

MASCOT ON BOARD OF HAYABUSA-2: THE QUEST FOR THE ORIGINS OF THE SOLAR SYSTEM

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Abstract:

MASCOT is a German-French lander to be placed on board of the Japanese mission Hayabusa-2. This JAXA space probe is an asteroid sample-return mission, whose target is the near Earth asteroid 1999JU3. Hayabusa-2 will be launched in December 2014 and its arrival at the vicinity of the asteroid is foreseen for summer 2018. Mission analysis studies for MASCOT descent trajectories to 1999JU3 are performed at CNES, in the frame of the collaboration between JAXA, DLR and the French agency. There are two main objectives related to these studies. Firstly, to prove the feasibility of MASCOT's mission under given hypothesis and determine the validity of such feasibility when the environment and the constraints change. Secondly, to develop the tools and the engineering confidence which will allow us to be operationally prepared for what will happen around the asteroid. This international collaboration is expected to enlighten the scientific community on topics such as the characteristics of small primitive bodies and the origin of the Solar system, in addition to continue preparing the way for future missions to asteroids.

Keywords: *lander delivery, optimization, separation conditions, mission design*

Glossary

ESA	European Space Agency
JAXA	Japanese Space Agency
MASCOT	Mobile Asteroid Surface Scout
NEA	Near Earth Asteroid
RF	Radio Frequency
TBC	To be confirmed
TMTC	Telemetry and Telecommand

1. Introduction

As thrilling as the exploration of small bodies of the Solar System is, MASCOT mission offers additional challenges. On the one hand, the current knowledge about the characteristics of asteroids is still very limited. So, placing a lander on their surface is not an easy task. Essential information such as the precise shape and density of the target body, or the regolith size and distribution on the surface, are barely known and difficult to predict within a reasonable level of confidence due to the small number of previous missions dedicated to asteroids and the limitations in ground-based observations. On the other hand, MASCOT is a small lander (approximately 10 kg) with no

propulsive system, so its descent to the surface of 1999JU3 will be passive. Therefore, the delivery strategy does not focus on the descent trajectory itself, but on aspects such as the mother-ship altitude over the surface, the release attitude, as well as the separation time and delta-v provided by the separation mechanism. Furthermore, it is not foreseen to anchor MASCOT on the surface after touchdown. This will result in a bouncing trajectory that has to be simulated as a part of the descent trajectory analysis.

Mission analysis studies regarding MASCOT descent trajectories to 1999JU3 are performed at CNES, in the frame of the collaboration between DLR and the French agency. Scientific models for the shape and estimated density of the asteroid are used, in addition to assumptions for the unknown quantities such as the bouncing coefficients. Then the constraints coming both from the lander and from Hayabusa-2 are taken into account in the computations. Dispersion analysis is applied only to the trajectories satisfying the constraints. As a result of these studies, quantities such as the size of the dispersion ellipses or the expected bouncing duration can be predicted and used for the landing site selection.

For given asteroid models and fixed Hayabusa-2 approach and delivery strategy, the only parameter that allows some flexibility on descent trajectory analysis is the separation time. In other words, once the current unknowns start becoming precisely defined and JAXA freezes the operational separation scenario, each separation time will lead to a nominal landing trajectory and a nominal touchdown point. The bouncing and the dispersion analysis will convert this touchdown point into a predicted $3\text{-}\sigma$ landing ellipse. The global constraint satisfaction level over the points of the ellipse, together with the suitability of the area for the desired scientific experiments will provide the key elements for the choice.

Some additional information on the general background and objectives of MASCOT mission is given in section 2. Then, section 3. describes the way in which nominal descent trajectories are computed. Moreover, the dispersion ellipses computation is explained in section 4. Finally, some conclusions of the MASCOT mission analysis studies are listed in section 5.

2. MASCOT as a part of Hayabusa-2 mission

The Lander MASCOT was proposed as a DLR/CNES contribution to the Japanese asteroid sample-return mission Hayabusa-2. MASCOT will be carried as an additional scientific package in this mission. Therefore, the target body, the overall mission timeline and other boundary conditions such as available mass and volume budgets and separation conditions are given by JAXA. Some relevant events in the Hayabusa 2 timeline are:

1. Hayabusa-2 is launched by a H-IIA from Tanegashima Space Center, Japan (end 2014).
2. Insertion of Hayabusa-2 into a transfer orbit to asteroid 1999JU3.
3. Hayabusa-2 arrives at 1999JU3 in July 2018.
4. Hayabusa-2 performs asteroid characterization activities, and performs sampling dress rehearsals.
5. MASCOT is deployed from Hayabusa-2 and descends to the asteroid surface.
6. MASCOT lands on the asteroid and performs surface operations (science activities and hopping maneuvers). Telemetry is relayed via Hayabusa-2.

7. In August 2019, impact experiment and sample collection will be performed by Hayabusa-2.
8. Return to Earth.

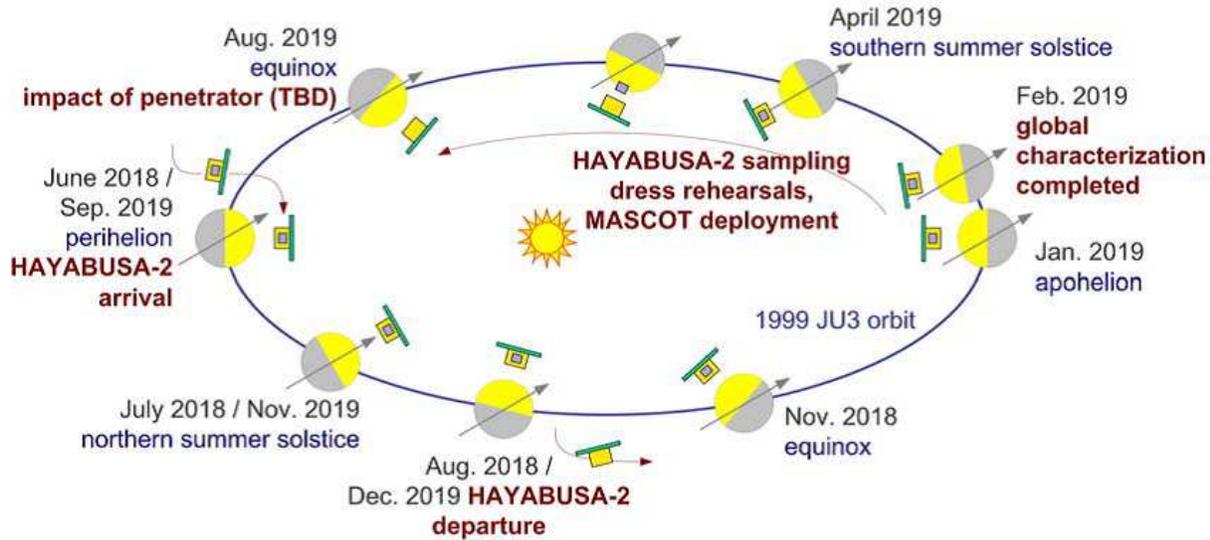


Figure 1. Hayabusa-2 approximate timeline during the asteroid phase.

For MASCOT delivery, the main-S/C will stepwise descend from its Home Position at 20 km distance from the asteroid to an altitude above the surface of 100 m. When reaching this altitude the Lander is deployed by initializing a ΔV through the separation mechanism, while Hayabusa-2 maintains a stationary position (hovering). The Lander falls ballistically to the surface while the main-S/C will ascend back to its Home Position. Permanent communication between MASCOT and Hayabusa-2 is foreseen during the 20 to 30 min of descent.

After separation, the Lander will first drift unguided towards the Lander surface, with minimal units operational. After final stop has been detected by the onboard systems, the Lander will first determine if it needs to re-orientate itself towards the ground. If this is the case, a reorientation manoeuvre will take place via a short hop on the asteroid surface; otherwise, science operations begin. All payloads and communication activities are managed by an onboard autonomy system, designed to account for uncertainties in the operations and failure scenarios. After a full science programme has been performed at that location, the Lander will then jump to a second site, and repeat the science operations. This cycle continues until the power is depleted, allowing for approximately from 12h to 15h of science activities (see [1]).

The arrival of Hayabusa-2 to the vicinity of 1999JU3 is foreseen for the beginning of July 2018. Delivery of MASCOT could theoretically take place from October 2018 (first touchdown rehearsal) until end of August 2019, when JAXA's impactor experiment will be triggered. Separation is not possible during the conjunction period, when the angle 1999JU3-Sun-Earth is larger than 170 degrees, a condition that is fulfilled from 18/11/2018 to 1/1/2019.

3. Descent trajectories computation

3.1. Modelisation of asteroid 1999JU3

The target body for the Hayabusa-2 mission is asteroid 1999JU3, a near earth Apollo type asteroid with a diameter of less than 900m.

As a result of an observation campaign in 2007/2008, the shape of asteroid 1999JU3 could be estimated. A shape model was created by Dr. Masanao Abe of ISAS and JSPEC in JAXA and his student Ms. Kyoko Kawakami using photometric observations from Earth-based telescopes and Earth-orbiting observatory by many world-wide researchers, and it is based on the computer program developed by Finish astronomer Dr. M. Kaasalainen. In 2011, a model by T. Müller and the same group from JAXA replaced the 2008 model.

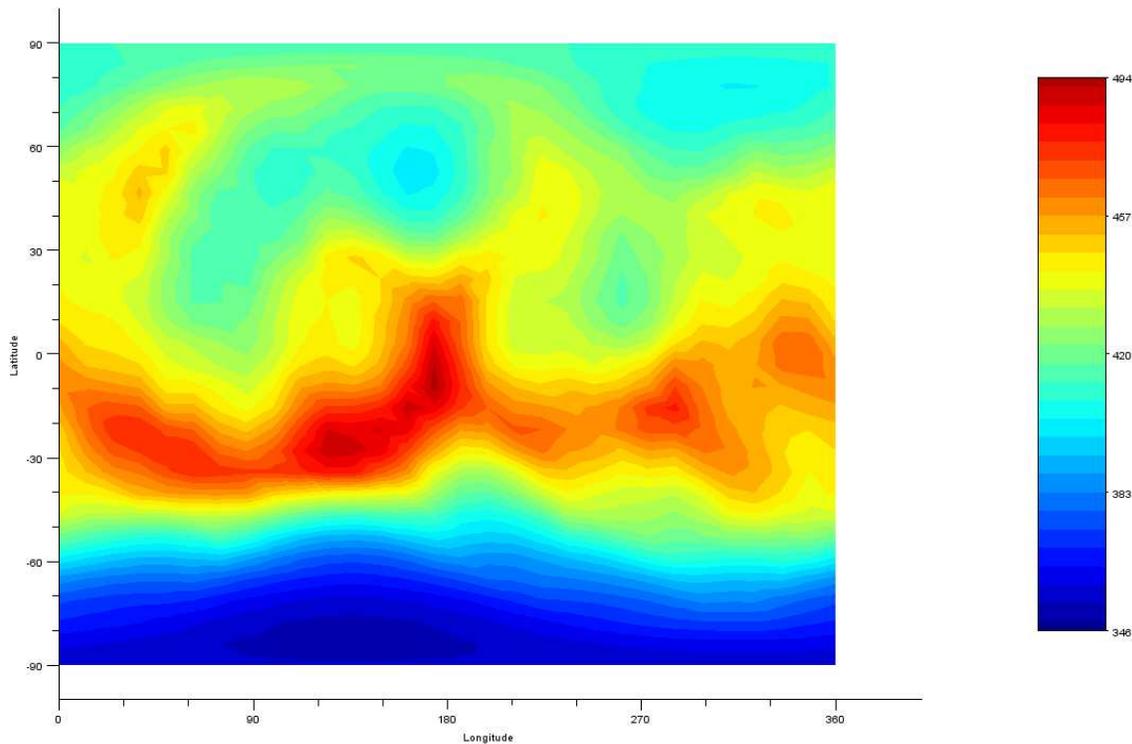


Figure 2. 2D representation of the relief on the surface of 1999JU3 according to Müller model.

Equivalent radius	435 m	Density	1300 kg/m ³ ($\pm 30\%$)
Minimum radius	374 m	Spin axis	$\lambda_{ecl}, \beta_{ecl} = (73.1, -62.3)$ deg
Maximum radius	495 m	Rotation period	7.63 h

Table 1. Main characteristics of 1999JU3 Müller model.

The shape model file used for CNES mission analysis studies is based on the Müller 2011 shape model (see figure 2 and [2]). The main characteristics of the model are summarized in table 1. It is important to bear in mind that there is a big uncertainty concerning the spin axis orientation. For the sake of simplicity, the present work presents only results based on Müller shape model and

axis. However, eight different spin axis orientations ([3]) have been used for the complete mission analysis document.

By assuming a constant density of the bulk material and using the shape model for the computation of the direction of the gravitational forces at each point in the vicinity of the asteroid, a file containing the gravity attraction inside a cube of 3km edge centered in the asteroid centre of mass is generated (see figure 3). Outside this cube, the gravitational attraction is considered to follow a central body gravity field, with μ derived from the corresponding density.

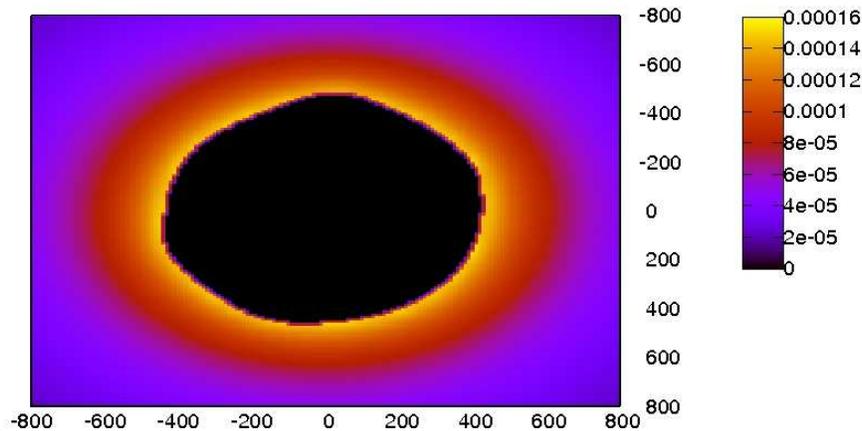


Figure 3. Acceleration caused by the asteroid gravitational attraction (in m/s^2) around the equator.

Finally, the Z-axis of the asteroid shape model is considered to be aligned with the spin axis (i.e. the axis passes through the centre of gravity for the fixed density model). At the same time, we consider this rotation axis to be fixed in inertial space. The rotation period has been estimated to 7.63 hours. In this way, if the ecliptic latitude and longitude of the axis are known, and the attitude of 1999JU3 in inertial space is specified at a given date, rotations with constant angular velocity allow us to compute the orientation of the X-Y-Z axis of the asteroid frame with respect to inertial space at any epoch. The date 7/07/2007 at 12h UTC is set as the origin of the rotational phases for the Müller model (see [3]).

3.2. Separation conditions

During the asteroid phase, instead of orbiting 1999JU3, the S/C will hover close to the line going from the center of the asteroid to the Earth, at a distance of 20 km from the small body in the so-called *Home Position* and descending to closer distances for observation, lander delivery and touchdown.

The nominal position of Hayabusa-2 at the moment of MASCOT's separation is (see figure 4):

- At an altitude of 100 m from the asteroid's surface
- In the Earth to asteroid line, or in the plane perpendicular to this axis at a distance ≤ 200 m.

Likewise, the attitude of Hayabusa-2 can be computed at any given date, provided that the ephemeris of the Sun and the Earth as seen from the S/C are known. Hayabusa-2 *Home Position frame* is oriented such that the $+Z_{HP}$ axis is aligned with the asteroid to Earth axis and the $+X_{HP}$ axis of Hayabusa-2 is perpendicular to $+Z_{HP}$ and in the plane generated by the Earth and the Sun directions, facing the Sun. The $+Y_{HP}$ axis completes a positively oriented system (as shown in figure 4).

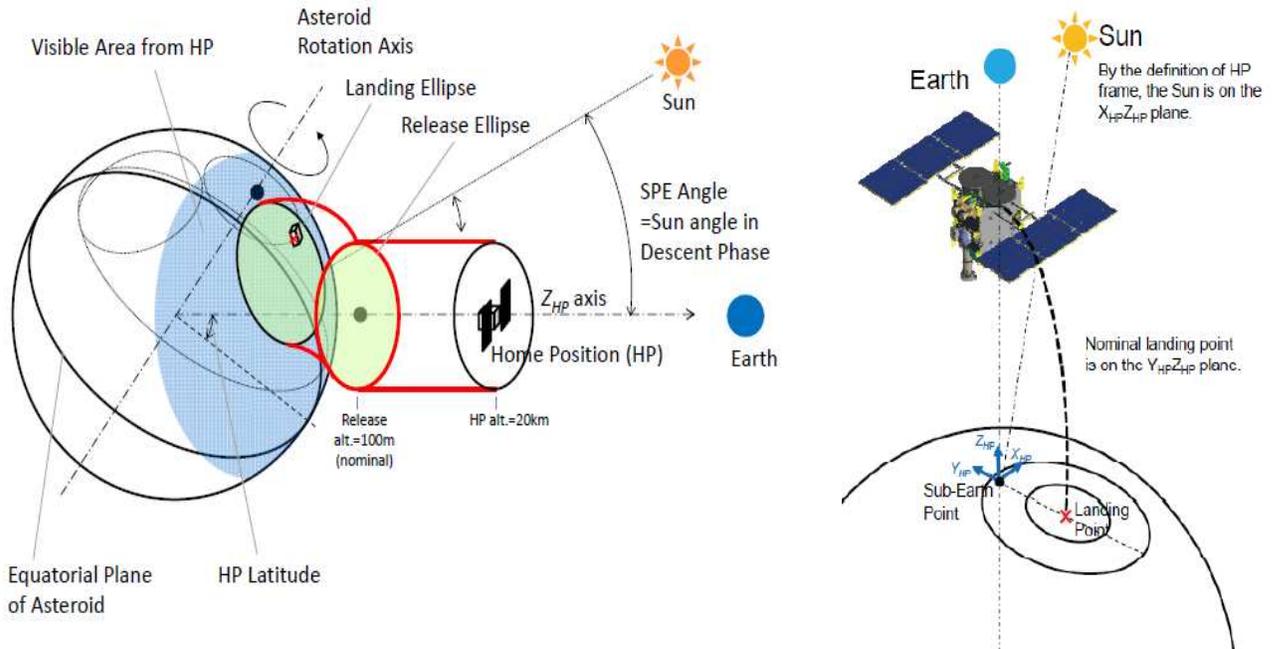


Figure 4. Hayabusa-2 nominal position and attitude at MASCOT's separation (from [4]).

From a position and attitude of Hayabusa-2 like the ones we just described, the nominal separation direction for MASCOT is under the $-Y_{HP}$ axis, forming an angle of 15 degrees with the $-Y$ solar panel.

It is important to note that under these assumptions, there are no optimisation parameters except for MASCOT's separation time. The computation of the descent trajectories is then just an extrapolation under the forces due to the asteroid's gravitational pull, the third body effect of the Sun and the solar radiation pressure. In other words, apart from the dispersion analysis related to S/C position errors and separation velocity and angle inaccuracies, the touchdown conditions are exclusively determined by the delivery time and the forces acting on MASCOT during its free fall arc to the surface of 1999JU3.

3.3. Constraints

Some of the conditions that have to be satisfied by the descent trajectory and the landing site for a given solution to be considered as acceptable for MASCOT mission are:

1. The nominal landing site on 1999JU3 should have a daylight duration between 50% and 70% of the asteroid's rotation period (limited due to thermal and scientific reasons).
2. The duration per asteroid rotation period of visibility of the landing site from Home Position

- must be over 40% (TM/TC link constraint).
3. The velocity at touchdown should be smaller than half the escape velocity.
 4. All the locations with a daily average surface temperature between -50C and +25C should grant acceptable landing conditions (TBC).
 5. The landing site is chosen from the area which has been observed for 30 days or longer (TBC).

The first two constraints are exclusively dependent on the separation date and the asteroid model that is used. Therefore, the zones on the surface of 1999JU3 in which landing is permitted can be obtained before the descent trajectories computation is started.

Moreover, the constraint on the impact velocity is to guarantee that in case of a perfectly elastic impact, MASCOT would not have enough velocity to escape or get in orbit around the small body.

As for the thermal constraint, a non adequate temperature could put MASCOT science at stake, especially for specific separation windows in which the asteroid orbit is not far from its perihelion (1999JU3 distance to the Sun is at its minimum in the beginning of June 2018 and mid-September 2019). The range of survivable temperatures for MASCOT, as well as the estimations of the temperature at the asteroid's surface, are currently under study.

Finally, the aim of the constraint stating that the landing site should be observable at least during 30 days previous to separation, is to be able to assess the risk at landing, by performing detailed surface maps of the landing zone.

3.4. Bouncing after impact

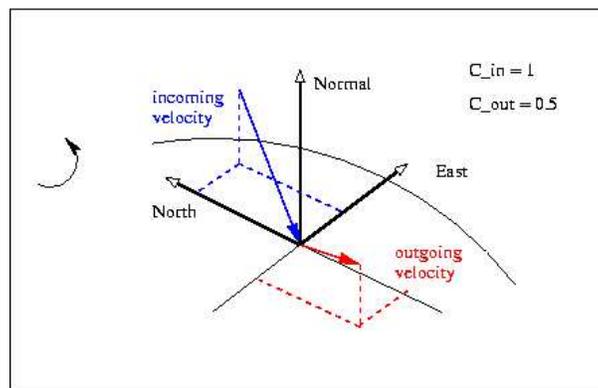


Figure 5. Schematic representation of the incoming and outgoing velocity vectors at the moment of bouncing on 1999JU3 surface (as an example, in-plane coefficient fixed to 1 and out-of-plane to 0.5).

The bouncing of MASCOT after touchdown may significantly affect the actual landing position. This should be taken into account when predicting the landing zone of MASCOT for a given separation time. The lack of empiric data describing the composition, size and distribution of the regolith, forced us to make some assumptions in order to be able to proceed with the mission analysis and start making reasonable predictions of the effects of bouncing. A very simple bounc-

ing modelisation has been used (see figure 5), considering two coefficients: the in-plane and the out-of-plane coefficients. In our model, the outgoing velocity vector is forced to be coplanar with the incoming velocity and the surface local normal vector. Note that the hypotheses used in this section may be far from the reality encountered on the body in 2019. Consequently, in order to palliate the uncertainties on the bouncing coefficients, a parametric study has been performed, for values between 0 and 1 of both coefficients (from all energy absorbed by the impact to perfectly elastic collision).

3.5. Thermal considerations

For an object landing on an airless body, the surface temperature is one of the most important boundary conditions. Thermal modelling of the surface of asteroid 1999JU3 has been performed by Active Space Technologies GmbH ([5]), based on the Müller 2011 asteroid model and the predicted asteroid ephemeris. Two values of the thermal inertia have been studied, as identified in [3]: a nominal value of $300 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ and a minimum value of $67 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$. As an output of this study, the predicted temperatures depending on the latitude and the date for these two thermal inertia values are shown in figure 6.

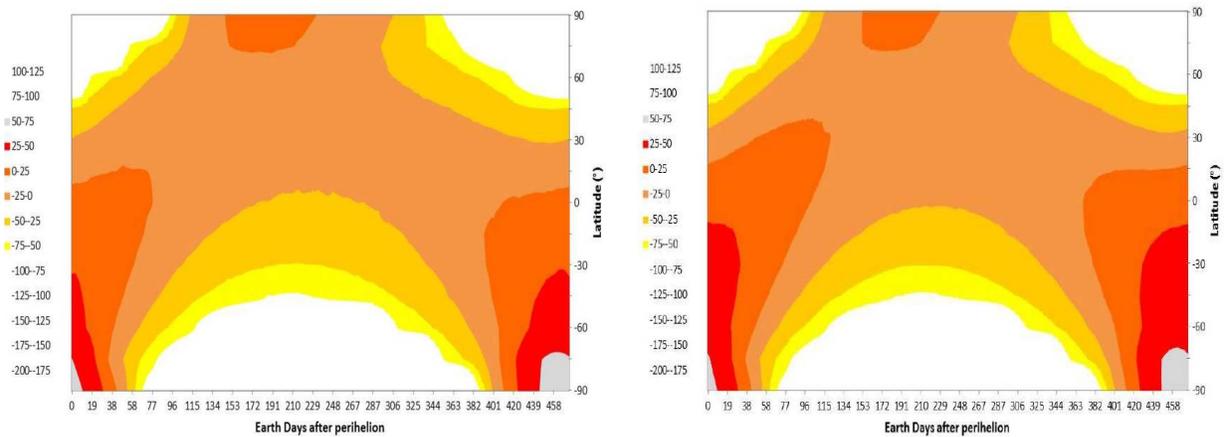


Figure 6. Predicted average daily temperature on the surface in C depending on the date for two values of the thermal inertia ($67 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ and right $300 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$). The origin of dates corresponds to 02/06/2018 in both figures.

As a preliminary approximation, the average daily temperature is considered to be constant for a given latitude. When studying a particular separation date, one can draw vertical lines on the figures and obtain in this way latitude bands on the surface of the asteroid for each of the indicated temperature ranges. For instance, this has been done for the 20/06/2019 in figure 7 (for the nominal value of thermal inertia).

More detailed studies of maximum and minimum temperatures on the predicted landing zone (including bouncing) will have to be performed in a further stage of the mission, because not only the average daily temperature is interesting for the survivability of MASCOT. In general, from a thermal point of view, separations in January-February 2019 are recommended because this is the

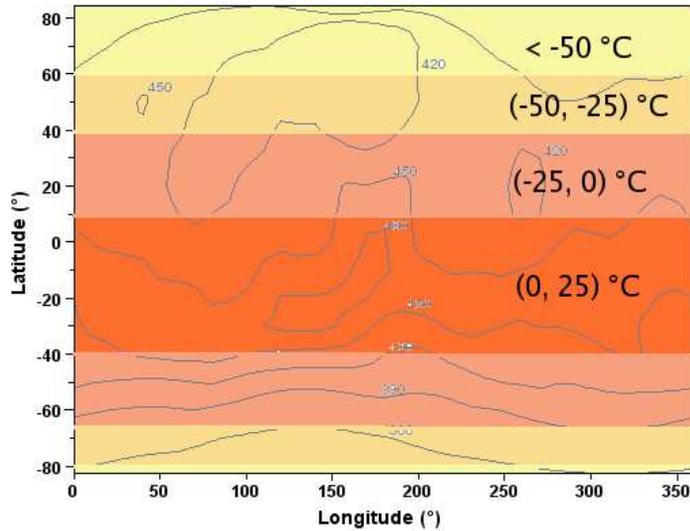


Figure 7. Average daily temperature depending on the latitude on the asteroid surface for the 20/06/2019.

moment in which the overall temperature is low, since 1999JU3 is not far from the apohelion of its orbit. However, more refined studies combining the predicted surface temperature with the expected latitude band at touchdown will be necessary, especially if the separation takes place close to perihelion.

3.6. Results

Descent trajectories have been computed for all dates in the possible separation period (September 2018 to August 2019). Moreover, computations have been done for several values of the separation velocity (in the range 2 cm/s to 9 cm/s) and also several asteroid density values (nominal value of approximately 1300 kg/m^3 , a lighter asteroid with $\rho=450 \text{ kg/m}^3$ and the "heavy" case with $\rho=4000 \text{ kg/m}^3$).

The impact velocity constraint is checked after the first bounce. Firstly, the impact velocity is computed in asteroid rotation frame. The bouncing coefficients are then applied to the velocity vector, and the outgoing vector in asteroid rotation frame is obtained. Next, this vector is transformed back to inertial reference frame and its norm is compared to half the escape velocity at the corresponding distance from the asteroid centre. In this way, the rotation of the surface is taken into account, because the bouncing coefficients are applied in asteroid rotation frame, but the comparison is done in inertial frame, since the constraint formulation comes from the central mass force approximation of the dynamics.

3.6.1. Preliminary results for the first touchdown of MASCOT

Some preliminary conclusions can be drawn from the analysis, concerning the touchdown conditions on the asteroid surface:

- The impact velocity constraint is one of the most difficult to satisfy.
- In particular, separation velocities of 7cm/s or larger lead to systematic violations of the impact velocity constraint for most of the separation dates. At the moment of writing this paper, the nominal separation Δv value is in the range from 3 cm/s to 5 cm/s.
- For a given separation date and fixed Hayabusa position, the touchdown points will have an almost fixed latitude and variable longitude due to the rotation, no matter at what precise time the separation takes place. Then, different positions of Hayabusa-2 in the 200 m circle account for a latitude band of possible first touchdown sites of ± 20 deg centred at the touchdown latitude value corresponding to Hayabusa-2 being exactly in the Earth to asteroid line at the moment of separation.
- Over the whole period of possible separation dates (11 months), for the current asteroid model and nominal values of the density (1300 kg/m^3) and the separation altitude (100 m), the area in which MASCOT would perform the first touchdown on the surface of 1999JU3 is contained in a latitude band of ± 45 degrees around the equator. More precisely, that is ± 25 degrees latitude band around the equator if Hayabusa-2 was exactly on the asteroid to Earth line and the separation velocity was 5 cm/s, plus 20 deg added to the boundary of this region, resulting from the distance between Hayabusa-2 and the aforementioned line (see above).
- Descent times for the baseline asteroid density are around 20 to 30 minutes. A lighter asteroid makes descent times become longer, thus giving more time for the gravity to increase the lander velocity. This fact results in a higher ratio between impact velocity and maximum allowed impact velocity, leading to more difficulties to satisfy the impact velocity constraint. On the contrary, for the case of an asteroid with a higher density value, descent times are shorter and impact velocities are smaller with respect to the maximum impact magnitude, generally well within the allowed boundaries.

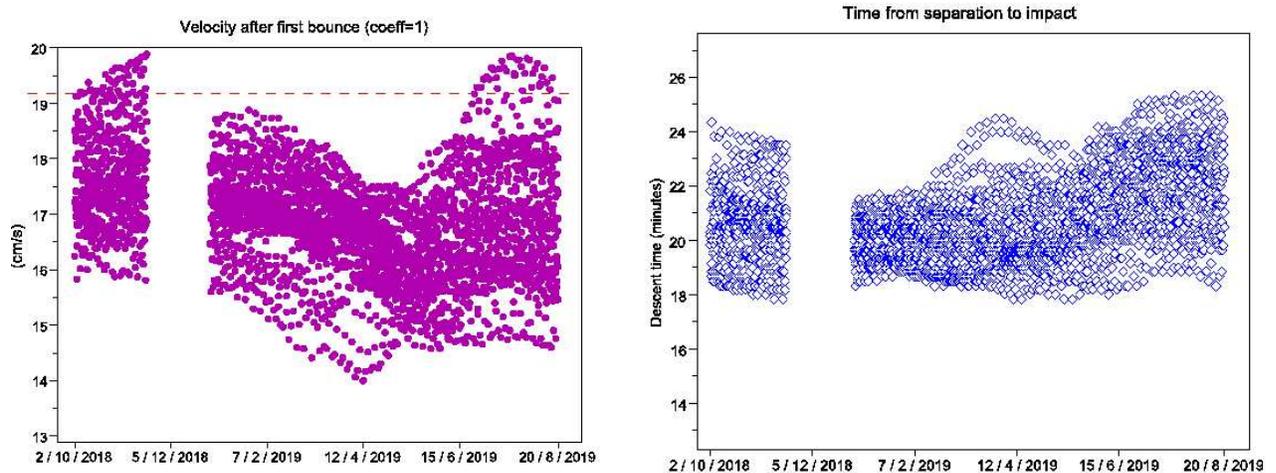


Figure 8. (left) Magnitude of bounce velocity in inertial frame, after first touchdown. (right) Descent times, from separation to touchdown.

Figure 8 shows the norm of the velocity in inertial reference frame after the first bounce for different separation times at each separation date, as well as the descent times (from separation to first touchdown). These results correspond to a possible baseline case: separation at 5 cm/s, at an altitude of 100m in the Earth to asteroid line and a constant asteroid density of 1300 kg/m^3 .

3.6.2. Preliminary results including bounces on 1999JU3 surface

As already mentioned, there is no reliable information on the characteristics of 1999JU3 surface and mechanical properties. For the present work, we have taken three reference values of the in-plane and out-of-plane restitution coefficients: 0.2, 0.5 and 0.8, and we have combined them to see the effect on the bouncing duration and final distance from initial touchdown point. Our modelisation of the bouncing on the surface is simple, as for instance it does not account for the changes in direction that the trajectory can suffer due to the presence of obstacles. If a model of the presence and distribution of rocks on 1999JU3 was generated, more trustworthy statistics could be obtained, especially concerning the final distance between the stop site and the first touchdown site (as MASCOT could just spring back to the initial zone). The model provides, however, an indication of the duration of bouncing until the lander has come to a stop condition. In this work, we arbitrarily defined 'stop condition' by a contact of MASCOT on the surface of the asteroid at less than 1 cm/s in asteroid rotation frame.

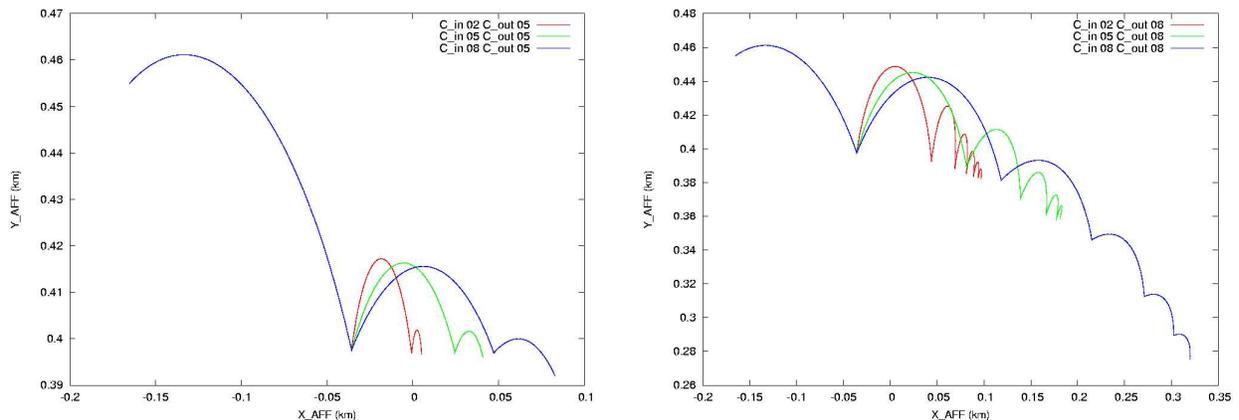


Figure 9. Example of descent trajectories for a separation on January 20 and different values of the in-plane coefficient. The out-of-plane coefficient is fixed to 0.5 on the left and 0.8 on the right.

From the analysis including bounces, the following preliminary conclusions can be drawn:

- The duration of bouncing of MASCOT on the surface of the asteroid is essentially driven by the value of the out-of-plane restitution coefficient.
- For an out-of-plane restitution coefficient of 0.2, results for the bouncing duration are shorter than 20 minutes. If this value is set to 0.5, the time until final stop can reach values of 45 to 50 minutes after the first touchdown. And finally, if 80% of the vertical component of the impact velocity is restituted, MASCOT can spend up to 3 hours from touchdown until final stop.
- The worst cases in terms of distance due to the bouncing, leave MASCOT at a distance of 500 m from the initial touchdown site.

It is foreseen that additional studies are performed, aimed at improving the predictions for final stop time and distance due to the bouncing. The identification of zones on the asteroid having different regolith characteristics, could strongly influence the choice of the separation time. The idea is to target a zone with a low out-of-plane restitution coefficient, in order to reduce the impact velocity, as well as the bouncing times and distances. Large unpredictable distances between touchdown and final stop sites can have serious consequences in terms of constraint satisfaction (daylight duration and RF visibility duration for instance).

4. Dispersion analysis

It has been explained in the previous section that once the nominal separation conditions have been fixed and the delivery time is chosen, the descent trajectory can be univocally computed. Obviously, a real-world situation will never be exactly as foreseen by the nominal case parameters. To account for these differences and predict the landing ellipse associated to a given trajectory, a dispersion analysis is performed on the nominal descent solutions.

4.1. 3 sigma errors considered

Hayabusa-2 Position	Vertical	33.3 m
	Horizontal	13.3 m
Hayabusa-2 Velocity	Vertical	1.55 cm/s
	Horizontal	1.66 cm/s
Hayabusa-2 Attitude	in the 3 axis	0.1 deg
Separation ΔV	magnitude (uniform)	± 1 cm/s
	direction	1.5 deg
Gravity	Uniform distribution	70%-130%

Table 2. 3- σ values used for the dispersion analysis, provided by JAXA

Hayabusa-2 nominal position at separation is at an altitude of 100 m over the surface (see 3.2.). Furthermore, in the present dispersion analysis, the probe is considered to be nominally placed on the Earth to asteroid axis. Additionally, positive vertical velocities of the S/C are not acceptable at the moment of separation. In case an ascending velocity of Hayabusa-2 is detected, a possible option is to wait for the gravitational pull of the asteroid to compensate for it and deliver MASCOT when the vertical velocity has come to 0 or negative. For our dispersion analysis, this means that dispersions on Hayabusa-2 vertical velocity are only added to the separation conditions if they have negative values (i.e. in the asteroid direction).

4.2. Dispersion ellipses at touchdown

Dispersion analysis of descent trajectories has been performed for different separation dates and separation times. First touchdown ellipses are obtained in this way and the maximum impact velocity constraint is checked. Later on, as explained in section 4.3., ellipses are computed including the bouncing on the surface of the asteroid and all constraints are checked on the final predicted landing zone.

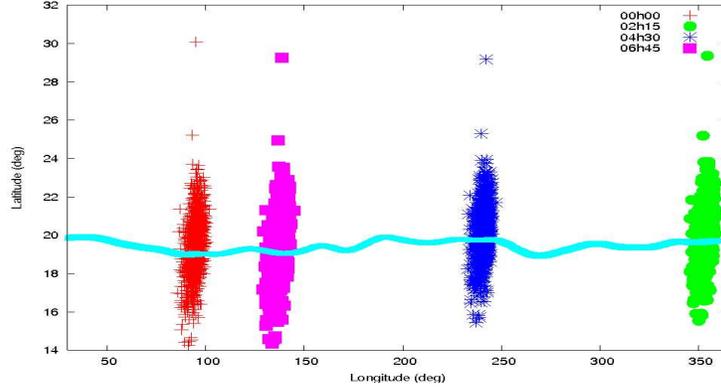


Figure 10. Examples of dispersion ellipses for 4 different separation times on 20/01/2019.

Some relevant characteristics of the touchdown ellipses for the reference separation velocity of 5 cm/s are detailed in table 3. Three different study dates in 2019 have been chosen for a detailed analysis. At each of these dates and for several separation times, descent trajectories have been computed and a dispersion analysis has been performed, with 10^3 random combinations of the dispersions in table 2. Then, the worst case ellipse (in terms of size) has been selected among the results and its characteristics are shown in the table. See also figure 10 for an example of the zones covered by the touchdown ellipses associated to 4 nominal descent trajectories on 20/06/2019.

Date	Angle wrt fixed latitude (deg)	Latitude band (deg)	Max semi-major axis (m)	Max semi-minor axis (m)
20/01/2019	36	± 6.5	83.5	45.5
30/03/2019	30	± 5	75.9	43.3
20/06/2019	31	± 7.2	106.3	45.2

Table 3. Size and orientation of the worst case dispersion ellipses for three different study dates

4.3. Dispersion ellipses after bouncing

Once all the touchdown points of the dispersion ellipse associated to a given trajectory have been computed, the restitution coefficients are applied to the impact velocity vectors as explained in 3.6.2. Then, each dispersed trajectory is integrated until complete stop on the surface. In this way, the dispersion ellipses after bouncing are not computed by performing a new dispersion analysis, but thanks to all the points that have been propagated from the touchdown ellipse.

When the final dispersion ellipse including bouncing has been computed, constraints are checked all over it. Figure 11 shows a way of graphically assessing the constraint satisfaction inside the ellipses. The colors of the background correspond to the daylight duration at each site. The zone satisfying the constraint on the illumination of the landing site is bounded by a violet line. The ellipses in blue correspond to first touchdown ellipses, while the ellipses in red are the $3\text{-}\sigma$ ellipses of the final stop points. Constant latitude lines in orange and red indicate the average daily temperature zones (see figure 7). The sub-Earth latitude is plotted in light blue, as well as the two approximate latitude lines that represent the sub-satellite latitudes at a distance of 200 m from the Earth to asteroid axis. If Hayabusa-2 is not exactly in the Earth to asteroid line at the

moment of separation of MASCOT, but somewhere inside the circle of 200 m radius from this axis, the nominal latitude line (in black) will be shifted north or south, and the first touchdown ellipses would be displaced accordingly. As for the bouncing ellipses, one has to be careful when making direct statements from this figure, as their size and orientation is much less predictable. Nevertheless, we could deduce from this particular example that there is very little margin to the south in terms of satisfaction of the illumination constraint on the dispersed landing sites. Therefore, a non desirable zone inside the 200 m circle could be identified for Hayabusa-2, that is the range of Hayabusa-2 positions leading to a displacement of the nominal landing latitude towards more negative latitudes.

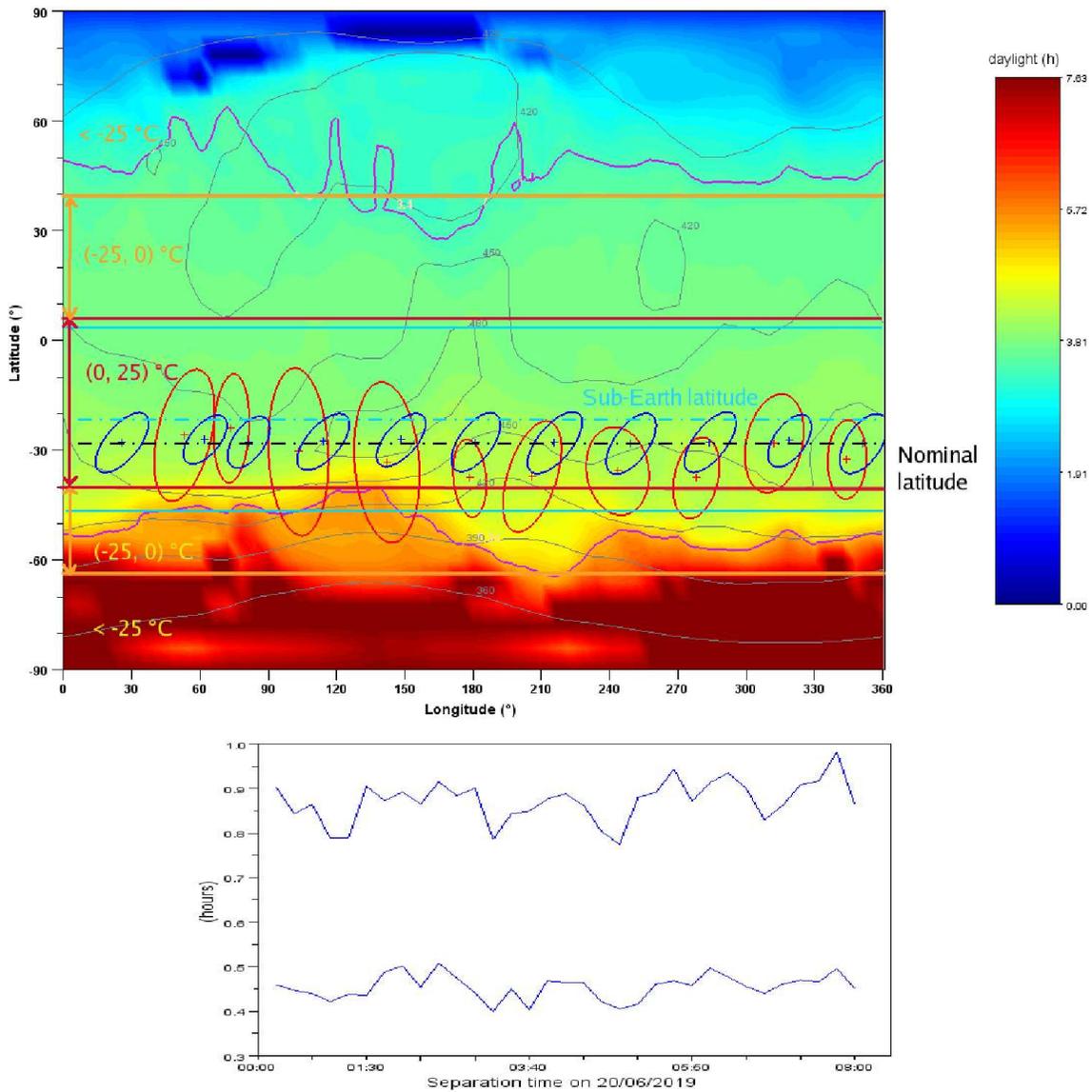


Figure 11. (top) Dispersion ellipses at touchdown time (blue) and after bouncing (red) for several separation times on the 20/06/2019. (bottom) Minimum and maximum bouncing times from touchdown to final stop. Both restitution coefficients are equal to 0.5 in this example.

5. Conclusions

A complete analysis of the descent trajectories of MASCOT, from separation from Hayabusa-2 until final stop on the surface of the NEA 1999JU3 has been performed, using the available models and hypotheses.

Constraint satisfaction inside the landing ellipses is difficult to check, due to the uncertainties affecting basic characteristics of the target asteroid such as density, regolith and boulder distribution or thermal inertia. Despite this level of unpredictability, results from parametric studies are encouraging, in the sense that they allow us to find satisfactory descent trajectories for the majority of the cases that have been studied. Nevertheless, some issues have been identified that should become a matter of concern if the worst case hypothesis are confirmed, as they may significantly reduce the acceptable range of separation dates or Hayabusa-2 desired positions at the moment of delivery.

Moreover, the magnitude of the impact velocity is driven by the total vertical distance travelled by MASCOT during descent. Generally speaking, it is better that this velocity is as small as possible, not only for constraint satisfaction but also because this would obviously reduce the bouncing time before final stop, leaving more time for science activities. Therefore, separation dates corresponding to local minimums of the altitude of the sub-satellite point (small distances from the asteroid centre to the sub-Hayabusa-2 point) will be usually preferred. The idea is that if the separation altitude of 100 m is computed above a zone with this characteristic, MASCOT will probably have to travel less than 100 m until the collision with the surface takes place (first touchdown point).

Last but not least, more detailed studies concerning the bouncing on the surface need to be done, in order to have better predictions of the bouncing times and distances, or determine for instance the zones on the surface of the asteroid with thick regolith layers, that would help absorbing the vertical impact.

6. References

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