Flight Dynamics Analyses to reconstruct MASCOT's trajectory on Ryugu's surface

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Abstract

The Mobile Asteroid Surface SCOuT (MASCOT) is a German-French lander successfully released by the Japanese space probe Hayabusa2 [1] at the surface of the near Earth asteroid (162173), also called Ryugu, on the 3rd of October 2018. Since it had no anchoring system, MASCOT followed a bouncing trajectory [4], before immobilizing and starting its science operations. A comprehensive knowledge of MASCOT's trajectory after its separation from the mother spacecraft is essential for the understanding of the science data gathered by the scout. As the team in charge of the prediction of MASCOT's trajectory before landing [2], the MASCOT Flight Dynamics Team at CNES is a self-evident contributor to the activities for the reconstruction of MASCOT's moves after its separation for the mother spacecraft. After a recap of the trajectories predictions before landing, the present paper focuses on the on-going flight dynamics analyses to reconstruct the trajectory, as well as on the future developments of this activity that is still in its very early stages.

Introduction

On the 3rd of October, after being released from an altitude of a few tenth of meters, MASCOT, the shoe-box sized lander of 10 kg finally reached the so-called "MA-9" landing site, carefully selected by all the actors of MASCOT engineering and science teams, in agreement with the decision of the Japanese space agency JAXA about the zones targeted for Hayabusa2 touchdowns operations. As expected, MASCOT bounced on the asteroid's surface before coming to rest and starting its operational activities. It was not possible to accurately predict this bouncing trajectory, first because MASCOT attitude was not stabilized during its descent, but more importantly because the exact nature of Ryugu's surface was unknown beforehand. In the frame of the MASCOT's landing site selection process [4], it was only possible to make reasonable assumptions about the interactions between the ground and the lander, and thus to determine possible landing zones resulting of Monte-Carlo simulations. Amongst the 10 candidates pre-selected for MASCOT landing, the zone called MA-9 was finally retained as the MASCOT landing site by all the members of the MASCOT team, that is to say the engineers of the German Space Agency (DLR) and of the French Space Agency (CNES), as well as the science teams whose instruments was embedded on MASCOT:

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

After a summary of the course of operations for MASCOT on the 3rd of October 2018, the preliminary contributions of MASCOT Flight Dynamics (FD) Team for MASCOT's trajectory and attitude reconstruction will be presented, as well as some insights about the future developments. This work fits into a large cooperation between all the members of the MASCOT team with the helpful support of JAXA whose final objective is to provide to the international scientific community a consolidated reconstruction of MASCOT's path on Ryugu's surface.

MASCOT bouncing on Ryugu: a dream come true

On the 3rd of October 2018, at the expected time close to 2:00 UTC, the command for MASCOT's release was sent to Hayabusa2 and the scout was nominally ejected by the separation mechanism at about 50 m of altitude above Ryugu's surface. After 6 minutes of ballistic descent, MASCOT hit the ground for the first contact with the asteroid's rocky surface against a large boulder. MASCOT came to rest approximately 13 minutes later, after only a few bounces. A first automated activation of its hopping mechanism, a swing arm, didn't manage to put it in the required position for an optimal science sequence. A second movement of the arm was thus commanded and successfully placed MASCOT on the right face to start a first science sequence a few meters farther than its original resting point. Before that point, only MASMAG and MASCAM were able to exploit their full potential, but from this point on, MicrOmega and MARA were correctly oriented toward the surface and were also able to start their nominal mission.
After 15 hours of scientific sensing, at the time corresponding to the beginning of the 3rd asteroid day spent by MASCOT on the surface, the main objectives of the mission were achieved. But MASCOT's battery was still delivering enough power to continue with Ryugu's exploration. It was thus decided to take this opportunity to command more operations: after a very small move at the surface called "mini-move", aiming at generating stereo images, a final bigger hop was commanded, finally triggering the end-of-life status of MASCOT. The communications with Hayabusa2 were lost after 17 hours of continuous operations, at about 19:00 UTC. A scheme summarizing the different phases is shown on Fig. 1.

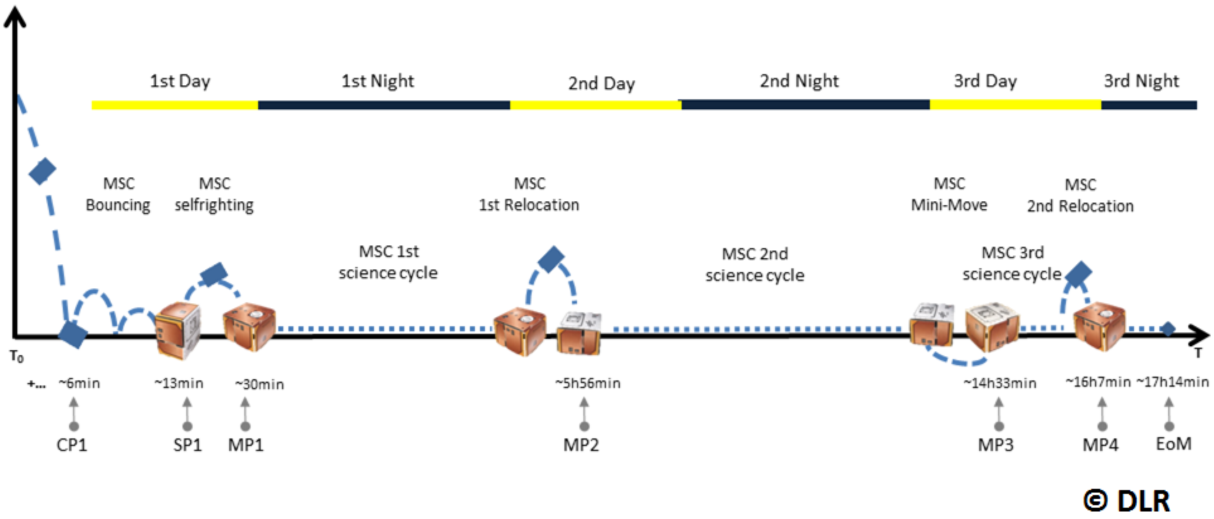

Fig. 1 Illustration of the main stages of MASCOT's mission. CP1 stands for first contact point, SPi for ith Settlement Point, MPi for ith Measurement Point (location after uprighting), EoM for End of Mission

From that point on, a new phase of the MASCOT mission has started. The significative amount of data gathered on the asteroid surface is the promise for months and even years of scientific studies. In this impressive work, the reconstruction of the exact sequence of events from the separation to the end of life of MASCOT can be very helpful, not only to give to scientists all the contextual data useful for a better understanding of the measurements, but also in order to learn from this extraordinary experience for the future of small body exploration. The next sections will then describe the work started and foreseen in the future by the MASCOT FD Team to contribute to MASCOT's bouncing trajectory and attitude reconstruction.

First steps on the way toward trajectory and attitude reconstruction

Thanks to the images taken by Hayabusa2 cameras and by MASCAM during MASCOT's landing, a very good estimation of MASCOT's path at the surface was reconstructed by the scientific teams and published by DLR only eight days after the landing. This path is shown on Fig. 2. In particular, one can see that the first contact of MASCOT with the ground very probably occurred against a quasi-vertical wall causing a very important deviation in MASCOT's trajectory. The first analyses allowed to count about 8 contacts with the ground before reaching the first rest position.

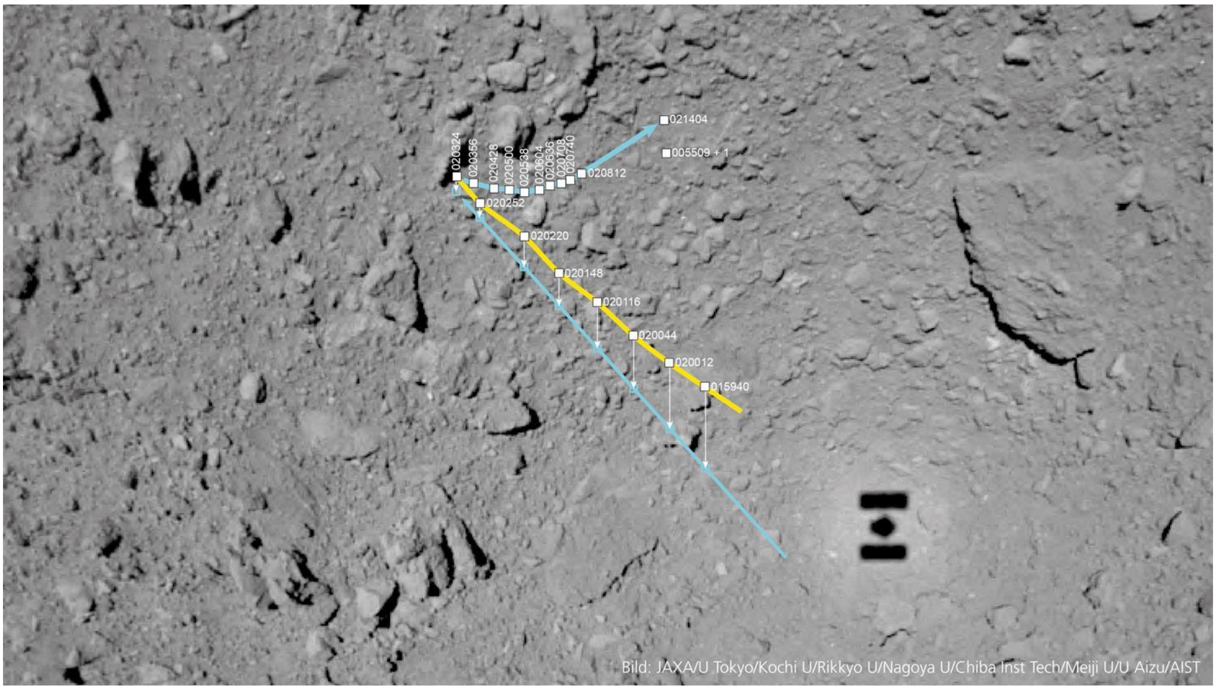

Fig. 2 Illustration of MASCOT's path on Ryugu surface, as reconstructed by science teams (Image from DLR website. Copyright JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, Aizu University, AIST)

Thanks to this excellent work, it was possible to confirm very early after MASCOT's landing to Hayabusa2 Teams that the scout was lying in the expected landing zone.

This first step being achieved, the objective is now to perform an in-depth analysis aiming at obtaining a continuous restitution of MASCOT's position, velocity and orientation as a function of time, during all MASCOT's lifetime on Ryugu's surface. This restitution requires to take into account the observations of all technical and scientific teams. The MASCOT FD Team is only one of the contributors to this long-term activity which has just begun. Due to the very short time between the landing operations and the deadline for the submission of the present paper, only partial results have been reported here.

Comparison of first data with Flight Dynamics predictions

MASCOT's landing site was selected after a process which required to predict MASCOT's trajectory. It can be interesting in a first step to compare the data observed during operations to

the predictions that were used for the MASCOT landing site selection. Details about the predictions and the landing site selection process can be found in Ref. 5.
Since one has to take into account many errors sources, the trajectory prediction is not a single path, but consists in a set of possible bouncing trajectories ending in the landing dispersion zone shown on Fig. 3. This set takes into account:

- uncertainties about the separation conditions: position, attitude and velocity of Hayabusa2 at the time of the separation, magnitude and direction of the velocity delivered by the mechanism used for MASCOT‘s separation,
- uncertainties about Ryugu: gravity, shape model and local topography, mechanical properties of the surface…

All these uncertainties were injected in Monte-Carlo simulations from which statistical quantities were computed. Some of them can directly be compared to the values observed.
First one can note that the descent duration of roughly 6 minutes observed during operations is fully consistent with the predictions, and close to the mean value computed according to the normal law, as shown on Fig. 4. The descent is indeed fully ballistic and its prediction is mainly affected by the uncertainty on separation conditions and on gravity of Ryugu which are basically Gaussian. The only non-Gaussian factor is the local topography.

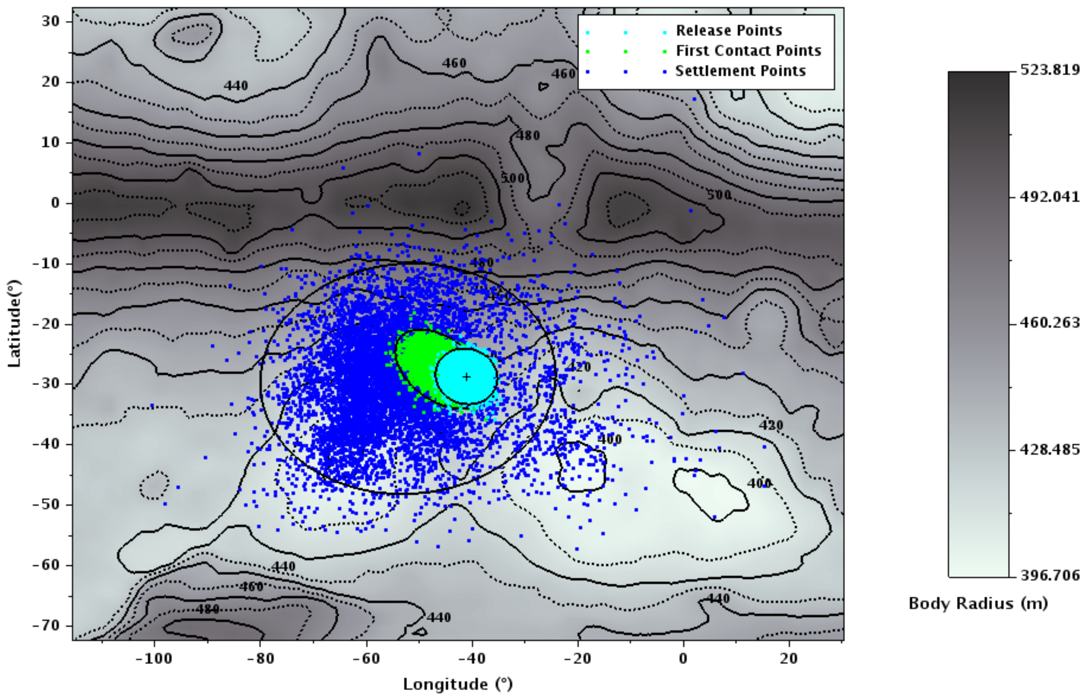

Fig. 3 Release, first contact point and final settlement points areas for the landing site eventually selected for MASCOT, computed from Monte-Carlo simulations.
In cyan: dispersed positions at release projected on the asteroid surface, with corresponding 3-sigma ellipse in black. In green: dispersed 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

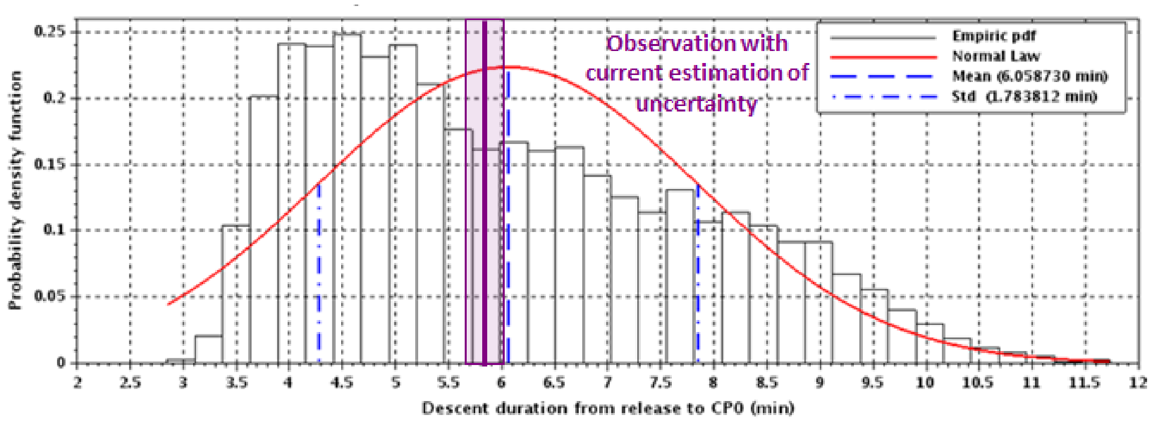

Fig. 4 Probability density for descent duration (CP0 = first contact point on asteroid's surface) computed from Monte-Carlo simulations before landing.

If one does the same comparison for the total rebounds duration, defined as the time between the first contact with the ground and the first rest position of MASCOT at the surface of the asteroid, one can note that the observed value of 13 minutes is still consistent with the predictions (See Fig. 5). As shown on the cumulative density function in the lower plot of Fig. 5, only 10 % of the simulated trajectories had rebound duration shorter than 15 minutes. A tentative explanation can be profiled by noting that MASCOT encountered a very specific situation, probably hitting a quasi-vertical rocky wall at the first contact and thus losing a lot of kinetic energy quite early in the trajectory. This scenario was covered by the parameters of the simulation but not considered as the most probable case.

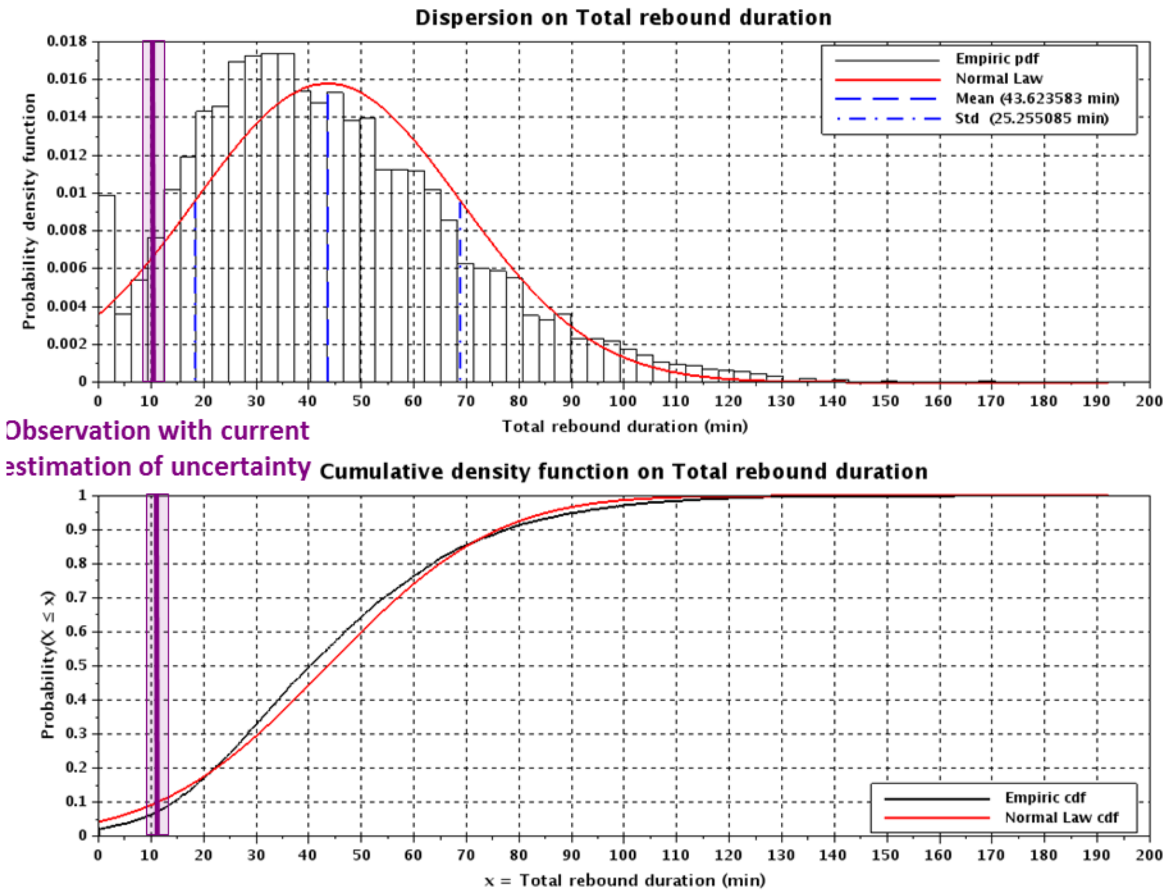

Fig. 5 Probability density and cumulative density function for total rebounds duration (time between the first contact on the asteroid and the first rest point after rebounds) computed from Monte-Carlo simulations before landing.

Finally, the Monte-Carlo simulations were giving a rough estimation of the number of bounces, a bounce being defined as the point where MASCOT starts to rise again after a contact with the ground. As per first analyses of data obtained during MASCOT's operations, a total of 8 bounces was observed, which is consistent with the predictions.

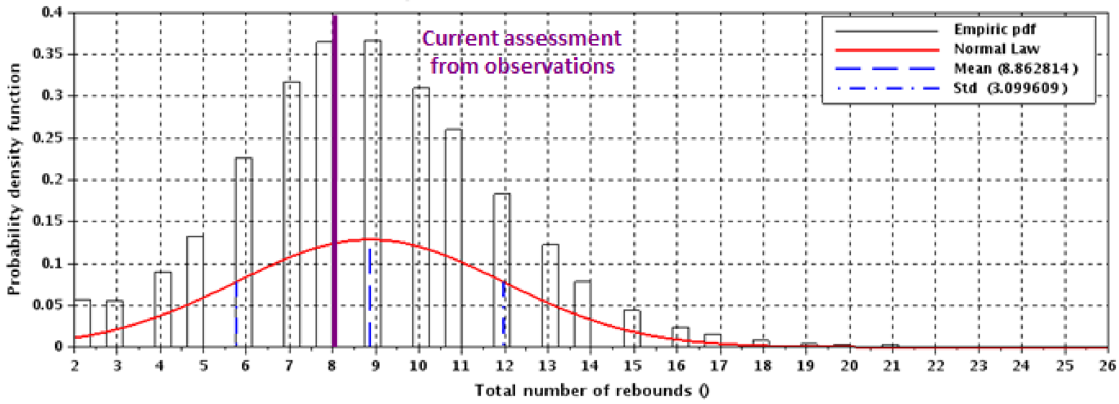

Fig. 6 Probability density for total number of bounces computed from Monte-Carlo simulations before landing.

Even if such comparisons are not sufficient to strictly evaluate the validity of the trajectory and bounces modelling used for the predictions, it allows at least to verify that it was not fully out of the scope. A more accurate evaluation will be done once a consolidated trajectory is available.

MASCOT FD Team contribution to trajectory reconstruction

For the MASCOT FD team at CNES, the objective of the trajectory reconstruction is to use all available input data about Hayabusa2 and MASCOT position and velocity to feed the algorithm used so far for the trajectory predictions and to see how it matches the actual observation, and especially the images taken by Hayabusa2 where MASCOT is visible.
The most deterministic part of the trajectory is MASCOT's ballistic descent toward Ryugu and this is thus the phase addressed at first by the reconstruction studies. This phase requires:

- the best available estimations of Hayabusa2 position and velocity at release epoch, coming from Hayabusa2-FD teams at JAXA (with associated uncertainty values),
- the actual separation manoeuvre, as reconstructed from MASCOT payload observations,
- the most accurate local shape model, spin axis orientation and gravity estimation for Ryugu.

Up to now, simulations were performed using the best available estimations of Hayabusa2 state vector at the time of the release delivered by JAXA very early after the operations. The result can be seen in Fig. 7. Whereas the green point (observed position) should be in the blue ellipse (simulated first contact points position), it is located outside of this dispersion area. This discrepancy can be due to many factors: Hayabusa2 state vector used for the simulations is still a preliminary determination and is currently being refined, the accurate local terrain model was not yet available at the time of the simulations and the used polyhedron shape model and its associated spin axis was probably too rough for a good estimation.

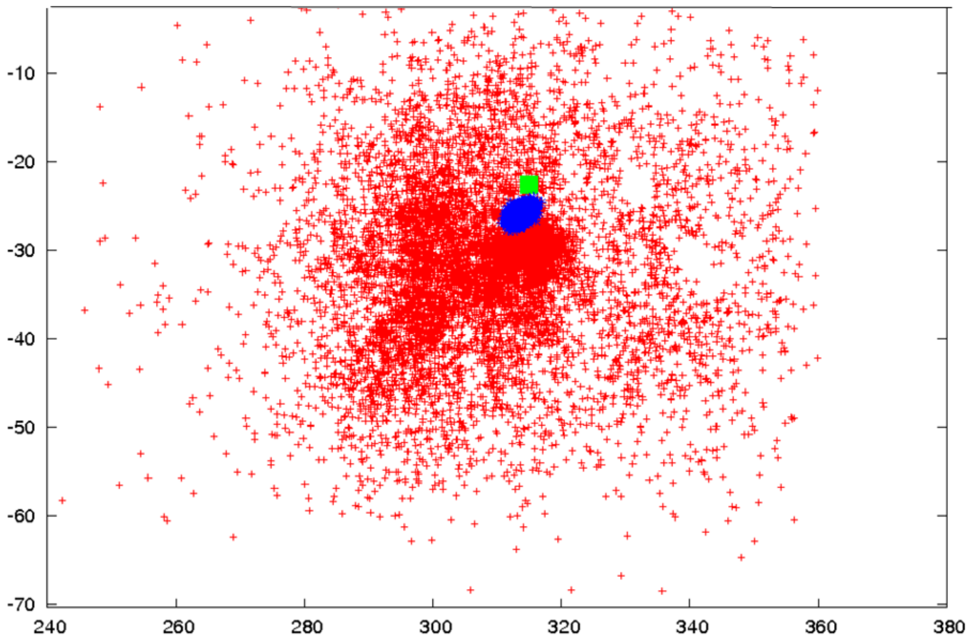

Fig. 7 Trajectories predictions based on the first assessment of Hayabusa2 position and velocity at MASCOT's release provided by JAXA. In blue: simulated locations of MASCOT's first contact with the surface. In red: simulated locations of MASCOT's first rest point (taking into account bounces). In green: actual position of the first contact point, voluntarily enlarged to be visible.

For the rest of the trajectory, the estimated positions of MASCOT at given dates as provided by the image processing and illustrated on Fig. 2 will then have to be used to fit a propagated trajectory. By this fitting, one can expect to be able to give indications of the mechanical properties of the asteroid's surface at each contact, helping scientific teams to consolidate their assumptions about the nature of Ryugu's surface.

Unfortunately, when this paper is being written, the processing of the data is only at its early beginning, and all input data are still not consolidated enough to provide reliable results. It will probably still take months to get good confidence on the most probable MASCOT trajectory as computed by flight dynamics propagation. An alternative way to obtain an initial position and velocity to begin the propagation would be to use the images of Mascot taken by Hayabusa2's ONC-W2 camera shortly after separation in order to estimate the position of the lander at those instants. Work is currently in progress on that subject.

MASCOT FD Team contribution to attitude reconstruction

In addition to the trajectory reconstruction, the reconstruction of MASCOT's attitude is also very important for the processing of science data. For a trajectory like the one followed by MASCOT, two kinds of attitude can be differentiated: the dynamical attitude, representing the tumbling of MASCOT during descent and bouncing, and the static attitude at MASCOT's rest positions. As a pre-requisite to FD studies, MASCOT's mission was divided into several sequences in agreement with the timeline shown on Fig. 1. The Table 1 presents a summary of such sharing with a column giving the status of FD work for each part.

Table 1 Description of the division in sequences for attitude reconstruction by MASCOT FD Team

Id	Start event	End event	Dynamic or Static	Status of processing by MASCOT FD Team (see next sections for details)
1	Release	At rest on SP1	Dynamic	Preliminary processing from Hayabusa2 On-Board Camera images processing
2	At rest on SP1	Start of uprighting	Static	Not processed yet
3	Start of uprigthing	At rest on MP1	Dynamic	Not processed yet
4	At rest on MP1	First relocation	Static	Not processed yet
5	First relocation	At rest on MP2	Dynamic	Not processed yet
6	At rest on MP2	Mini-move	Static	Processing of Photoelectric cells telemetry and MASCAM images (with possible unintentional slides detected)
7	At rest on MP3, after mini-move	2nd relocation	Static	Processing of Photoelectric cells telemetry and MASCAM images (with possible unintentional slides detected)
8	2nd relocation	At rest on MP4	Dynamic	Not processed yet
9	At rest on MP4	End of mission	Static	Not processed yet

Exploitation of Photo-Electric Cells (PEC) data

The role of the PEC is to provide measurements allowing the on-board software to determine which wall of MASCOT is facing the ground. All MASCOT faces are equipped with such cells and continuously recorded data during all MASCOT mission. The following subsections describe how these measurements can be used in the attitude determination.

Step 1: Determination of the Sun direction in the lander frame using the PEC voltages
For each point where three PECS are simultaneously illuminated, it is possible to determine a Sun direction in the lander frame using the voltages recorded by the PEC in the telemetry.
At first order, the voltage U produced by a photo electric cell is proportional to the cosine of the Sun ray incident angle i as described in Eqn 1. The maximal voltage U_0 is reached under normal incidence of the sun ray:

$$U = U_0 \cos i \qquad (1)$$

If at least three PEC are illuminated by the Sun at a given epoch, the dependency between PEC voltages and solar azimuth and elevation can be written as follows:

$$\begin{pmatrix} U_i \\ U_j \\ U_k \end{pmatrix} = \begin{pmatrix} U_{i,0}\cos(\alpha-\alpha_i)\cos(\delta) \\ U_{j,0}\cos(\alpha-\alpha_j)\cos(\delta) \\ U_{k,0}\cos\left(\frac{\pi}{2}-\delta\right) \end{pmatrix} \qquad (2)$$

Where:

- U_i, U_j are the voltages produced by to PEC located on two consecutive lateral walls (i.e. PEC with the outside normal along ±X and ±Y),
- U_k is the voltage produced by the PEC located on MASCOT face –Z or +Z,
- $U_{i,0}$, $U_{j,0}$, $U_{k,0}$ are the voltage produced by each PEC at normal incidence,
- (α, δ) are the Sun azimuth and elevation expressed in the lander frame,
- α_i is the azimuth normal of the PEC located on a lateral wall (0 for PEC along +X, 90 degrees for PEC along +Y, 180 degrees for PEC along –X, 270 degrees for the PEC along –Y.).

The Sun azimuth and elevation can thus be derived from Eqn 2 as follows:

$$\begin{cases} \alpha = \tan^{-1}\left(\cos\alpha_j - \frac{\widetilde{U_j}}{\widetilde{U_i}}\cos\alpha_i\,, \frac{\widetilde{U_j}}{\widetilde{U_i}}\sin\alpha_i - \sin\alpha_j\right) \\ \delta = \tan^{-1}\left(\frac{\widetilde{U_k}}{\widetilde{U_i}}\cos(\alpha - \alpha_i)\right) \end{cases} \tag{3}$$

With $\widetilde{U}_i = \frac{U_i}{U_{i,0}}$, $\widetilde{U}_j = \frac{U_j}{U_{j,0}}$ and $\widetilde{U}_k = \frac{U_k}{U_{k,0}}$.

On top of this theoretical first approach, the estimation can be improved by taking into account corrections in the measured voltages in order to better represent the physical reality of the measurements: temperature dependency, calibration factors, losses in reflection and transmission, local masking by the lander structure…. Once these corrections have been applied, one obtains an equation system that cannot be analytically solved. A non-linear least square approach is then used to obtain the Sun direction. The initialisation of this algorithm uses the results of evaluation of Eqn 3.
At the end of this step, one has a set of Sun directions in the lander frame for a given number of discrete epochs.

Step 2: Attitude determination
For each point processed at step 1, one can determine a prediction of the Sun direction in the Asteroid's Centred Asteroid Fixed Frame (ACAF) for the same epoch based on the asteroid ephemerides and rotational state.
A least square approach tailored to the estimation of quaternions, known as q-method and described in Ref.3 is then used: the principle is to adjust the quaternion describing the transition between the lander frame and the ACAF in order to decrease the discrepancies between the Sun angles measurements determined in step 1 and the Sun angles predictions.
The quality of the attitude determination can be assessed by computing the measurements residuals for the Sun direction, that is to say the difference between the Sun direction in lander frame deduced from PEC voltages and the Sun direction computed from the theoretical predictions in ACAF converted into lander frame using the estimated quaternion.

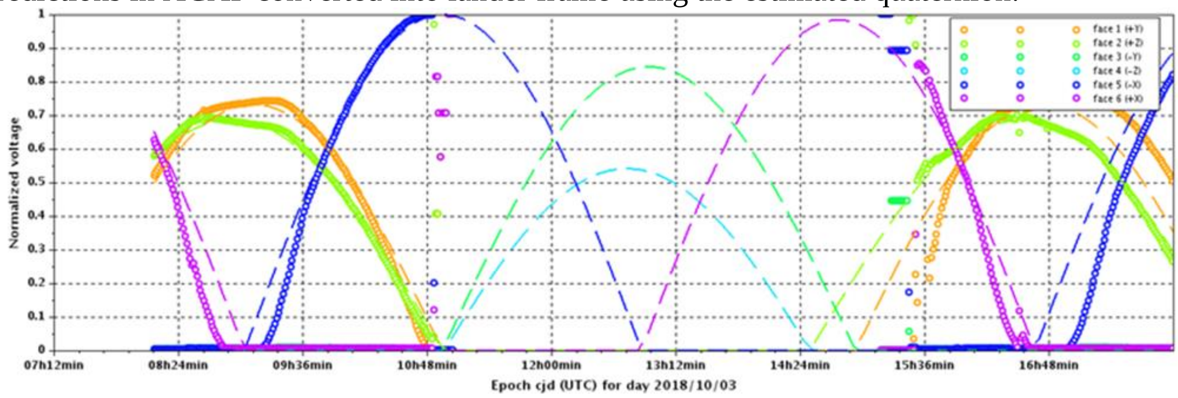

Fig. 8 Comparison between the PEC observed voltages (colour circles) and the predicted voltages (dashed lines) based on the attitude determination. The absence of observed voltages is due to asteroid night.

Preliminary results
This methodology was applied for 2 static phases of the second asteroid day spent by MASCOT at Ryugu's surface, where there were enough points with at least 3 simultaneous PEC measures available. Fig. 8 shows the comparison between the observed PEC measurements and a reconstruction of the same measurements based on the reconstructed attitude obtained for one of the static phases of the mission. The obtained results are promising, but the residuals between

determined and observed Sun direction still show some signals tending to prove that some physical corrections are not yet fully understood. This is an ongoing process that will be extended to more phases of MASCOT's mission.

Exploitation of MASCAM images

In parallel to the reconstruction of attitude based on telemetry from PEC, the CNES robotics team is also exploring a way to estimate the attitude changes of MASCOT using the images taken by MASCAM once the lander was lying on the surface on its –Z face (periods 6 and 7 of Table 1). This reconstruction takes advantage of the slightly different points of view due to the small movements of MASCOT (the "mini-move" and some even smaller "slides") to compute the relative changes in attitude produced by these movements. By identifying salient features on the ground and matching them between successive images, the changes in the orientation of the camera (and thus that of MASCOT to which it is solidly fixed) can be estimated, as well as the direction of motion.
Unfortunately, the big differences in lighting conditions between images prevented automatic matching from working, so salient points were matched by hand and were therefore sparse, leading to larger uncertainties. However, the first reconstruction using this methodology gave results consistent with the outcomes of PEC data processing.

Future developments

In addition to the continuation of static attitude reconstruction as described in the previous sections, the dynamic attitude reconstruction will also be addressed.
For the attitude during descent, the idea is to obtain an accurate attitude for MASCOT in-flight for at least two different epochs, in order to have an estimation of MASCOT's rotation axis and velocity. The three pictures taken by Hayabusa2 On-Board Camera (ONC) showing MASCOT tumbling shortly after separation can be used to estimate the attitude at those instants. The processing of the magnetic field measured by MASMAG and compared to the solar wind magnetic component can also help in this estimation.
Under the assumption that no torque is induced on MASCOT during the descent, one can then propagate MASCOT attitude with the help of the Euler equations until reaching the contact with the ground. The obtained attitude ephemeris can then be cross-checked by simulating the MASCAM pictures taken all along the descent, in order to confirm that the captured scenes are consistent with the observed ones.

An example of the possibilities offered by such a cross validation is shown on

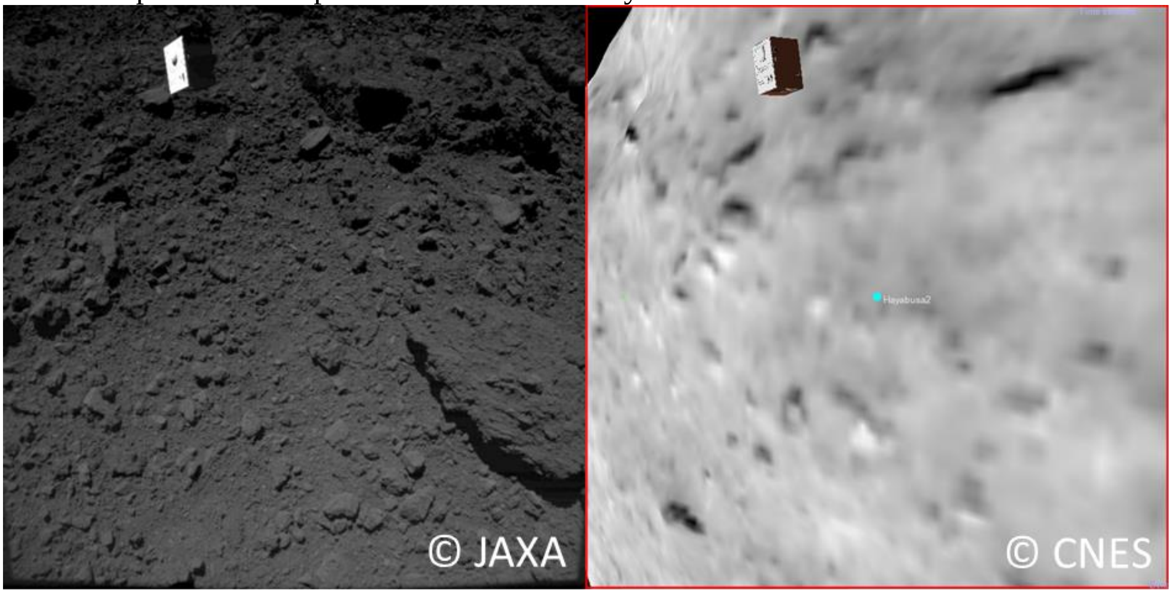

Fig. 9, based on very preliminary results, clearly inaccurate. It has to be noted that the distortions corrections are not applied to ONC image on this illustration.

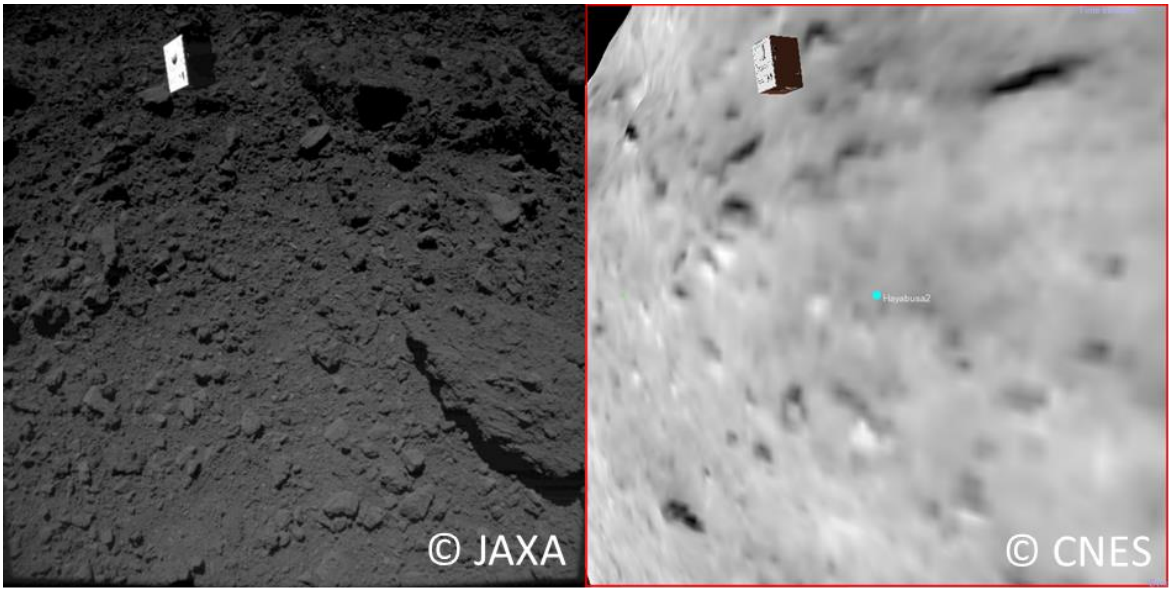

Fig. 9 Illustration of the comparison between Hayabusa2 ONC image where MASCOT appears (on the left) and simulation using very preliminary determination of MASCOT position and attitude just after release (on the right)

For the attitude during bounces, the same process can theoretically be applied but the difficulty will be to have enough data in each arc to determine 2 attitudes, or 1 attitude and an associated rotational state.

Conclusion

Only a few weeks after the execution of MASCOT's operations, the reconstruction of MASCOT's trajectory and attitude is still at its early beginning. This joint effort of all science and engineering teams involved in Hayabusa2 and MASCOT missions requires to rigorously and systematically process all available data and a special attention has to be paid to the coordination between teams. That is why an international working group has been created. So far, the contribution of MASCOT Flight Dynamics Team at CNES focused mainly on the determination of MASCOT descent trajectory and static attitudes. The preliminary results that have been obtained are quite promising, but still need consolidation.

Acknowledgements

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