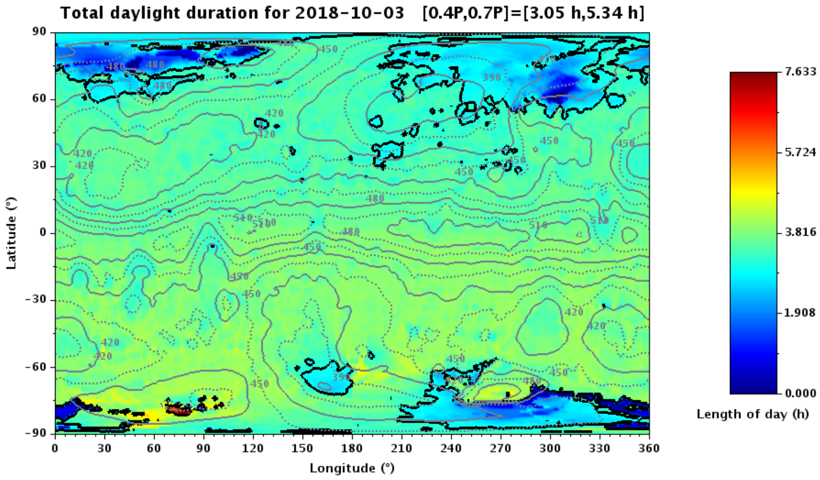


*Fig. 8: Daylight duration in hours as a function of latitude and longitude computed on the 3rd of October 2018 with bold lines identifying the limit at 40%-70% of asteroid period, noted P in the caption above*

### Ryugu's gravity

Before the arrival in the vicinity of Ryugu, a quite large range of possible densities were considered in the assumptions for the preliminary studies. The trajectories computations were performed with a GM (Product between the gravitational constant G and the asteroid's mass M) varying between 11 and 92 $m^3.s^{-2}$, as described in Ref. 4, with a reference value of 32 $m^3.s^{-2}$. The GM measured by JAXA after a few weeks spent by the probe at its Home Position was very close to the reference value, since it was estimated at 30 $m^3.s^{-2}$ with a very low associated uncertainty. There was thus no surprise on that front. Due to the Hayabusa-2 mission profile and asteroid very weak gravity, JAXA was only able to determine the GM of the asteroid. So the MASCOT FD team derived the gravity field from a polyhedron shape model assuming a constant bulk density by using the polyhedron method developed in [9].

## Selection of MASCOT landing site

As a consequence of trajectories characteristics described in the previous section, the selection of MASCOT's landing site cannot be simply achieved by choosing a location at the surface which complies with engineering constraints and scientific objectives and by doing a backward propagation to find the corresponding release conditions to be delivered by JAXA. The stochastic aspect of the bouncing phase in MASCOT's trajectory, as well as the fact that the same location can be reached with two different sets of release conditions forced us to set up a process based on systematic exploration of the possible initial conditions to find out the better initial conditions for a given target on Ryugu's surface.

### Overview of the process

The landing site selection process is an iterative process whose final objective is to deliver to JAXA the time and position at which MASCOT has to be released. These release conditions have to be chosen in such a way that they maximize the chance to have MASCOT resting in a place where it will not disturb Hayabusa2 mission, and where the scientific return can be maximized for its four instruments:

- MicrOmega, a hyperspectral infrared microscope for in situ mineralogical analyses of the ground, developed by IAS (Institut d'Astophysique Spatiale) Orsay (France)
- MASCAM, a multispectral wide field camera to provide geological images of the visited sites, developed by DLR Berlin (Germany)
- MARA, a radiometer to determine the surface temperature and the thermal inertia of the asteroid, developed by DLR Berlin (Germany)
- MasMag, a magnetometer, developed by Braunschweig Technology University (Germany)

Thus, this process involves strong and iterative interactions between the different actors and the CNES Flight Dynamics is only one of them. The scheme in Fig. 9 proposes a summary of different steps and interactions centred on CNES Flight Dynamics Team's role.

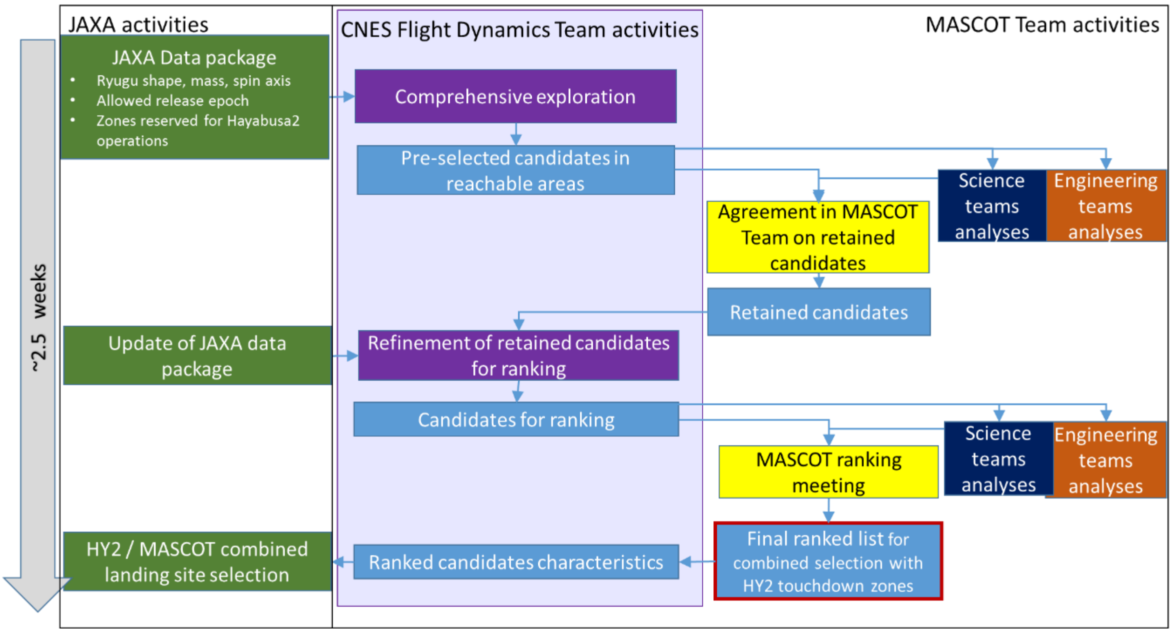


*Fig. 9 Simplified representation of MASCOT landing site selection process, centred on CNES Flight Dynamics Team Contribution*

One should first note that the schedule of the landing site selection process was quite tight, since only two weeks were available between the delivery by JAXA of the first set of data about Ryugu and the date required for the delivery of finalized ranked list of possible candidates to JAXA. In this process, the trajectories predictions and optimization under the responsibility of the CNES Flight Dynamics Team was a pre-requisite to analyses of other teams and of internal meetings and discussions (in yellow boxes). Another tricky aspect was the refinement of data delivered by JAXA during the landing site selection. As Hayabusa2 global observation campaign was going along, the data about Ryugu were thus refined, as well as the JAXA analysis of possible Hayabusa2 touchdown zones. That's why the selection had to be run in several steps, with a necessary adjustment of pre-selected candidates to take into account updated deliveries by JAXA.

During the year before the arrival of Hayabusa2 in the vicinity of Ryugu, the process was exercised 2 times. The first training in August 2017 was a full landing site training driven by JAXA during which a full test model of Ryugu created by the Japanese Team was used. After this first training, an internal repetition based on the same set of data was performed in February 2018 by the MASCOT team, in order to improve the procedures and to take into account the lessons learned from the first exercise.

After a summary of the main mission constraints that had to be considered in the candidates' pre-selection, the following sections describe the main steps of the real landing site selection process, as implemented between July and August 2018.

**The mission constraints**

The constraints to be considered in the pre-selection of the candidates can be divided into two main categories.

*Operational constraints*

The first kind of constraints are imposed by the operational requirements for a correct operation of MASCOT and its instruments. First, it was initially required to have MASCOT resting in a place where the daylight duration is between 50% and 70% of the asteroid rotational period. This constraint aims at guaranteeing a good thermal environment, both for battery behaviour and for scientific interest. After Ryugu revealed its particular spin axis, it became obvious that such a constraint would have made the selection of a candidate impossible. This is illustrated on Fig. 10 where the zones showing a daylight duration higher than 50% of the asteroid period are identified between the bold lines. It can be seen in this figure that the allowed zones are reduced to only fractioned parts of the southern hemisphere.

On a proposal from the MASCOT FD Team, the extension of the range to 40% - 70% of the asteroid rotational period was endorsed by the whole MASCOT Team.

Then, a constraint on minimum guaranteed link between the mother spacecraft and the scout was imposed. Visibility of MASCOT by Hayabusa2 had to be active for at least 40% of one asteroid's period, in order to have enough time to transfer data gathered on the surface.

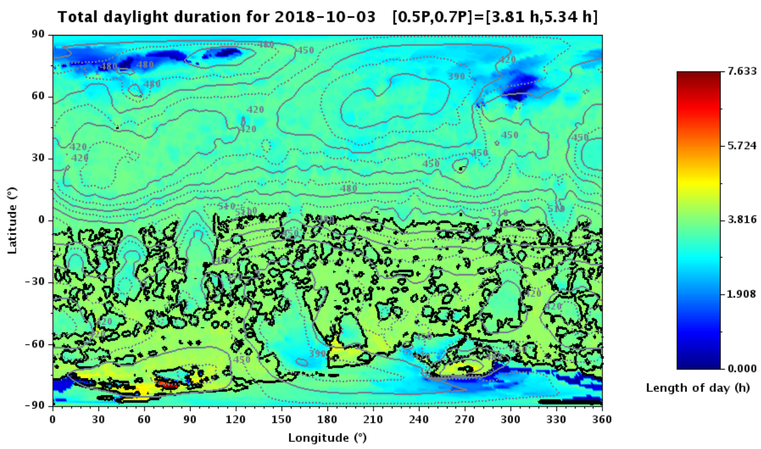


*Fig. 10 Daylight duration in hours as a function of latitude and longitude computed on the 3rd of October 2018, with bold lines identifying the limit at 50%-70% of asteroid period, noted P in the caption above, to be compared to Fig. 8*

*Hayabusa2 constraints*

The second type of constraints is imposed by Hayabusa2 operations design.

The first JAXA's constraint is the Release Epoch Range (RER) giving the slots of time allowed for separation of MASCOT. A time interval of 3 days between 1st and 3rd of October 2018 was reserved by JAXA in Hayabusa2 timeline for MASCOT's release. Within this interval, allowed slots for MASCOT's separation were computed by JAXA according to availability of Earth-Hayabusa2 link. The computation takes into account several parameters like availability of Earth ground stations and time needed for release preparation operations. The result was delivered by JAXA to MASCOT team as ranges of possible release epoch. A representation of the RER is shown in Fig. 11. This representation was used by the MASCOT FD team to quickly identify the range of longitude not accessible due to RER limitations. When several blue lines in several different rotation numbers have an overlap in abscissa, that means that the same longitude can be reached with different separation epochs, due to periodic rotation of the asteroid below the Home Position.

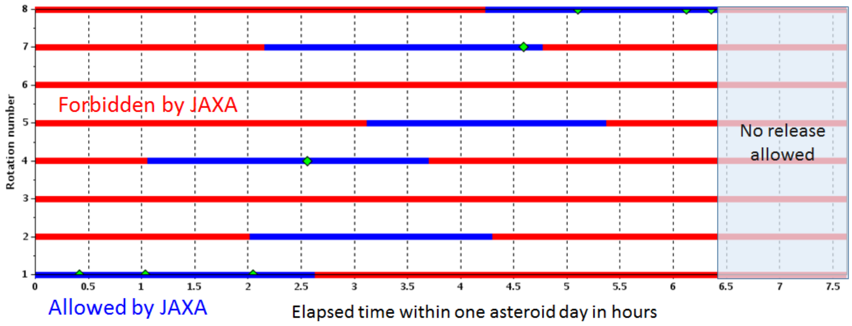


*Fig. 11 Representation of JAXA RER. The RER timespan has been divided into asteroid rotation periods starting with the first date and time of the delivered RER t0. Each line corresponds to 1 asteroid rotation. The rotation number is the number of asteroid rotation since t0. The line with rotation number equal to n is thus the $n^{th}$ rotation in the RER period. The slots when MASCOT separation is possible are in blue, the slots when MASCOT separation is not possible are in red.*

The second constraint imposed by JAXA is called Final settlement point Acceptable Areas (FAA) and defines the zone in the asteroid's surface where MASCOT is authorized to land. Practically, it is rather defined by the "forbidden" zones where it is envisaged to have Hayabusa2 performing its touchdown(s). Since the presence of MASCOT in such zone could disturb the autonomous optical navigation of the probe, and also to a lesser extent contaminate the ground, it is required that MASCOT avoid these zones to preserve them for the sampling operations.

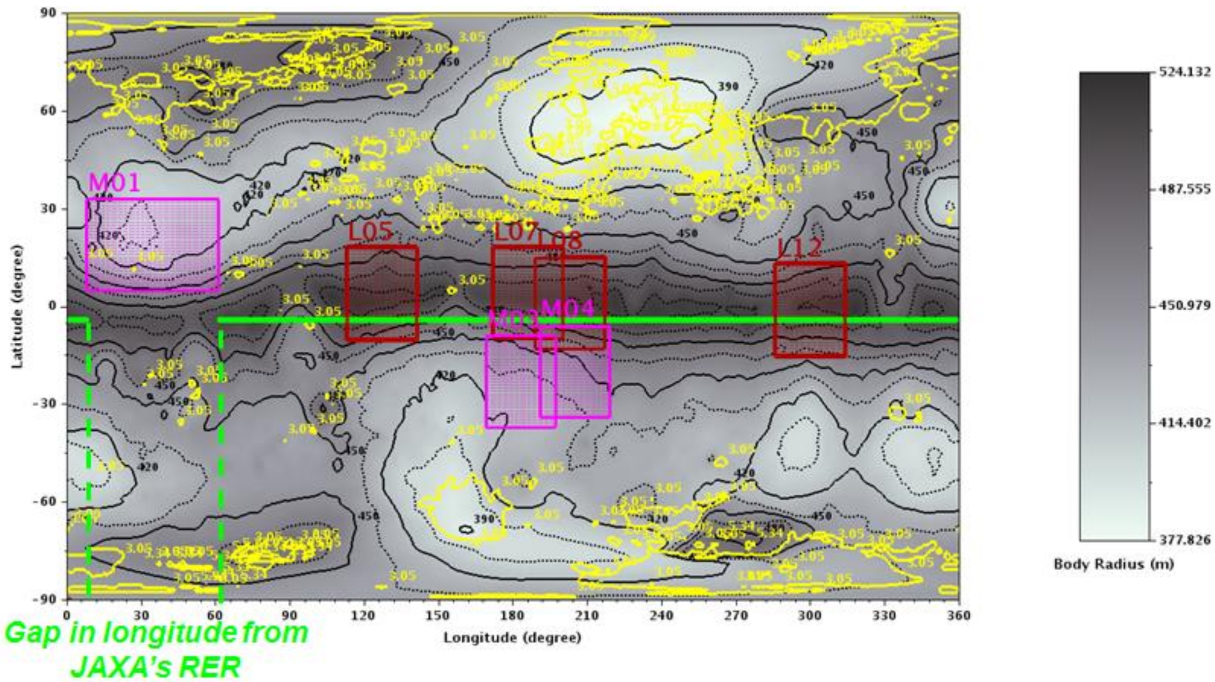


*Fig. 12 Final Settlement Point Acceptable Areas (FAA). The forbidden zones reserved by JAXA for Hayabusa2 touchdown operations are plotted in red for low latitude zones, and in*

*magenta for medium latitude zones, with labels giving a name to the zones. The daylight duration threshold of 40% of the asteroid period are also plotted in yellow, as well as the sub-Earth point in green, for the dates in which separation is possible according to RER allowing to see the gap in longitude already identified in Fig. 11*

In a first delivery, JAXA provided a total of 15 pre-selected zones with which the first step of MASCOT's landing site selection was performed. These zones were covering the equatorial latitudes band for almost all longitudes. That's why a preference was given since the beginning to MASCOT settlement zones exploiting the maximum allowed distance from the Earth to asteroid axis for the release conditions. After analyses refinement, 7 zones were down selected by JAXA. The representation of such zones on a longitude / latitude map is presented in Fig. 12.

The constraint is not to find a landing site avoiding all of these zones, but simply to be able to propose several possible MASCOT landing zones, each of them avoiding at least one of the zone defined above, so that a couple composed of one zone for Hayabusa2 touchdowns and one compatible zone for MASCOT can be found. That's why the MASCOT landing site selection has to be performed at the same time as Hayabusa2 touchdown zone pre-selection.

**The comprehensive exploration**

The principle of the exploration phase is to identify the areas of Ryugu's surface where MASCOT can possibly land. This exploration phase requires to compute possible trajectories with separation conditions varying in their respective allowed ranges.

- The time of separation can be anywhere in the RER defined by JAXA. For the comprehensive exploration, no restriction was considered, since the RER was not yet consolidated at the time it was first run. 14 possible dates have been considered over one asteroid period, the longitude being reached at a fixed date t being roughly the same as the one reached one asteroid period later. Such discretisation results in dates separated by roughly 30 minutes, which allows for a good coverage of the whole reachable longitudes, with enough overlap between the reachable zones at each position and at each date.
- The position of Hayabusa2 at MASCOT's release can be located anywhere in a disk of 200 m around the Earth-Ryugu line. This 2-dimensional range has been discretised into a finite number of possible positions defined by the distance d and the angle a shown in Fig. 2. 19 positions have been analysed for each separation time.

Once these ranges have been defined, a Monte-Carlo simulation taking into account all the known errors and uncertainties is performed for each combination of separation time and position giving 266 candidates for release conditions. In this first phase, only 1000 draws are performed per simulation in order to keep reasonable computing time.

The resulting coverage of the asteroid surface after MASCOT descent and bouncing is shown in Fig. 13. Each group of green points on the upper plot corresponds to CP1 area computed from a given set of separation conditions (Epoch and position), taking into account the known errors thanks to a 1000 draws Monte-Carlo simulation. On the lower plot, the ellipse-shaped groups after bouncing are overlapping and cannot be distinguished from each other, which demonstrates the good coverage of the asteroid's surface.

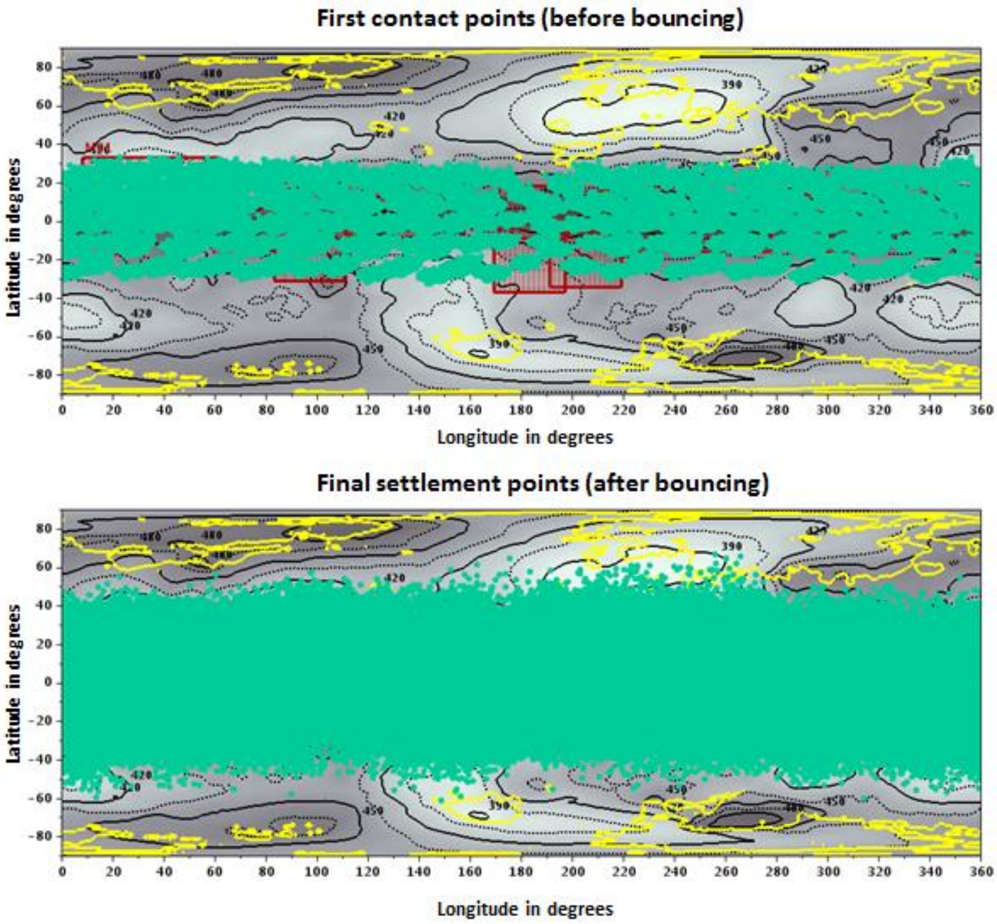


*Fig. 13 Areas reachable by MASCOT obtained with the exploration process. The upper plot shows the first contact points (CP1) in green (for all considered separation dates and positions), the lower plot shows settlement points after bouncing in green ((for all considered separation dates and positions). The zones reserved by JAXA are in red, and the yellow lines are the thresholds for illumination constraints.*

## The pre-selection of candidate's areas

In order to select the most valuables candidates among the ones obtained in this first process, a score is computed by MASCOT FD Team for each set of separation conditions allowing to quickly rank the 266 candidates. In this first step, candidates fulfilling one of the following criteria are directly eliminated:

- The candidates for which there are more than 2% of trajectories (i.e. more than 20 trajectories over 1000 draws) flying for more than 3 hours after separation or during a rebound, without impacting the ground, called "Probability not to land",
- The candidates for which there are more than 5% of trajectories (i.e. more than 50 trajectories over 1000 draws) ending in a zone reserved by JAXA for Hayabusa2 touchdown operations,
- The candidates for which there are more than 15% of trajectories ending in a place where the daylight duration constraint is not fulfilled,
- The candidates for which there are more than 10% of trajectories ending in a place where the radio-frequency link is not sufficient (i.e. possible link lasting for less than 40% of one asteroid's period).

Initially, the elimination of candidates for which more than 5% of trajectories were ending in a place that has never been observed by Hayabusa2 was also implemented, but this criterion was fully inactive, due to the spin axis of Ryugu allowing a good observation of nearly the whole surface.

In addition, the probability to land in each zone reserved by JAXA for Hayabusa2 touchdown operations is computed for each dispersed settlement zone. This probability is computed as the number of trajectories ending up in one of areas pre-identified by JAXA for Hayabusa2 operations. The size of the MASCOT dispersed final settlement areas, as well as the large range of longitudes reserved by JAXA in the equatorial zone for the touchdown operations make it impossible for MASCOT team to find candidate zones that do not overlap any of JAXA's reserved zones. Therefore, the choice of HY2 touchdown areas and MASCOT landing sites will be performed in a combined way, and the settlement areas for MASCOT that only overlap one or two JAXA's reserved zones were retained as possible candidates.

After applying this scoring process, a total of about 60 candidates settlements areas, corresponding to 60 sets of separation conditions (epoch and positions) were found to respect the criteria listed above. A manual selection was then performed to retain a reasonable number of candidates covering all the reachable zones and avoiding redundant computations. The same zone can indeed be reached with 2 different sets of release conditions. After this manual selection, 10 candidates were retained. They are shown in Fig. 14.

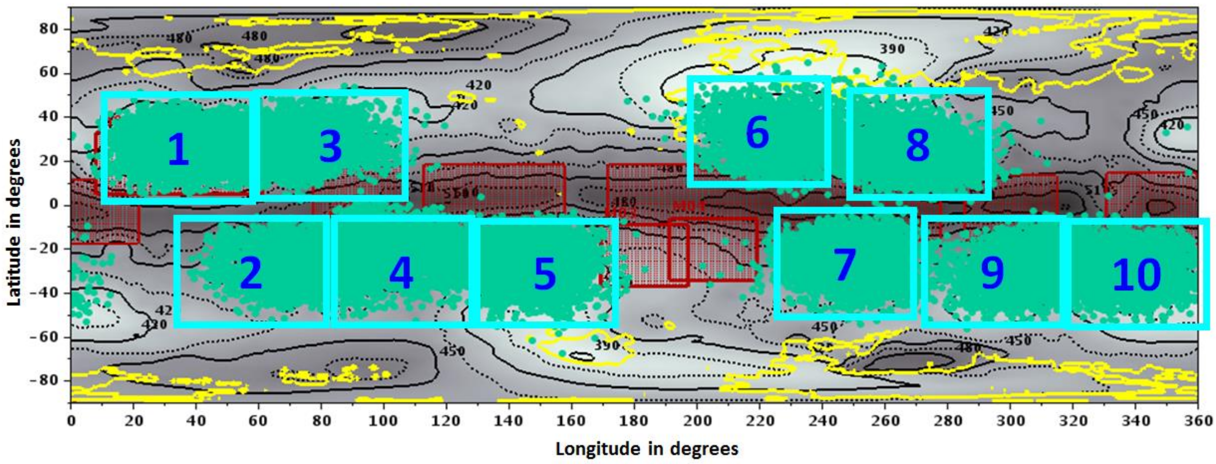


*Fig. 14 10 pre-selected zones after the global exploration.*
*Settlement points after bouncing are in green and the 10 candidates are represented with a turquoise box associated with a blue number (Each box corresponds to one set of separation conditions). The zones reserved by JAXA are in red, and the yellow lines are the thresholds for illumination constraints.*

One can see that the 10 different settlement zones retained cover roughly the latitude band located between -50 degrees and + 50 degrees. However, there are four areas in the aforementioned latitude band on both sides of the equator for which no candidate settlement zone was selected. They are named A to C in Fig. 15.
The reasons for them being discarded can be summarized as follows:

- For the zones A, B and D, the bad score can be explained by the poor fulfilment of the radio-frequency link constraint.
- For the zone C, the bad score can be explained by the significant interference with two JAXA reserved zones simultaneously.

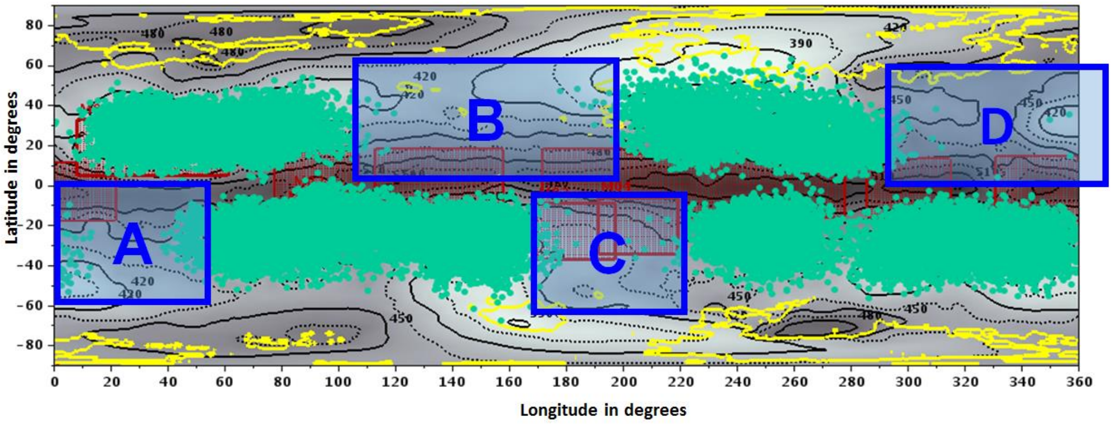


*Fig. 15 Discarded zones after the global exploration.*
*Settlement points after bouncing are in green and the 10 candidates are represented with a turquoise box associated with a blue number (Each box corresponds to one set of separation conditions). The zones reserved by JAXA are in red, and the yellow lines are the thresholds for illumination constraints.*

As explained earlier and shown in Fig. 9, this first list of possible candidates was presented to the whole MASCOT Team and roughly analysed with respect to engineering constraints and scientific objectives. The follow-on of the process with such preliminary candidates was endorsed and none of the pre-identified candidates had to be discarded at this point.

**The refinement of the retained candidates**

The next step was to refine the 10 candidate zones pre-identified during the comprehensive exploration in the light of the updated data delivered by JAXA, in order to propose to the whole MASCOT team a consolidated list so that each team can rank the 10 sites and form an informed opinion about what are the best or worst locations.
Before this proposition, the MASCOT FD team had to refine the first rough pre-selection. The objective of this refinement was first to take into account the latest data delivered by JAXA during the landing site selection computations, in particular the improved shape model, the refined rotational model and the re-worked constraints due to Hayabusa2 operations (i.e. FAA and RER). A special attention had to be paid to the update in rotation data: even a small update in the asteroid's rotation definition would have an impact on the first contact point longitude and thus on the final settlement area. The separation time defined in the comprehensive exploration has thus to be adapted if one wants to target the same location.
Based on the updated computations, an attempt was done for each site to slightly modify the release conditions in order to try to improve its final characteristics. By improvement, one means:

- Increase the probability to land in a place where the RF link and/or illumination constraints are fulfilled.
- Decrease the probability to interfere with zones reserved by JAXA.

This was obtained by trying to explore a very limited range of separation conditions around the ones determined by the comprehensive exploration, both in terms of separation time and separation positions.
At the end of this refinement, Monte-Carlo simulations were run with 10 000 draws rather than only 1000, in order to improve the accuracy of the statistical predictions. Given the large number of pre-selected sites, it would have been difficult to run larger simulations, but a precision of $10^{-4}$ was anyway considered as very acceptable, given the significant uncertainties. The results of such simulations is shown in Fig. 16.

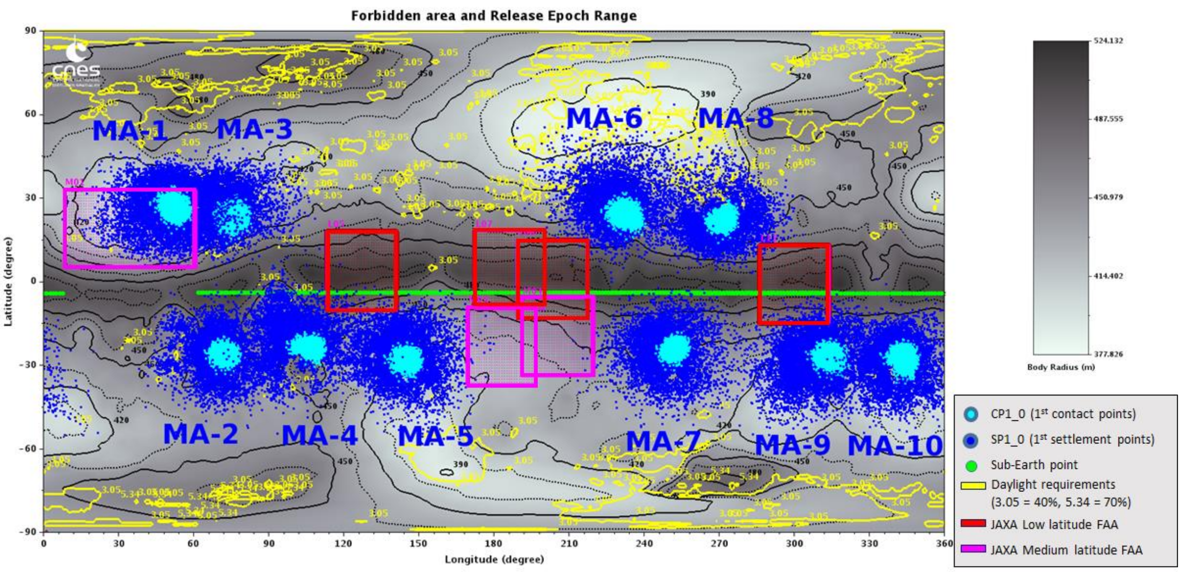


*Fig. 16 10 pre-selected candidates proposed to MASCOT Team, resulting of 10 000 draws Monte-Carlo simulations*

The probabilities to fulfil the constraints are given in
*Table 1* for each pre-selected candidate and each main constraint. These probabilities are obtained after the refinement.

*Table 1 Probabilities to fulfil the main constraints for each pre-selected site, computed over 10 000 draws. The worst value for each column is in bold.*

| *Site ID* | *Probability to land inside a zone with required daylight duration* | *Probability to land inside a zone with required RF link duration* | *Probability to land inside JAXA reserved zones* |
|---|---|---|---|
| MA-1 | 100.0 % | 99.14 % | **78.80 %** |
| MA-2 | 99.84 % | 93.54 % | 0.00 % |
| MA-3 | 99.97 % | 92.16 % | 10.57 % |
| MA-4 | 99.55 % | 93.68 % | 0.77 % |
| MA-5 | 99.94 % | 99.11 % | 0.38 % |
| MA-6 | 98.50 % | **81.77 %** | 0.07 % |
| MA-7 | 99.99 % | 99.65 % | 0.07 % |
| MA-8 | 98.33 % | 86.91 % | 0.21 % |
| MA-9 | 99.75 % | 95.56 % | 2.13 % |
| MA-10 | **97.18 %** | 91.18 % | 0.00 % |

At the end of this step, the consolidated list of possible candidates was finalised and ready for the last stage: the ranking of this list to select the most valuable candidate for MASCOT landing. Each candidate site was named MA-<N> with N varying from 1 to 10, 1 being arbitrarily attributed to the site at the right of the plot in Fig. 16, and then increasing with the longitude.

## The final ranking

The objective of the landing selection process for MASCOT team was to propose to JAXA a ranked list of possible candidates for the landing site of MASCOT, so that Hayabusa2 touchdowns sites and MASCOT sites can be selected in a concerted way. The ranking of the 10 selected sites was a joint effort between all the MASCOT engineering subsystem teams and the scientific teams driven by the final objective to have the best possible scientific outcomes from the mission.

*Full characterization of the candidates*

In order to support this ranking, the CNES Flight Dynamics team has computed a full set of statistical information for each site, aiming at helping the evaluation of each site by each team. It has to be noted that such statistical information is not only used for a qualitative evaluation of each site, but is also used for the tuning of the operational sequence of activities at the surface of Ryugu. For example, a time-out has to be loaded on board, in order to trigger the science sequence even if there is a failure in the automatic detection of the ‘rest’ at the surface.
However, due to the high uncertainty about the conditions that will be found by MASCOT at the surface, some parameters have been dispersed in a quite wide range, in particular the parameters related to the bounces modelling. In such a context, including in the analyses the whole set of trajectories simulated in the Monte-Carlo runs would lead to take into account singular trajectory realizations, and for example, to oversize some parameters like the time-out for the start of the science sequence, simply because simulations resulted in a very long flight duration for only a few bouncing trajectories.
In order to filter the more extreme cases of the Monte-Carlo simulations and to extract what we consider as the most probable final settlement points, at least for the most relevant parameters, the so-called “N-sigma data set” has been defined as follows: using the total number of dispersed trajectories, the ± N-sigma value over the whole set of possible final settlement points are computed for the following quantities:

- Latitude of final stop point: $lat_{-N\sigma}$, $lat_{N\sigma}$
- Longitude of final stop point: $lon_{-N\sigma}$, $lon_{N\sigma}$
- Total flight duration or time of flight, i.e. duration from release to final settlement point: $Tof_{-N\sigma}$,$Tof_{N\sigma}$

Then, a trajectory noted “i” is included in the “N-sigma data set” if and only if it satisfies:

- $lat_{-N\sigma}$ < Latitude of the final settlement point (i) < $lat_{N\sigma}$
- $lon_{-N\sigma}$ < Longitude of the final settlement point (i) < $lon_{N\sigma}$
- $Tof_{-N\sigma}$ < Total flight duration of the trajectory(i) < $Tof_{N\sigma}$

With such a definition, the most interesting quantities could be filtered in a way that favour the spatial proximity and that discard the trajectories that last too long compared to the average of the set.

First an assessment of the size of the final settlement area was given. In order to have a simple way to compare final settlement areas with each other, even if they do not have a comparable shape, a surrounding disk is computed as follows. The centre of the disk is the mean of the distribution considered as Gaussian. The radius of the disk is the distance between the centre and the farthest point (in a straight line) belonging to the 2-sigma Gaussian distribution in latitude/longitude. With such a definition, the surrounding disk contains at least all the points belonging to the 2-sigma Gaussian distribution.
Table 2 gives the evaluation of the radius as defined above, for each of the 10 pre-selected zones.

*Table 2 Radius of the surrounding disk computed at 2-sigma*

| *Site ID* | *MA-1* | *MA-2* | *MA-3* | *MA-4* | *MA-5* | *MA-6* | *MA-7* | *MA-8* | *MA-9* | *MA-10* |
|---|---|---|---|---|---|---|---|---|---|---|
| *Radius (m)* | 160.3 | 155.8 | 170.0 | 195.1 | 154.5 | 179.5 | 168.6 | 155.5 | 196.9 | 148.4 |

One can see that the candidates have a (2-sigma) radius between ~150 and ~200 m.

Then, for each candidate, interesting quantities were computed over the 2-sigma data set as defined above, among which:

- Total flight duration, from release to final settlement point: this value is important for science and operational design because it defines the lifetime of the battery lost for most of the instruments, during which MASCOT is moving and not being able to start a full science sequence. It is also a crucial parameter for the thermal environment of MASCOT.
- Duration from release to start of night: this duration defined the time that MASCOT would spend heated by the Sun and has thus a huge impact on MASCOT thermal behaviour. This value depends on the flight duration, on the flight path and on the location of the final settlement point of MASCOT.
- Length of day and percentage of the asteroid rotation period with visibility of the spacecraft, which are the two main mission constraints as described before.

*Table 3 Comparison of relevant quantities for all the sites used for the ranking process. Median, minimum and maximum are computed over 2-sigma data set*

| *Site ID* | | *MA-1* | *MA-2* | *MA-3* | *MA-4* | *MA-5* | *MA-6* | *MA-7* | *MA-8* | *MA-9* | *MA-10* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Total flight duration (min)* | *Median* | 43.3 | 38.8 | 47.1 | 45.2 | 37.1 | 45.4 | 39.9 | 44.1 | 44.4 | 37.7 |
| | *Minimum* | 19.0 | 7.7 | 22.2 | 7.3 | 6.1 | 21.2 | 7.7 | 10.6 | 6.9 | 7.0 |
| | *Maximum* | 100.4 | 102.2 | 104.6 | 110.9 | 91.1 | 104.3 | 97.4 | 99.1 | 103.3 | 91.5 |
| *Duration from release to start of night (h)* | *Median* | 1.9 | 1.7 | 1.7 | 2.1 | 1.6 | 1.9 | 2.0 | 1.4 | 2.0 | 1.7 |
| | *Minimum* | 1.2 | 0.7 | 0.8 | 0.6 | 0.8 | 0.7 | 1.1 | 0.1 | 0.5 | 0.8 |
| | *Maximum* | 2.4 | 2.4 | 2.3 | 2.7 | 2.1 | 2.4 | 2.8 | 2.0 | 2.3 | 2.2 |
| *Length of day at final settlement point (h)* | *Median* | 3.7 | 3.9 | 3.6 | 3.8 | 3.9 | 3.6 | 3.9 | 3.6 | 3.9 | 3.7 |
| | *Minimum* | 3.3 | 2.9 | 2.9 | 3.0 | 3.1 | 2.8 | 3.2 | 2.6 | 2.6 | 2.6 |
| | *Maximum* | 4.0 | 4.5 | 4.0 | 4.4 | 4.3 | 4.1 | 4.4 | 4.2 | 4.6 | 4.3 |
| *%age of the asteroid period with RF link* | *Median* | 44 | 44 | 43 | 45 | 46 | 42 | 45 | 43 | 45 | 43 |
| | *Minimum* | 38 | 33 | 34 | 35 | 36 | 32 | 36 | 30 | 29 | 29 |
| | *Maximum* | 49 | 53 | 49 | 53 | 51 | 49 | 52 | 51 | 53 | 51 |

Comparison of these data for all the selected zones are shown in Table 3.

*Flight Dynamics Ranking*

Based on this statistical information, the MASCOT FD Team proposed its own ranking, in the same way as all the other teams involved in the process. It was concluded that all pre-selected sites are acceptable and roughly equivalent from a flight dynamics point of view, which is not really a surprise since the MASCOT FD Team at CNES had initiated the list of candidates. The candidates were nevertheless tentatively ranked into 3 groups, according to the criteria studied in the present analysis. The best candidates were MA-1, MA-5 and MA-7, because they obtained the best scores in MA notation based on RF link, illumination and JAXA preservation criteria. MA-2, MA-3 and MA-4 were considered as fairly good candidates. The worst candidates were MA-6 MA-8 and MA-10 because of the less favourable RF link conditions. At this stage, MA-9 was also considered as a worst candidate because it was the site presenting the largest overlap with a JAXA low latitude zone.

*Final decision*

The final MASCOT ranking meeting was held on the 14th of August 2018 in the facilities of CNES in Toulouse (France). All the contributors were assembled under the lead of the MASCOT project team to discuss the results of their respective analyses of the different candidates and to rank together the 10 preselected candidates based on the data provided by the MASCOT FD Team. As far as the engineering criteria are concerned, the following results were considered:

- the analysis of the key parameters for the good progress of operational sequence by the operations team, mainly the durations characterizing the trajectories,
- the results of thermal simulations by thermal team to verify that the thermal conditions are favourable to MASCOT operations [10],
- the results of the mobility team analysis, in charge of the hopping mechanism on board MASCOT, to take into account the influence of gravitational acceleration.

Once the engineering criteria had been evaluated, the largest place was given to the evaluation by scientific teams of the interest presented by each candidate, as well as their compliance to the constraints required for the instruments measurements.
The finalized ranked list was established at the end of this meeting, after a fruitful and constructive discussion. MA-9 was finally considered to be the best candidate, the main reason being its attractiveness in terms of scientific interest associated with an acceptable fulfilment of all engineering criteria.

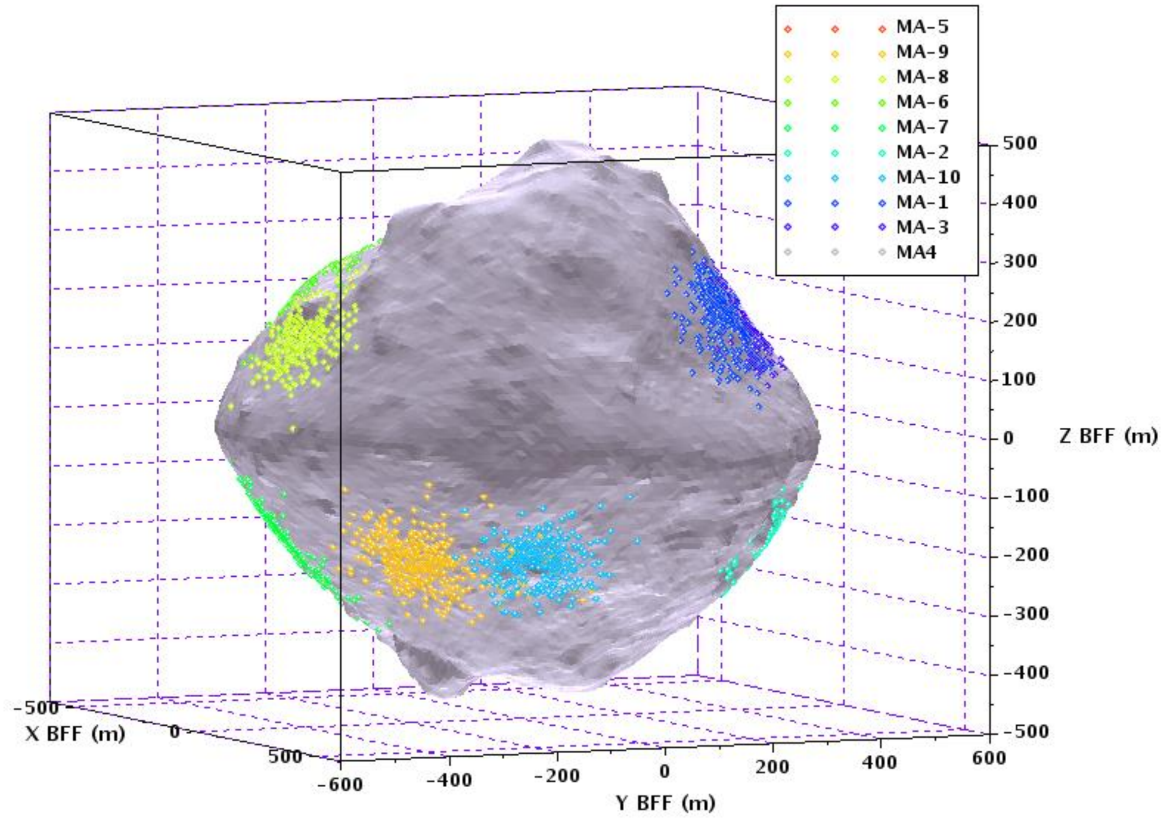


*Fig. 17 Candidates final settlement areas projected on a 3D representation of Ryugu in the body fixed frame (BFF). The image shows MA-9 in orange in the centre of the plot.*

MA-9 was formally presented to JAXA as the best candidate for MASCOT landing and was retained by JAXA in the combined selection with Hayabusa2 touchdown areas. The final approval was given by JAXA and the Hayabusa2 Joint Science Team (HJST) on Aug 17 and 18 in Japan. It has to be noted that the sampling site for Hayabusa2 first touchdown operations and the Mascot landing site were sought to be in the same geological area, or at least in areas which appear similar composition-wise, to maximize the use of MASCOT data for later sample analysis. Since the surface of Ryugu, according to the remote sensing instruments, appeared rather uniform, this was not really a hard constraint. As there was no interference with any of the zones identified for Hayabusa2 operations, the designation of a back-up MASCOT landing site was not necessary. On the 3rd of October 2018, Hayabusa2 successfully reached the position computed by the MASCOT FD Team at the expected separation time and MASCOT was nominally released to MA-9.

## Conclusion

With only a few weeks of hindsight after the execution of MASCOT's operations, it is already possible to tell that the process set up for the selection of MASCOT's landing site was a real success which has contributed to the MASCOT full mission's achievements. Despite the very tight schedule, the knowledge gathered by Hayabusa2 about Ryugu during the first weeks of remote sensing was fully exploited at each step of the selection. The MASCOT FD Team computations were an essential input data at each stage of the selection, facilitating the analyses of all the involved actors and creating the conditions for a smooth and informed decision. The best evidence demonstrating the efficiency of the process is probably the fluency of the MASCOT final ranking meeting. The selected site MA-9 was endorsed by JAXA without any hesitation, showing that the Hayabusa2 operational constraints were perfectly taken into consideration. The extraordinary success of MASCOT operations proves that MA-9 site was indeed fulfilling all the major constraints required so that MASCOT completed its mission. Last but not least, the MASCOT landing site selection process can be seen as a perfect example of close international cooperation involving space agencies as well as scientific laboratories, and serving the international scientific community.

## Acknowledgements

The authors would like to thank the Hayabusa2 team at JAXA/ISAS for the unique opportunity to work on such an exciting mission. We also warmly acknowledge the experts who helped us to better understand and simulate the bounces of MASCOT on this pristine surface: Stefaan Van Wal (JAXA/ISAS), Simon Tardivel (CNES), Patrick Michel and Florian Thuillet (Observatoire de la Côte d'Azur, Nice, France).

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