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MASCOT operations on Ryugu – focus on some specific tasks

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Abstract

Hayabusa2 is an asteroid sample return mission operated by the Japanese space agency, JAXA. It was launched in December 2014. In July 2018, the spacecraft has reached the mission target after a 4-year-long cruise. The objective is a C-type primordial asteroid called Ryugu, in search of organic and hydrated minerals that might give essential clues for the solar system formation.
The small lander MASCOT (Mobile Asteroid surface SCOuT) carried aboard Hayabusa2 landed on the surface on the 3rd of October 2018 for preliminary in-situ investigations while the probe is aiming to study Ryugu on a global scale and to return samples to Earth.
MASCOT was jointly developed by the German Aerospace Centre (DLR) and the Centre National d'Etudes Spatiales (CNES). It is equipped with a sensor suite consisting of four fully-fledged instruments. DLR was responsible for developing the MASCOT lander and ground segment, and was in charge of planning and conducting lander joint operations from MUSC. CNES supplied the hyperspectral IR spectrometer (MicrOmega, IAS Paris), antennae and power system, provided a support to operations and was in charge of the flight dynamics aspects of the mission.
The 17 hours of on-asteroid operations exceeded expectations and the overall landing and operations were a huge success. Indeed, the characteristics of the Ryugu asteroid such as the shape and the gravity were known only after arrival of Hayabusa2 in July 2018 and the operating ccontext was very constrained but did not provide from fulfilling the objectives.
This paper is a complement to the overall paper on MASCOT landing and first results. It will focus on several operational tasks such as communication and power subsystems assessments as well as flight dynamics computations needed in real time and for postprocessing.

Keywords: Asteroid, Lander, Mascot, Hayabusa2, Operation

Acronyms/Abbreviations

Astronomical Units (AU)
Centre National d'Etudes Spatiales (CNES)
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Guidance Navigation Control (GNC)
Hayabusa2 or HY2 (Hayabusa2)
HouseKeeping telemetry (HK)
MASCOT Autonomy Manager (MAM)
MASCOT CAMera (MasCam)
MASCOT Radiometer (MARA)
MASCOT MAGnetometer (MasMag)
Measurement Point (MP)
Mechanical and Electrical Support Structure (MESS)
Mobile Asteroid surface SCOuT (MASCOT)
On-board Computer (OBC)
Power Conditioning and Distribution Unit (PCDU)
Release Epoch Range (RER)
Separation, Descent and Landing phase (SDL)
Settlement Point (SP)

Telemetry (TM)
TouchDown (TD)

1. Introduction: Hayabusa2 mission and MASCOT Lander

Hayabusa2 carrying the MASCOT lander is an ambitious asteroid exploration mission. For the first time an asteroid is observed and mapped remotely, its surface analysed (remotely and in-situ) and surface's samples retrieved (Fig.1).

The objective of the Hayabusa2 (Fig.2) sample return mission was to visit and explore a C-type primitive asteroid of about 900 m in diameter.

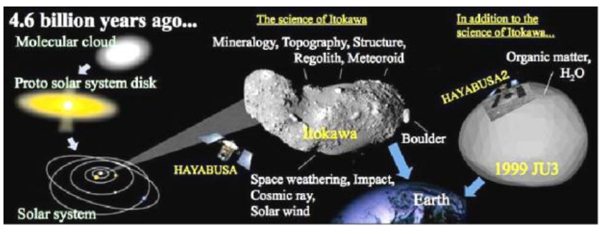

Fig.1. Schematic of the science of Hayabusa and Hayabusa-2 missions (image credit: JAXA)

The mission is designed to study the asteroid from multiple angles, using remote-sensing instruments, a lander (MASCOT) and 3 rovers (MINERVA-II-1A/1B/2). It has already collected surface and possibly subsurface materials from the asteroid and will return the samples to Earth late 2020 for in-depth analysis.

MASCOT is an agile, lightweight, mobile science platform that has been developed by the German Aerospace Centre (DLR) in collaboration with Centre national d'etudes spatiales (CNES). This lander was launched on December 3rd, 2014, aboard the Japanese Hayabusa2 sample-return mission towards the near-Earth asteroid Ryugu.

Hayabusa2 has reached the asteroid vicinity during summer of 2018 and will leave Ryugu late 2019. As a scout the MASCOT lander was released on Ryugu to perform in-situ exploration on the 3rd of October 2018 before any touchdown of Hayabusa2 [3][11].

2. MASCOT Lander description

MASCOT has been developed by the German Aerospace Center (DLR) in cooperation with the Centre National d'Etudes Spatiales (CNES) as well as the TU Braunschweig and the Universite de Paris Sud-Orsay, The main objective of MASCOT is to perform in-situ investigations of the asteroid surface and to support the sampling site selection for the mother spacecraft.

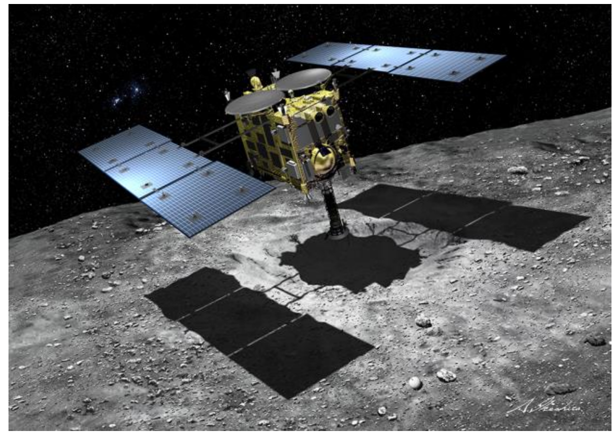

Fig.2. Hayabusa-2 spacecraft during its touch down on Ryugu asteroid for sample collection (artist's view).

MASCOT is a 9,8 kg lander with a 3 kg payload, of 0.28 x 0.29 x 0.21 m3 volume and a single energy source (of 220 Wh) dimensioned to cover 2 asteroid days and allow the Lander to relocate once. [4]

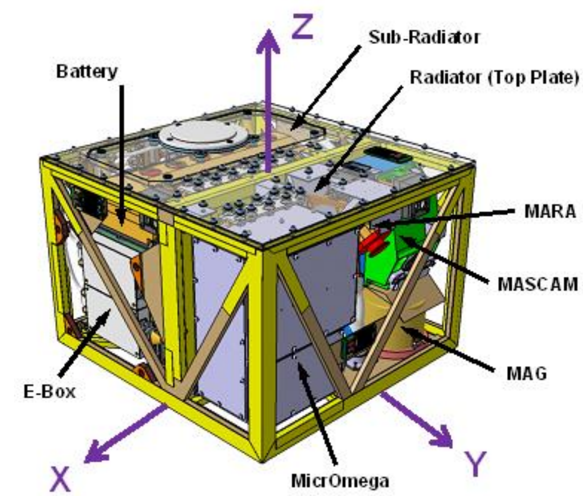

Fig.3. Schematic of MASCOT Lander.

Asteroid surface science is obtained by four experiments: MicrOmega, a near-IR hyperspectral microscope provided by IAS[6], MASCAM, a wide-angle Si CMOS camera with multicolor LED illumination unit [7]; MARA, a multichannel thermal infrared radiometer [8]; MASMAG, a magnetometer provided by the Technical University of Braunschweig [9].

The MASCOT lander includes an internal mobility mechanism, a GNC sensor package and on-board autonomy software that enable MASCOT to self-right itself and to perform relocation leaps on the asteroid surface. A redundant on-board computer (OBC) provides autonomous control, command and data handling, and pre-processing power. Power is supplied by primary battery via a redundant power subsystem (PCDU).

During cruise and commissioning, the power is supplied by Hayabusa-2 via a regulated power line and during the on-asteroid phase the power and energy supply is maintained by a primary battery.

3. MASCOT Operation organisation

MASCOT operational team is an integrated team with members from DLR and CNES.

For critical operation such as landing the operational team members and the scientists involved in MASCOT were collocated in the MASCOT control center located at DLR (Cologne). MASCOT flight dynamics team worked from Toulouse CNES center and a representative was located in Cologne to ensure proper communication between the two centers.

A member of MASCOT team was also located in the Hayabusa2 control center in JAXA-ISAS (Sagamihara).

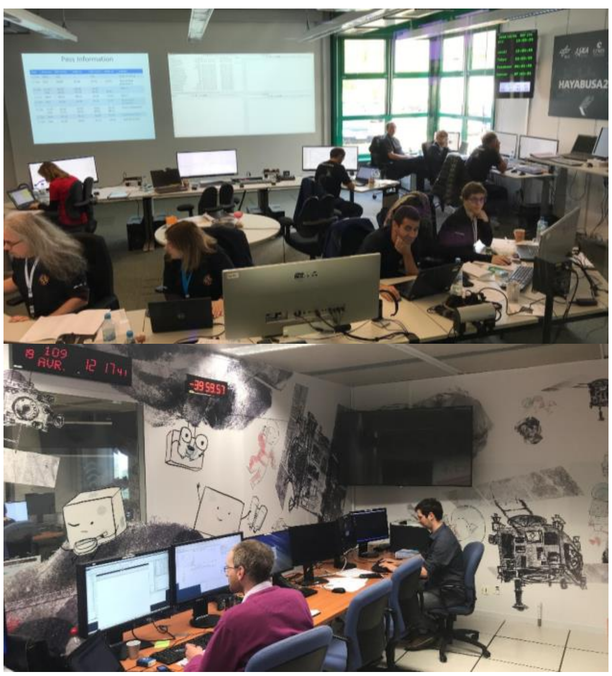

Fig.4. View of MASCOT Control Center in DLR Cologne (up) and Comet and Asteroid French Expertise Team in CNES Toulouse.

4. Operation preparation

4.1 Subsystems preparation

During the on-asteroid mission, Hayabusa2 is hovering above the surface, with its solar panels oriented towards the Sun, while Ryugu is rotating underneath the spacecraft. This implied that MASCOT measurements were the only possibility to observe the asteroid's surface during night time. However, this also implied that MASCOT had no contact during night time operations.

Because of the long signal travel times (16 minutes one way) and the limited lifetime of the MASCOT primary battery, ground loops were not part of the MASCOT nominal operation strategy.

The science sequences for each instrument were planned, prepared and intensively tested on ground. All sequences had to be prepared beforehand, as ground interactions with MASCOT were limited. The planning focused on robustness with the aim to maximize the science return during the limited lifetime of MASCOT.

The measurements were timed for an optimal usage of the link budget from MASCOT to the Hayabusa2 spacecraft, so that all MASCOT data were stored on-board the HY2 spacecraft before the Lander's end of life. Due to the mission design it was impossible to locate precisely MASCOT settlement point and thus predict the day/time duration and RF links. The number of attempts necessary to self-right correctly the Lander was also unknown.

Consequently, the operational sequence had to be managed autonomously on-board. The MASCOT Autonomy Manager (MAM) triggered different MASCOT operations upon detected events, such as:

- Separation from HY-2 spacecraft
- Descent
- Coming to rest on the surface
- Day/Night transition

Based on such events, the MAM executed:

- Self-righting maneuver
- Relocation maneuver
- Surface science activities
- End-of-life activities

Each of the instruments took benefit from the calibration activities during the cruise phase by improving their procedures in terms of better robustness, less power consumption and optimized data volume.

Several de-passivation operations were performed on the battery in order to provide the best functioning conditions to the Lander. Indeed, it was impossible to know the state of charge of MASCOT battery and the on-surface temperature of the Lander so the battery had to be performing as soon as possible.

On the other hand, several antennae calibrations in anechoic chamber and helicopter tests for long range communication were performed to assess the link budget between hayabusa2 and MASCOT which was a critical parameter for MASCOT success.

4.2 Landing Site Selection and mission analysis

MASCOT had to land onto Ryugu's surface after a ballistic descent from an altitude of a few tens of meters. In the frame of the collaboration between the German Aerospace Centre (DLR) and the French Space

Agency, CNES was responsible for the activities related to MASCOT landing trajectory prediction and optimization [10]. 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 engineering aspects (thermal, communications) as well as by scientific interest.

MASCOT was expected to bounce on the asteroid surface causing the lander to possibly stop far (up to ~100 m) from its first touchdown point. So modelling the rebounds was a key activity for the prediction of the final rest position.

MASCOT landing site selection was performed in parallel and in agreement with Hayabusa2 landing sites selection. A major constraint for the release of MASCOT was to avoid the areas selected by JAXA for the sampling touchdowns of Hayabusa2, in order not to disturb its descent process (by confusing the sensors guiding the spacecraft to the target markers). This constraint required a close interaction with JAXA during summer 2018 in order to select landing and sampling sites in a consistent way.

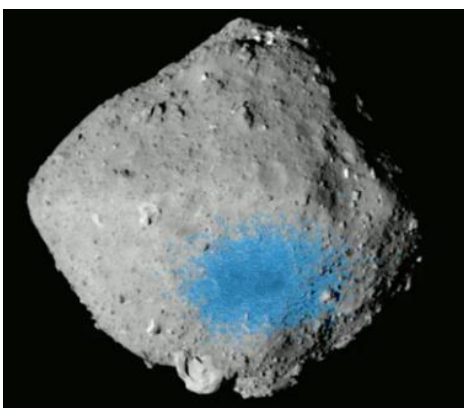

Fig.5. Landing ellipse (blue dots) assessed by MASCOT fight dynamics team for MASCOT Landing Site.

The following steps were followed for landing site analyses:

1- Before the arrival in asteroid's vicinity, a grid in release time and release position was defined.
2- Once the first products of Ryugu's observation were available, dispersion spots of the possible final positions were computed for each point of the grid defined in step 1.
3- Release positions and times which do not fulfill the constraints were discarded.
4- The remaining candidates were analyzed in detail and results presented for pre-selection of the best candidates from engineering and scientific interest point of view.
5- Updated models derived from the latest Ryugu observation by Hayabusa2 were used to refine the knowledge of the best candidates selected at step 4.
6- The best 2 candidates were selected based on updated analyses, prioritized and presented for review to the Hayabusa-2 team together with associated release position and times.

In a joint discussion with the H2 team, Hayabusa2 TD1 and MASCOT nominal and backup sites were determined simultaneously 1 month before MASCOT operations [13]. After a rehearsal operation by H2, the final site MA-9 (Alice's Wonderland) was confirmed.

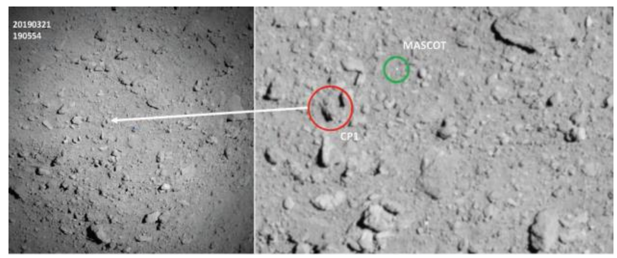

Fig.6. MASCOT landing site (Alice's Wonderland) observed from Hayabusa2

The deployment concept of MASCOT with its bouncing profile led to a spread-out landing area (Fig. 5). So the flight dynamics team had to confirm in real-time operations the predictions once the exact parameters of the release were confirmed by JAXA.

4.3 Operation sequence prepared

MASCOT on-asteroid operations after the lander has reached its first settlement point (SP1) are divided into night and day phases in which the instruments will be operated in different configurations. Once MASCOT is stabilized on the surface the mobility system is then actuated to self-right MASCOT to its nominal surface orientation (MP1).

Once the investigation of the first site has finished a relocation had to be performed to the next spot (SP2) to continue its scientific investigation of Ryugu's surface.

MasMag and MARA instruments were expected to be permanently switched on and taking measurements. MASCAM and MicrOmega activities followed pre-defined sequences scheduled by the MAM on specific events.

During daytime the camera had to take pictures of the surface. The day imaging sequence included a photometry sequence. The images acquisition was commanded at different Sun angles over the course of a day to characterize time-dependent processes and photometric properties of the regolith.

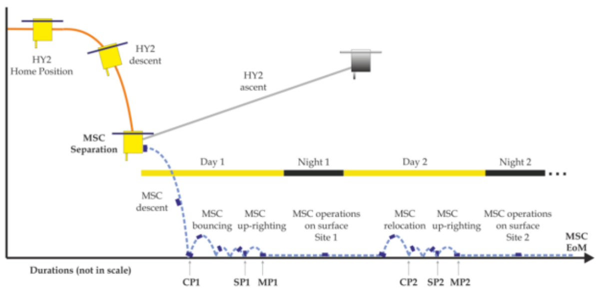

Fig.7. Schematic of MASCOT and Hayabusa2 relative positions during the expected on-asteroid sequence.

During the night, illumination of the dark surface by means of a 4-band LED illumination device allowed color imaging to identify minerals, organics, and, possibly, ices. The spectrometer MicrOmega was in charge of surface mineralogical investigations during day and nighttime by taking spectra in the near infrared wavelength range focusing on the composition at grain size.

Following Sunrise of the second asteroid day, a link between Hayabusa2 and MASCOT was expected and devoted to night collected data. Then a small movement (a few centimeters) called “mini move” had to be scheduled to expose MicrOmega to a different target and get a setereo perspective of the landing site with the camera. After finishing the MicrOmega and CAM activities the data had to be again uploaded and MASCOT had to use the mobility mechanism for the first relocation to another site on the asteroid. After a second potential bouncing phase to the second measurement point (MP2) the surface science phase of this second site had to start (see Figure 7).

5. Performed Operation

5.1 Cruise phase

Between the Hayabusa2 launch in December 2014 and the approach to asteroid Ryugu, MASCOT has performed a large number of in-flight operations. The main objectives of these operation activities were health status checks of the MASCOT bus and instrument in-flight calibrations [1]. The MASCOT health checks have been performed for an analysis of the functionality of the lander instruments and subsystems. The calibration of the instruments focused on the monitoring of the instrument performance. Additional objectives were to test HY-2 and MASCOT interaction as well as preparation tests for the on-asteroid phase.

For this purpose, the integrated team and its sub-systems experts gathered twice a year for these cruise operations.

Once HY2 reaches Ryugu, the cruise phase is concluded and the asteroid mapping and monitoring phase begins. During this phase, the spacecraft maintains altitude at 20km, sends images and other data, which is used – among others - for selecting a landing site for MASCOT.

5.2 Pre-separation, Separation and Landing

MASCOT on-asteroid operation at the asteroid started several hours before separation. MASCOT is switched on while the Hayabusa2 spacecraft is still hovering at its home position 20 km above Ryugu’s surface. Last activities and checks were performed before the spacecraft will enter its descent phase towards the release altitude of MASCOT (Figure 8).

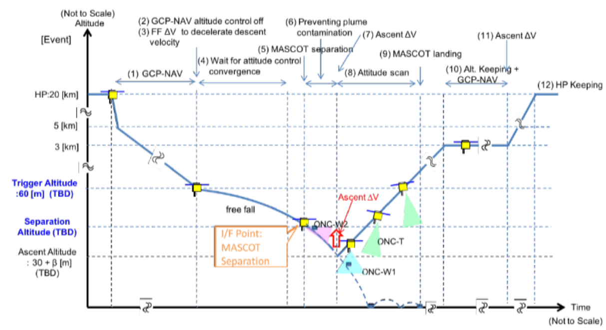

Fig.8. MASCOT deployment.

HY-2 spacecraft slowly initiated its descent from its home position (20km above the asteroid’s surface) towards the release altitude and MASCOT was separated at 51 m [2].

The lander free fall towards the asteroid ended when MASCOT touched the surface at the first contact point (CP1) and bounced over the Ryugu surface till it comes to rest. After MASCOT release, HY-2 spacecraft ascended to an altitude of 3 km and hovered at this altitude during MASCOT operations to ensure communications.

MASCOT performed scientific measurements throughout all operational phases starting with the descent immediately following separation from the main spacecraft. MasMag and MARA were switched-on before separation, and CAM operated during descent, taking pictures during MASCOT approach to Ryugu’s surface. MicrOmega started its operations after MASCOT has reached the asteroid surface.

5.3 On-asteroid sequence

Hayabusa2 released MASCOT at 01:57:20 UTC on the 3rd of October 2018 at 51m above Ryugu’s surface.

The descent in freefall lasted less than 6 minutes and MASCOT first contact point (CP1) with Ryugu was exactly where it was expected in the mission analysis.

This first contact was followed by a 15 minutes bouncing phase and MASMAG instrument detected up to 3 impacts. MASCOT finally settled down at the first settlement point (SP1) and assessed autonomously its orientation. The Guidance, Navigation and Control (GNC) sensors detected an undesired orientation of the lander, thus a self-righting manoeuvre has been executed to move the lander into the required orientation for scientific measurements at measurement point MP1. However, when MASCOT came to reset after the self-righting manoeuvre, it failed to determine the correct orientation and believed MASCOT would have the required orientation. This was likely the consequence of a wrong signal interpretation resulting from the dark surface. Following the predefined sequence MASCOT, assuming a correct attitude, started its first science cycle.

The first science data quickly retrieved and analysed in real time in the control center led to the conclusion that MASCOT was upside down and its instruments were facing the Sun. It was then urgent to take a decision so the project office composed of the project managers, the ops manager and the PIs had to debate.

During the first night on Ryugu it was decided to force MASCOT relocation regardless of the risk induced for the whole mission. The decision was taken within half an hour in order to provide enough time to the ops team to prepare, validate and upload the necessary commands thanks to Hayabusa2 support.

The measurement sequence was consequently interrupted at the end of first night on Ryugu immediately after the link was established with Hayabusa2. A first relocation was performed to correct the orientation and MASCOT jumped for about 70cm. Once it came to rest, its GNC detected the orientation correctly and the 2nd science measurement cycle was initiated at MP2. This second cycle covered the second day and second night on Ryugu.

From the separation and at each link established with MASCOT an assessment of the battery behaviour was performed. The objective was to evaluate the lander life time based on the primary battery cells models developed for Philae mission and updated for MASCOT cells. [5]

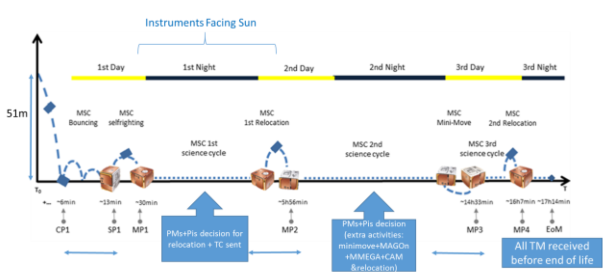

Fig.8. Schematic view of MASCOT performed on-asteroid sequence.

During the second night on Ryugu the battery behaviour was evaluated as promising as a third unexpected science cycle and extra activities have to be considered. A second project office meeting was then organised and decided to perform the first mini-move of a few cm dedicated to stereo measurements at MP3.

Time (UTC)	Event
01:57	MASCOT released from HY2 (velocity ~4cm/sec.; altitude 51m) then free-fall
02:03	First impact of MSC with Ryugu (**CP1**) followed by a bouncing phase.
02:18	MSC reached its first settlement point (**SP1**)
02:34	Upright performed & 1st measurement point (MP1) reached. Start of 1st science cycle.
03:13	End of 1st day and start of 1st night on Ryugu.
07:18	TC sent to MSC to interrupt its science measurement and force the relocation
07:51	End of 1st night and start of 2nd day on Ryugu.
08:27	MSC relocated and reached its 2nd measurement point (**MP2**). GNC sensors confirmed the correct orientation and 2nd science cycle started.
10:50	End of 2nd day and start of 2nd night on Ryugu.
15:27	End of 2nd night and start of 3rd day on Ryugu.
16:30	MSC made a mini-move (to **MP3**) and initiated its 3rd science cycle
18:05	2nd relocation performed and 4th measurement point (**MP4**) reached: science sequence
18:29	End of 3rd day and start of 3rd night on Ryugu.
19:04	End of mission: reception of last MSC HK packets (final link break by horizon occultation)

Table 1. Main events in MASCOT ops sequence.

A second MASCOT relocation was also commanded to reach its fourth and last measurement point (MP4) at an additional distance of 10cm. However, at this time the "best" anticipated operational lifetime of 16 hours was already exceeded. The remaining energy just allowed MASCOT to enter a predefined "end of life" status with priority on data transmission and only minimal scientific operations.

Battery depletion happened during the third night on Ryugu and after 17hours and 14 minutes of operation and after all MASCOT telemetry was safely uploaded to Hayabusa2.

The long-lasting on-asteroid operation allowed each MASCOT instrument to measure several times:

- MARA was ON continuously [15]
- MASMAG was ON continuously till second night and on again during third science cycle
- MASCAM was ON 19 times and produced 120 images during descent, bouncing phase and science cycles (day and night)[14]
- MicroMEGA was ON 7 times and performed 4 of these measurements when facing the surface

MASCOT team is now post-processing all data in order to rebuild the trajectory and attitude of MASCOT and MASCOT science team is analysing the measurements. MMEGA data might be the more difficult to be analysed as the instrument was not able to be in close contact with the surface due to the inhospitable surface.

5.4 Focus on communications subsystem during operation

During SDL phase the RF link was continuous with a telemetry bit rate constantly higher than 0 and no link interruption detected. It means that the autonomous onboard protocol worked perfectly even during the rebound phase.

During the night the transceivers remained active as the initiative of the link came from Hayabusa-2. The autonomous protocol behaved as expected, switching periodically the antennae and the transceivers. The night 1 lasted ~5 hours. The Sunrise for day 2 was expected at 07:50:23 UTC and the first indication of active RF link is seen in the telemetry at 07:49:28 UTC. The fact that link is established at Sunrise is a good indicator of an open field around the lander with no mask related to presence of high rocks. The self-right attempt was commanded at the beginning of the day and is visible in the antenna switchover, from bottom to top.

The day 2 was nominal for the RF link and no link interruption was noticed until the end of the day.

The mini-move had no impact on the RF link while the relocation led to an antenna switchover (from top to bottom) indicating that MASCOT attitude has changed and that bottom antenna was a better choice for maximizing the link capacity and downloading the last scientific data.

The end of day 3, corresponding also to the end of the MASCOT mission, occurred with the loss of RF link at 19:03:52 UTC. The Sunset was expected at 18:29:41 UTC meaning that MASCOT transmitted its last data while being in the night.

The real end of MASCOT occurred at an unknown time after the loss of the RF link, during the night 3.

6. Conclusions

The Hayabusa2 mission is about to leave asteroid Ryugu after a series of historical successes. Despite a surprisingly difficult surface, the mission objectives were reached or surpassed. Thanks to the improved navigation accuracy of Hayabusa2, touchdowns were huge success and MASCOT was also able to fulfill his scout role for the mother ship and last longer than expected on Ryugu. MASCOT operations were, as usual on exploration missions, full of surprise and the operational team has to demonstrate its reactivity. The operational sequence had to face the rough surface of Ryugu and the reactivity of the team was confirmed. The lander itself worked very well and the instruments were able to be activated more than expected. Following this huge success, the team is now eager to see the next step of the mission with the sample return and curation phase on Earth.

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