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Mascot: Analyses of the Descent and Bouncing Trajectories to Support the Landing Site Selection

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The Japanese mission Hayabusa2 was launched in December 2014 towards the near Earth asteroid 1999JU3, also called Ryugu. This carbonaceous asteroid considered to conceal unchanged traces of the Solar System's origin will be reached by the JAXA space probe in 2018. Among other passengers, Hayabusa2 carries the German-French lander Mascot (Mobile Asteroid Surface Scout).The shoe-box sized spacecraft of 10 kg is planned to land onto Ryugu's surface by the end of 2018 after a ballistic descent from an altitude of a few tenths of meters. In the frame of the collaboration between the German Aerospace Centre (DLR) and the French Space Agency, CNES is responsible for the activities related to Mascot landing trajectory prediction and optimization. The simulated trajectories resulting of the dispersions analysis are essential inputs for the preparation of the operational phase and for the selection of a landing site satisfying constraints imposed by technical aspects (thermal, communications) as well as by scientific interest. Since Mascot has only a limited mobility capacity using a hopping system, the choice of the landing site has to be carefully planned.

The paper gives an overview of the principles and results of dispersion analyses performed for the preparation of Mascot landing in the context described here above, from the descent phase to bouncing and final rest on the surface of Ryugu. The landing site selection process is also addressed, including the presentation of the Mascot release optimization process and the main principles of its operational implementation.

Key Words: Lander, Bouncing, Mission Design, Optimization

Nomenclature

a : angle between XHP and hayabusa2 at release
C_F : coefficient of friction for bouncing
C_R : coefficient of restitution for bouncing
d : offset between asteroid-Earth line and Hayabusa2 at release
GM : standard gravitational parameter
LIDAR : LIght Detection And Ranging
MAM : Mascot Automatic Manager
N : Local normal vector
R : Distance from the centre of mass of the central body to the orbiting object.
V : velocity
θ : deviation angle for the bouncing model

Subscripts
IN : incoming parameters in a rebound
OUT : outgoing parameters in a rebound

1. Introduction

If landing on one of the small body cruising through our Solar System always is an exciting scientific adventure, Ryugu's exploration by Mascot poses also several stimulating challenges in the field of mission analysis. As for the Philae/Rosetta mission,[1)], the environment that will be found at the end of Hayabusa2 interplanetary travel is very uncertain: the characteristics of the asteroid, like its shape or its density, are barely known and their knowledge will improve only after arrival, that is to say just a few weeks before landing. This context imposes to perform a flight dynamics mission analysis covering a wide range of possible situations and to implement tools and procedures flexible enough to take into account last minutes updates. Secondly, Mascot does not have any anchoring mechanism, so it is expected that it will bounce unavoidably on the asteroid surface causing the lander to possibly stop far from its first touchdown point. So modelling the rebounds is mandatory for the prediction of the final rest position. For such modelling, a good compromise has to be made between a reasonable computation time compatible with the constraints of the operational timeline, and a sufficient representativeness to be confident in the selection of the landing site, bearing in mind the lack of data concerning asteroid mechanical properties. Finally, technical requirements and scientific objectives of the mission are not the only drivers for the landing site selection process. A major constraint for the release of Mascot is also to avoid the areas selected by JAXA for the three sampling touchdowns of Hayabusa2, in order not to contaminate the place before sampling and not to disturb the probe descent process. This constraint requires a close interaction with JAXA in order to select landing and sampling sites in a consistent way. The determination of the Mascot trajectory will finally consist in taking into account all these constraints to tune at best in pre-defined and limited ranges the exact time of release and the exact position of release, with the intention of maximizing the chances to have Mascot resting in a suitable place for valuable scientific experiments without endangering Hayabusa2 sampling.

After a short description of Mascot operations in the Hayabusa2 mission in section 2, the modelling of Ryugu's environment used for trajectories analysis and based on the current knowledge of the asteroid is described in section 3. Mascot operations conditions and constraints are described in section 4. Section 5 focuses on the analysis of the descent trajectory, from separation to first contact with asteroid's surface. The main results of bouncing phase studies are described in section 6. Finally, the application of these analysis results to landing site selection process is summarized in section 7. Section 8 gives some conclusions and ways forward.

2. Mascot as part of Hayabusa2 mission

As additional scientific package on board of Hayabusa2, Mascot mission design follows the main timeline defined by JAXA and has to cope with constraints imposed by the mother spacecraft mission.

Hayabusa2 was launched on December 3, 2014 from Tanegashima Space Center in Japan. After an Earth swing-by in December 2015, the probe was inserted into an orbit similar to Ryugu's one. The rendezvous with the asteroid is planned to occur after about 2 revolutions around the Sun in early July 2018. The global Hayabusa2 mission phase in asteroid vicinity is planned to last approximately 18 months, from July 2018 to December 2020.

2.1. Mascot Operations General Timing

Possible slots allocated to Mascot release operations inside Hayabusa2 mission have been defined by JAXA taking into account the following main constraints:

- First, Mascot's release has to be integrated in a timeline including a lot of other critical operational events of the on-asteroid phase: three touchdowns of the main spacecraft are foreseen all along the mission phase with the objective to gather samples of asteroid's surface, the release of three Japanese mini-rovers called MINERVA-II…Secondly, Mascot's separation is not possible during the conjunction period when the angle between Ryugu, the Sun and the Earth is larger than 170 degrees. Mascot's release is thus forbidden from 2018/11/18 to 2019/01/01,
- Finally, Mascot's target landing site shall have been observed from the home position of Hayabusa2 for at least 30 days before the separation, so that the knowledge of the asteroid's surface is good enough to allow safe Hayabusa2 descent for Mascot's delivery.

These constraints have led to the definition of three possible time windows for Mascot's separation:

1. Early October 2018: after minimum time requested for asteroid's mapping and release operations preparation and before Hayabusa2 first touchdown,
2. Late January 2019: after conjunction and before second Hayabusa2 touchdown,
3. End of May 2019: after the third Hayabusa2 touchdown.

The current nominal baseline is to schedule Mascot's release during the first window in early October 2018, the second and the third ones being kept as back-up solutions. This choice is justified by the fact that Hayabusa2 touchdown is a very complex operation during which Mascot may be damaged.

2.2. Detailed Mascot On-Asteroid Sequence

For Mascot delivery, the mother spacecraft will first descend stepwise from its Home Position at 20 km altitude above Ryugu's surface to an altitude of 60 m. When the altitude of 60 m is detected by Hayabusa2's LIDAR, the main spacecraft performs a deceleration maneuver in order to start a free fall phase. Mascot's deployment is triggered exactly 140seconds after this deceleration maneuver, at an altitude which will depend on Ryugu's gravity and relief, estimated to be higher than 50 m for all considered gravity assumptions. After Mascot's release, Hayabusa2 will ascend back stepwise to Home Position at 20 km altitude.

Mascot's is deployed by initializing a ΔV through the separation mechanism, whose characteristics are fixed and cannot be adapted. Since Mascot has neither attitude control nor anchoring mechanism, the descent is fully ballistic and is expected to be followed by several rebounds before the final stop on the surface. During descent, only vital units are activated onboard Mascot. After final stop has been detected by onboard systems, the lander will first autonomously determine if it needs to re-orientate itself. In that case, a reorientation maneuver is performed via a short hop on the asteroid surface. As soon as the correct attitude on ground is reached, the science operations sequence driven by the MAM will begin. This onboard autonomy system is designed to manage and optimize all payloads and communication activities accounting for uncertainties in operations and failure scenarios (See Ref. 3) for details). After a full science sequence has been performed at this first location, the lander will then jump to a second site using the swing arm of the hopping mechanism to start a new science phase. This cycle continues until the power is depleted, allowing for approximately 12 to 15 hours of science activities, knowing that Mascot does not contain any power reloading capability.

3. Ryugu's shape model

The target body for the Hayabusa2 mission is the near Earth asteroid 1999JU3, renamed Ryugu. This carbonaceous asteroid is an Apollo type asteroid with a diameter of less than 900 m.

Several observation campaigns have been performed between 2007 and 2013 providing data used by different teams to build reference models for Ryugu. Successive models used for Mascot mission analysis are reminded in Ref. 2). The current design reference model used by Hayabusa2 and Mascot teams has been developed by T. Müller, J. Ďurech et al. in Ref. 4). The best fit solution has been found to be a relatively spherical shape with main characteristics summarized in Table 1. A representation of Ryugu's topography is shown in Fig. 1.

Table 1. Main characteristics of Ryugu design reference model.

Rotation period	7.631 h
Spin axis (ecliptic geocentric J2000 coordinates)	λ_{ecl} = 329 ±10..20 degrees β_{ecl}= - 39 ±10..20 degrees
Epoch of zero rotational phase (julian date)	2454289.0
Radius of volume-equivalent sphere	440 m

The Z-axis of the shape model is considered to be aligned with the spin axis, with a constant and fixed rotation axis in the inertial frame.

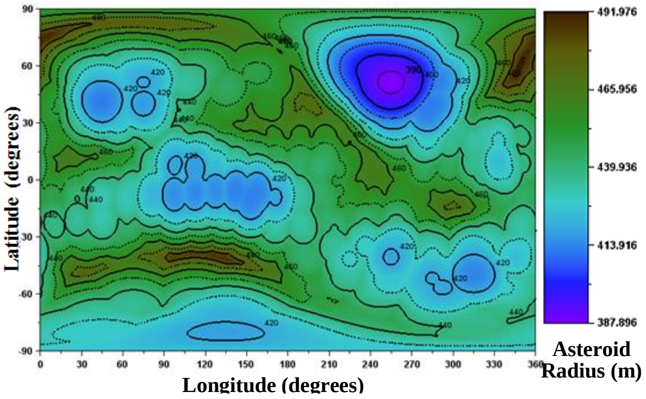

Fig. 1. 2D representation of Ryugu topography.

Taking into account the range of bulk density for C-type asteroid and the Ryugu estimated volume, the standard gravitational parameter GM has been assessed in the range going from 11 m^3/s^2 to 92 m^3/s^2. The current value is set at 32 m^3/s^2. For analyses purposes, the gravitational acceleration is derived from a constant density polyhedron defined by the reference shape model and such that GM is equal to the required value. Gravitational potential at asteroid surface is plotted in Fig. 2.

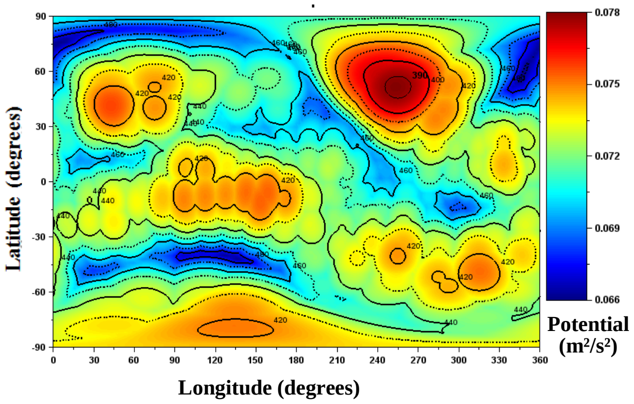

Fig. 2. Ryugu gravitational potential map (GM = 32 m^3/s^2).

The fact that Mascot has no anchoring system and will then bounce on Ryugu imposes to care about escape velocity, to ensure that the lander will not escape or get in orbit around the small body. The canonical definition of parabolic escape velocity valid for a mass point and in inertial frame is given in Eq. (1):

$$V_{esc} = \sqrt{\frac{2GM}{R}} \tag{1}$$

With this definition, the escape velocity computed in inertial frame for a radius of 440 m is 22.4 cm/s for GM = 11 m^3/s^2, 38.1 cm/s for GM = 32 m^3/s^2 and 64.7 cm/s for GM = 92 m^3/s^2. If such definition can be used for preliminary mission design, it has the disadvantage of not taking into account the rotational state of the asteroid.

Based on the gravitational potential model presented in Fig. 2 and for a more refined study, one can thus introduce the surface escape velocity also called escape speed at Ryugu's surface as defined in Ref. 5). This velocity indicates the necessary energy to escape from a specific point at the surface of Ryugu along the local normal taking into account the gravitational potential and the centrifugal force. As a consequence the surface escape velocity is a function of the longitude and the latitude. An example of such a map for the baseline GM of 32m^3/s^2 is shown in Fig. 3. In summary, the minimum surface escape velocity with current shape model and spin axis assumptions is 16.8 cm/s for GM = 11 m^3/s^2, 33.1 cm/s for GM = 32 m^3/s^2 and 59.3 cm/s for GM = 92 m^3/s^2.

It is important to bear in mind that there is still a big uncertainty concerning the shape and spin axis orientation of Ryugu and that the actual asteroid can be quite different from the design reference model here described and used as work assumption.

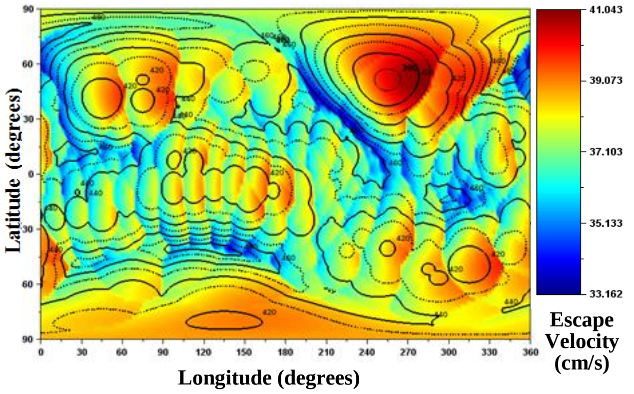

Fig. 3. Ryugu escape velocity map (GM = 32m^3/s^2).

4. Mascot's operations conditions and constraints

4.1. Separation conditions

The separation conditions are a direct consequence of Hayabusa2 position and attitude at epoch of release. On the one hand, the nominal position of Hayabusa2 at the moment of Mascot's release is defined by the following conditions:

- The altitude at the time of separation results of a Hayabusa2 free fall of 140 seconds starting at an altitude of 60 m (detected by LIDAR onboard Hayabusa2). This altitude will of course depend on the gravitational acceleration created by Ryugu, and on the asteroid relief under the spacecraft when using LIDAR. Typical altitude at the time of separation for GM = 32 m^3/s^2 is circa 54 m.

- The main spacecraft is necessarily in the Earth to asteroid line, or in the plane perpendicular to this axis at a distance d shorter than or equal to 200 m to the Earth to asteroid line. This limit is imposed by Hayabusa2 communications and operational constraints. d will be one of the parameters that can be used to optimize the Mascot separation and to target a specific landing area.

On the other hand, the attitude of Hayabusa2 at Mascot's release is fixed. 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. 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.

4.2. Constraint on first touchdown

The main concern for the first contact with the ground is to ensure that Mascot will not have enough velocity to escape or get into orbit around the asteroid. If this condition is satisfied for the first impact, it can be considered as fulfilled for the following ones, after bouncing, since the energy will decrease. In a conservative approach, the first rebound can be considered as a perfectly elastic contact where the outgoing velocity is equal to the incoming velocity. With such assumption, one can guarantee that Mascot won't escape from Ryugu if the norm of the impact velocity in the inertial frame is lower than the escape velocity in inertial frame. Since this condition is not sufficient to guarantee that Mascot won't be placed in orbit around Ryugu after the first bouncing, it has been decided to impose a more restricting condition on the impact velocity accounting for safety margins. In this way, the velocity at touchdown in inertial frame shall be limited to half the escape velocity as defined by Eq. (1).

4.3. Constraints on final landing site

Several technical constraints are considered for the landing site selection:

1. Mascot landing site shall be located outside the areas selected by JAXA for the sampling operations by the main spacecraft.
2. For thermal and scientific reasons, Mascot landing site shall be in a zone where the daylight duration is comprised between 50 % and 70 % of the asteroid rotation period.
3. Because of TM/TC link constraint, the duration of landing site visibility from Home Position shall be over 40 % of an asteroid rotation period.
4. The landing site shall have been observed for 30 days or longer before landing.
5. The landing site shall also be selected so that Mascot thermal requirements are met. This will be verified through thermal simulations and depends a lot on the real spin axis, shape and thermal inertia of Ryugu.

Once these technical constraints have been taken into account, the scientific objectives and interest will guide the choice of a target site for landing. Some constraints have to be satisfied for each instrument to fulfill at best its mission, like for example minimum night duration for thermal inertia measurements, or a good sunlight illumination for acquisition of usable images.

5. Descent trajectories analysis

The first step of mission analysis consists in analyzing the descent from release point to first contact with the ground as a function of date, position at release and of Ryugu gravitational attraction.

5.1. Variations with release date, release position and GM

The descent has been computed for all dates in the asteroid phase of Hayabusa-2, excluding the conjunction period (see 2.1), with a step of one day. The objective of this first study is to assess the impact of separation date on the reachable latitude range and on the impact velocity at first contact which is the most restricting to ensure that Mascot will remain at Ryugu's surface. Such computations have been performed usingthe polyhedron shape model of the asteroid. Obtained results for GM = 32 m^3/s^2 are shown in Fig. 4, Fig. 5 and Fig. 6. The red circles can be interpreted as the variation of parameter as a function of release epoch, and the blue points gives the range of variations due to flexibility in Hayabusa2 release position. The same computations have been performed for the two extreme current assumptions for Ryugu GM, 11 m^3/s^2 and 92 m^3/s^2.

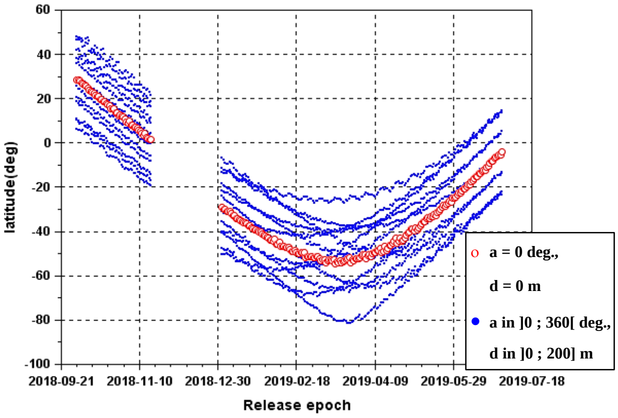

Fig. 4. First contact point latitude range for GM = 32 m^3/s^2, as a function of release date.

The reachable range of latitude at first touchdown goes from about +50 degrees to –80 degrees depending on the release date, and is not affected by GM. For a given date, the variation in latitude allowed by the flexibility in release position is between 40 and 60 degrees, due to the Ryugu-Earth-Sun geometry.

The descent time depends on the considered GM and the asteroid's relief creates also a dependency to release date and position. Main statistics values are given in Table 2.

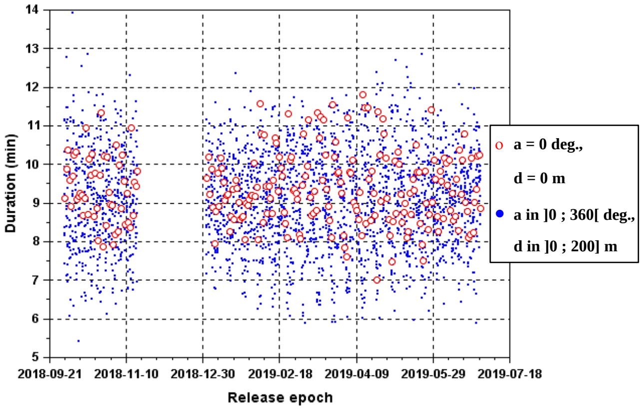

Fig. 5. Flight duration from release to first contact point for GM=32m^3/s^2, as a function of release date.

Table 2. Statistics on descent times as function of GM (Polyhedron shape model).

GM (m^3/s$^{2)}$	Mean (min)	Standard deviation (min)	[Min; Max] (min)
11	13.9	2.7	[7.4;25.6]
32	9.1	1.2	[5.4; 13.9]
92	5.2	0.5	[3.2; 6.7]

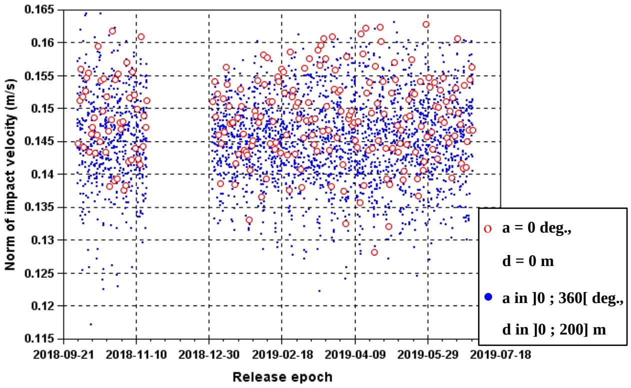

Fig. 6. Impact velocity norm in inertial frame, computed at first contact point for GM = 32 m^3/s^2, as a function of release date.

Table 3. Statistics on inertial velocity as function of GM (Polyhedron shape model).

GM (m3/s2)	Maximum inertial velocity over studied timeframe (cm/s)	Limit = half escape velocity (see Eq. (1)) (cm/s)
11	11.5	11.2
32	16.5	19.0
92	26.0	32.3

The inertial impact velocity is directly linked to descent time: the longer the descent, the more time the gravity has to increase the lander velocity. Table 3 shows that the condition for inertial impact velocity is fulfilled for baseline value of GM and higher values with current spin and shape model assumptions.

Should Ryugu have a weaker gravity field, the impact velocity would become a key criterion for mission analysis and would have to be analyzed in detail in order to find a release time and a release position which minimize the risk of escaping. Such detailed analysis could consider the surface escape velocity map shown in Fig. 3 in order to find areas where the impact velocity, computed in the asteroid rotating frame as shown in Fig. 7 for GM = 32 m^2/s^3, is as low as possible compared to the surface escape velocity.

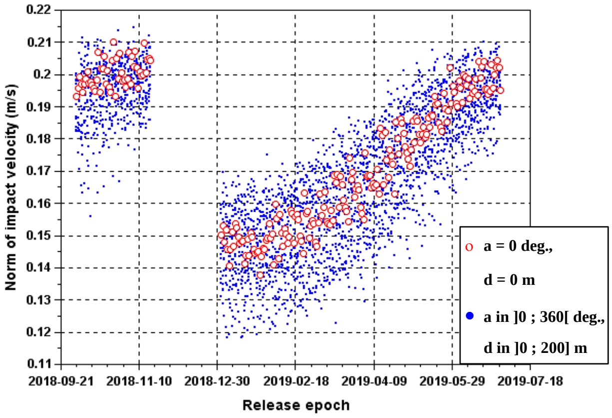

Fig. 7. Impact velocity norm in asteroid rotating frame, computed at first contact point for GM = 32 m^3/s^2, as a function of release date.

5.2. Variations with separations conditions dispersions

Once the separation window slot has been chosen, the remaining variations in the descent trajectory will come from the different sources of uncertainties in the separation conditions. A dispersion analysis was thus performed in order to assess the impact of each of these sources described in Table 4.

Table 4. Errors values used for the dispersions analysis.

Hayabusa2 Position (Navigation error)	Horizontal	Gaussian law	28.4 m (3σ)
	Vertical	Gaussian law	20.3 m (3σ)
Hayabusa2 Velocity (Navigation error)	Horizontal	Gaussian law	1.4 cm/s (3σ)
	Vertical	Gaussian law	1.7 cm/s (3σ)
Trigger epoch error		Gaussian law	203 s (3σ)
Mascot separation velocity (Mechanism uncertainty)	Magnitude	Gaussian law	1.74 cm/s (3σ)
	Direction	Uniform law	5 degrees

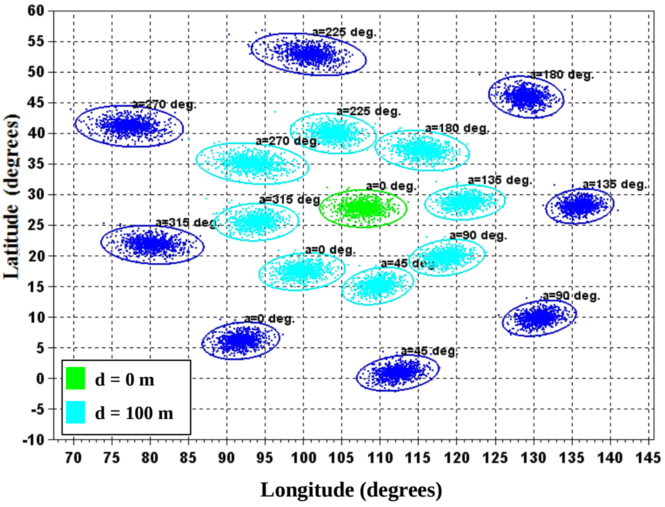

Fig. 8. Mascot positions at first contact with asteroid's surface for different positions of Hayabusa2, and taking into account dispersions. Polyhedron shape model and GM = 32 m^3/s^2.

Figure 8 shows the results of such dispersion analysis for different Hayabusa2 positions. For each release position, 1000 Monte-Carlo draws have been computed. The variability induced in latitude and longitude of first touchdown for a given separation time by the different uncertainties is in a range of about 5 degrees in latitude and 10 to 15 degrees in longitude.

This is roughly one order of magnitude below the flexibility induced by the tuning of Hayabusa2 position at release around the Asteroid-Earth line, allowing 50 degrees of shift in latitude, and 70 degrees of shift in longitude.

6. Bouncing

The bouncing of Mascot after the first touchdown is bound to significantly affect the final landing position. This should be taken into account when computing Mascot trajectory after release and predicting the landing zone. The characteristics of the rebounds will depend not only on the first impact conditions (velocity and Mascot attitude at contact), but also on the composition, size and distribution of regolith at the touchdown site.

6.1. Bouncing model

For trajectory analysis purposes, the simulation of the interaction with asteroid surface at the time of contact has to be a compromise between complexity and representativeness. A too complex model would require too much computation time for analysis which has to be performed in a short delay after asteroid arrival and would not be relevant taking into account the poor a priori knowledge of Ryugu. But the model should still be elaborated enough to cover all kind of situations that can be encountered.

The trade-off resulted in modelling the contact with the ground thanks to three parameters (See Fig. 9.):

- The out-of-plane coefficient or coefficient of restitution C_R to be applied to the projection of the incoming velocity along the local normal vector,

$$C_R = \frac{|\overrightarrow{V_{OUT}}.\vec{N}|}{|\overrightarrow{V_{IN}}.\vec{N}|} \tag{2}$$

- The in-plane coefficient or coefficient of friction C_F to be applied to the projection of the incoming velocity in the plane perpendicular to the local normal,

$$C_F = \frac{\|\overrightarrow{V_{OUT}}\times\vec{N}\|}{\|\overrightarrow{V_{IN}}\times\vec{N}\|} \tag{3}$$

- The angle θ between the plane containing V_{IN} and the local normal, and the plane containing V_{OUT} and the local normal.

Then maps can be created to assign a set of parameters to each point at Ryugu's surface, supposed as uniquely defined by its longitude and its latitude. Such mapping can be done either using statistical laws to take into account the poor knowledge of the soil characteristics, or using data coming from Hayabusa2 observations if clear properties can be detected, like for example flat areas covered with regolith. When computing the bouncing trajectories, the corresponding set of parameters is then used at each contact to compute V_{OUT} from V_{IN}.

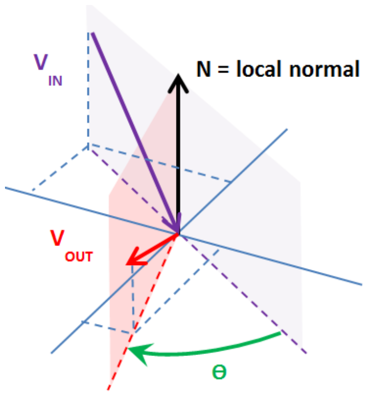

Fig. 9. Representation of bouncing parameters.

Several preliminary analyses have been performed, using conservative values aimed at estimating the maximum bouncing distances and times. For instance, C_R is set at 0.6, from the tests performed in drop tower which showed a uniform distribution between 0 and 0.6 for this coefficient, as described in Ref. 7). The reference value for C_F was set to 0.9. As far as deviation angle is concerned, the current dispersion is modelled thanks to a Gaussian law centered in 0 and with 1 σ = 30 degrees. In a next step, the deviation angle variations will be implemented based on the modeling described in Ref. 6).

6.2. Effect of bouncing parameters

The sensitivity to bouncing parameters has been studied by running Monte-Carlo analysis for different values of bouncing coefficients and angles. First, a spherical shape model has been used in order to obtain results which are only affected by the bouncing model and not by variations in the local normal direction. Mascot is supposed to be released along the Earth-asteroid line (no offset in Hayabusa2 position). The values used for dispersion are the ones defined in Table 4.. Six different combinations of bouncing parameters have been analyzed. 2 different values have been considered for CR and CF. The impact of the bouncing angle θ has been studied by comparing bouncing obtained with a constant null angle with a Gaussian distribution around 0 with a 3σ of 90 degrees, in order to simulate local variations of the terrain (rocks…) causing deviations in the bouncing velocity. Resulting final landing sites are shown on Fig. 10. Some significant values are also gathered in Table 5.

Table 5. Significant values for trajectories computed with different bouncing parameters combinations (spherical shape model, GM=32m³/s²)

	C_F	C_R	θ	Number of rebounds	Maximum flight duration (min)
🟦	0.9	0.6	0	10	55
🟦	0.9	0.6	Normal law (1σ =30 degrees)	10	63
🟥	0.9	0.4	0	6	31
🟥	0.9	0.4	Normal law (1σ =30 degrees)	6	37
🟩	0.5	0.4	0	6	30
🟩	0.5	0.4	Normal law (1σ =30 degrees)	5	28

One can note that the duration of the bouncing trajectory together with the number of rebounds is essentially driven by the value of CR. Considering a non-null bouncing angle adds dispersion in latitude and longitude amplified for higher CR. The effect of CF is less important.

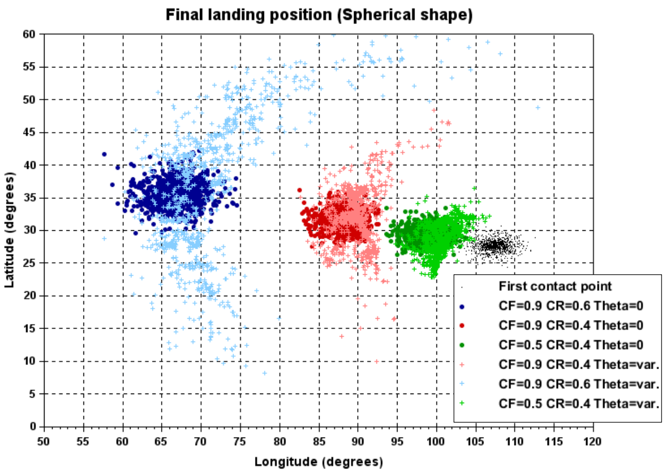

Fig. 10. Mascot final landing site taking into account dispersions of Table 4. for different combinations of bouncing model, for spherical shape model and GM = 32 m^3/s^2. Theta=var. means angle θ dispersed according to a normal law centered around 0 degrees and with $1\sigma = 30$ degrees.

7. Landing Site Selection and Optimization Process

The main objective of the studies presented in the previous sections is to be prepared to predict Mascot trajectory at best using the data gathered by Hayabusa2 during Ryugu's mapping once in asteroid's vicinity. This capacity of prediction will then be used to optimize the tunable parameters in order to maximize the probability to have Mascot resting in an appropriate landing site.

Given all mission constraints, the separation time and position are the only parameters that can be adjusted and provide some degrees of freedom for the landing site selection. As Hayabusa2 is in a fixed position in inertial space (i.e. the sub-satellite point essentially has a fixed latitude in time spans of the other of a few days), and the asteroid is rotating around its rotation axis underneath the S/C, playing with the separation time is equivalent to targeting different longitudes. Besides, the separation position can be chosen in the 200 m radius circle allowed by JAXA around the asteroid-Earth line in order to change the reachable latitude.

7.1. Main steps of landing site selection process

In the landing site selection process, the mission analysis team is in charge of processing data coming from Hayabusa2 remote sensing of Ryugu in order to deliver to the engineering and scientific teams products facilitating the selection of a reachable and attractive landing site amongst the locations authorized by the imposed release conditions and technical constraints. As result of this landing site selection process, two target landing sites, one nominal and one back-up, will be delivered by Mascot Team for review to JAXA with associated release position and time maximizing the chance to reach it. Due to the poor knowledge of Ryugu and to the random nature of bouncing process, like throwing a dice on an unknown surface, the Mascot trajectory prediction has to be envisaged only from a statistical point of view. As a consequence, there is no obvious direct relationship between a point on the asteroid's surface and the initial conditions that can lead to it. Finding the best solution will thus necessarily pass through a systematic exploration of all possible trajectories in a trial-and-error method.

Once a given slot of a few days is chosen for the release, one can consider that the Earth-Sun-Asteroid geometry is fixed over this period. Then, the time dependency can be directly considered as longitude dependency with a recurrence period equal to the asteroid rotation period. Delaying the release will thus be equivalent to shifting the first contact point in longitude. For a given release time (modulo the asteroid rotation period), one can modify the final site latitude by changing the release position. The set of reachable landing sites can therefore be computed thanks to a systematic exploration in release time and release position in the ranges allowed by mission constraints.

The following steps will thus be followed for landing site analyses:

1. Before the arrival in asteroid's vicinity, a grid in release time and release position is defined (trade-off between the computational time and the desired accuracy of exploration).
2. Once the first results of Ryugu's observation are available, dispersion spots giving the possible final positions are computed for each point of the grid defined in step 1.
3. Release positions and times which do not fulfill the constraints are discarded. This includes forbidden areas and times defined by JAXA, areas which are not compliant with required impact velocity, daylight duration…
4. The surviving candidate sites are analyzed in details and results are presented for pre-selection of the best candidates from scientific interest point of view.
5. The updates of models obtained thanks to further Hayabusa2 observations of Ryugu are used to refine the knowledge of the best candidates selected at step 4.
6. The two best candidates are eventually selected based on updated analyses and presented for review to Hayabusa2 team together with associated release position and times.

7.2. Example: Guidelines for the pre-selection of the best candidates for landing site (technical criteria)

Before knowing better the small body on which Mascot will have to bounce, some trend analysis was started in order to draw characteristics which can help the flight dynamics team to quickly pre-filter the best candidates. Such analyses are illustrated in this section with an example chosen to demonstrate the high variability of the possible bouncing trajectories.

The following plots are generated by running Monte-Carlo simulations (1000 draws considering dispersions defined in Table 4.) for two different release dates on the 1st of October 2018, with a delay of 4h30 between both times, selected in order to have the first touchdown contact with different local normal. The reference polyhedron shape model is used with baseline assumption of 32 m^3/s^2 for GM. The bouncing is simulated at each contact with maps of slightly varying C_F and C_R coefficients, and bouncing angle equal to 0 (Linear bouncing). For each release time, several release positions have been explored.

As shown on Fig. 11., the pattern of final rest dispersion spots can be very different for 2 different release times. For the first release time (on the left of both plots), the first contact occurs in a location with relatively flat relief (radius between 420 and 440 m) ending with a relatively symmetrical pattern of dispersion spots. For the second release time (on the right of both plots), the first contact occurs in rougher terrain, with a basin surrounded by hills (radius between 390 m and 460 m).

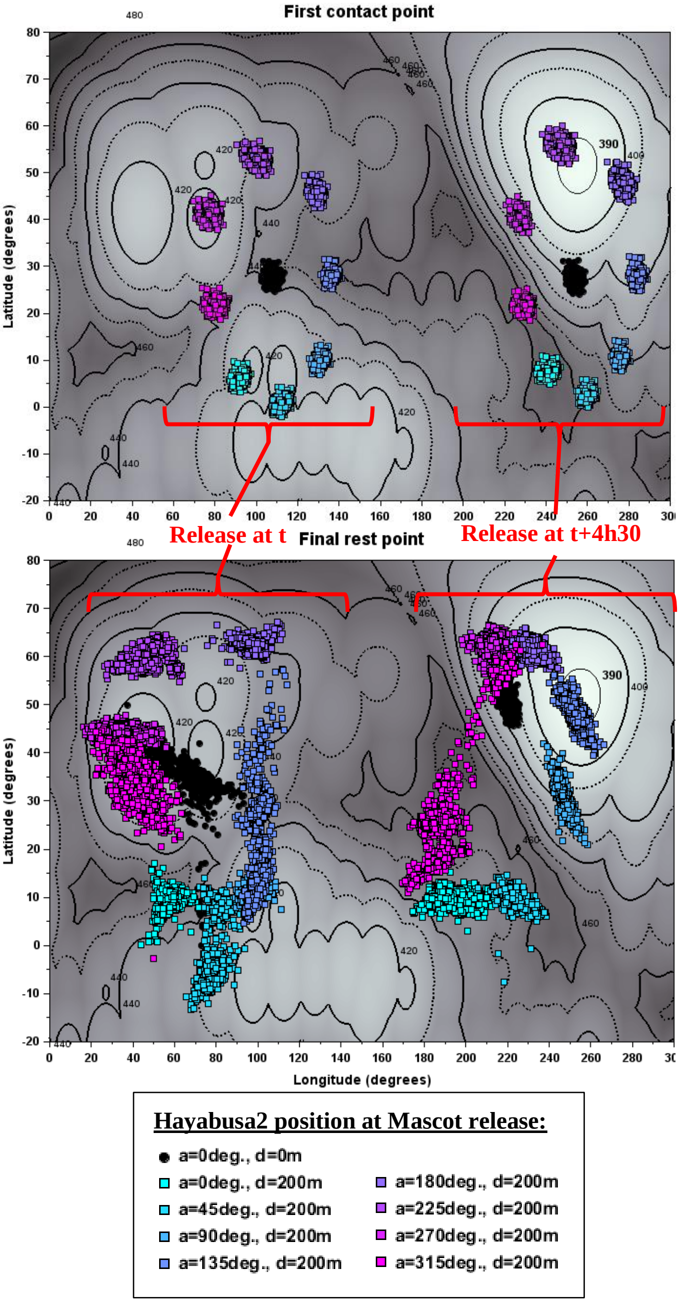

Fig. 11. Mascot first contact point and final landing sites dispersion spots for two different release times, all other assumptions being equal.

The resulting dispersion spot for final rest position varied a lot, with accumulations and tight dispersion spots created by the basin and scattering for touchdowns in the basin external slopes. As expected, the first contact spots are very close to Gaussian distributions, whereas final spots distributions are very different from Gaussian ones. This is due to variations in local normal directions which can cause a single cluster of incoming trajectories to be fully reshaped or even split into separated parts after several rebounds.

As shown on Fig. 12., the same landing site can be reached from 2 different Hayabusa2 positions at release. This can be seen as an interesting advantage since it shows some robustness to release position dispersion. Another interesting characteristic of this landing site is the short distance between the first touchdown and the final point as computed with the bouncing model. It means indeed that, even if the bouncing should stop earlier than simulated due to difference between actual and simulated bouncing behavior and terrain characteristics, Mascot should not rest too far from the target landing site. In such a case, and under the assumption that the 2 solutions are exactly equivalent, the initial conditions leading to the most compact dispersion spot should be prioritized, in order to maximize the chance to rest at the target position. For this example, the position with a = 225 degrees seems the most relevant choice from a purely technical point of view.

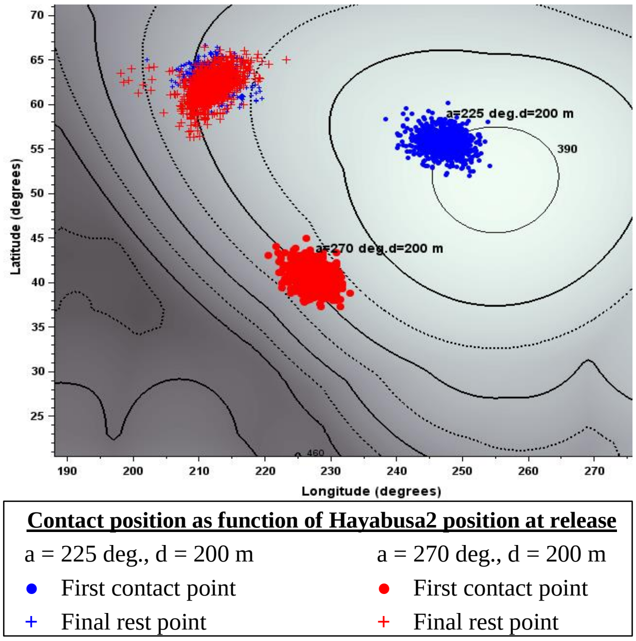

Fig. 12. Mascot first contact point and final landing sites dispersion spots for two different release positions.

For each dispersion spot, statistical quantities can be analyzed in order to compare and rank the accessible areas. The list of relevant values for this ranking is still under definition and will be consolidated within next months.

8. Conclusion

Landing Mascot on a small body like Ryugu is a complex problem in which many parameters must be considered. The available models of the asteroid environment have been used to perform preliminary analyses in order to assess the impact of each parameter on the descent and bouncing trajectories.

Based on the current knowledge of the asteroid, these analyses show that the descent towards Ryugu should last between 5 and 15 minutes. When simulating rebounds using different bouncing models, the total flight duration from release to final rest varies from 28 minutes to more than 1 hour including 5 to 10 rebounds. Some adaptations still have to be done to improve the bouncing models based on numerical simulations results.

Targeting a specific landing site at Ryugu’s surface requires taking into account the random nature of bouncing and the variability ranges allowed by Hayabusa2 mission constraints. The baseline of a landing selection process based on systematic analysis of reachable areas has been defined. Study of engineering and statistical criteria for this selection is on-going and some preliminary outlines have been described. This process will be fine-tuned within the next months with the help of a landing site selection training based on simulated data generated by scientific teams.

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