MASCOT: Communications with a small probe on Ryugu asteroid

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ABSTRACT

On October 3rd, 2018 and after a 4-year travel into space attached to the Japanese probe Hayabusa-2, the German French probe MASCOT, the size of a big shoebox, landed on the asteroid Ryugu. The objective was to study in-situ the structure of the asteroid. The article focuses on the communication subsystem of the mission providing a radiofrequency link between Hayabusa-2 and MASCOT. This subsystem, including the transceivers, the harness, the antennae and the onboard intelligence has been at the heart of a multinational team to provide the best conditions for MASCOT data to be transmitted. The first part of the article details the overall communication system architecture and validation before landing, including some validation operations during cruise. A second part presents the analysis of the communication system telemetry during the mission, from separation to the very end, giving an understanding of the mission events sequence.

INTRODUCTION TO HAYABUSA-2 AND MASCOT PROJECT

Hayabusa-2 (HY2) is the second step of an ambitious Japanese space program aiming at exploring asteroids. In 2003, Hayabusa, first of its name, visited the asteroid Itokawa and managed to bring back some dust to Earth in 2010.

On December 3rd, 2014, Hayabusa-2 took off for a 4-year travel to Ryugu asteroid for a new sample return mission. Ryugu is a C-type asteroid (formally 1999 JU3), a space body of about 920 m in length and of particular interest to scientists because, as a primitive body, it is a precious witness of the solar system's birth.

The Hayabusa-2 spacecraft is designed to study the asteroid from multiple angles. It will collect surface and possibly also subsurface materials from the asteroid and return the samples to Earth in a capsule for analysis in 2020 [1].

In July 2018, it reached the vicinity of the asteroid and started to collect technical and scientific data in prevision of the releases of 3 landers. Two were Japanese, the Minerva-1A and 1B and one was Franco-German, MASCOT.

MASCOT (Mobile Asteroid surface SCOuT) 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) [2][3][5].

TECHNOLOGIES AND SCIENCE IN A SHOE BOX

Payload and subsystems brief description

The MASCOT (MSC) lander has the size of a large shoebox (28 cm × 29 cm × 21 cm, Figure 1) and a mass of ~9.8 kg, approximately three times smaller than Philae body alone, a probe that landed on Churyumov-Gerasimenko comet in 2014 [6]. It carries four full-scale science instruments: MARA, a multichannel thermal infrared radiometer provided by DLR, MASCAM, a wide-angle Si CMOS camera with multicolour LED illumination unit also provided by DLR, MASMAG, a magnetometer provided by the

Technical University of Braunschweig and MicrOmega, a near-IR hyperspectral microscope provided by IAS.

Alongside these scientific instruments, MASCOT includes an internal mobility mechanism, a GNC sensor package and on-board autonomy software that enable MASCOT to upright 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 a single energy source of 220 Wh allowing about a 12 hours of mission duration via a redundant power subsystem (PCDU). The communications with MASCOT from Hayabusa-2 are ensured by two transceivers (also named CCOM) and two antennae. They are coupled to an onboard intelligent system capable of choosing the best hardware configuration for communication taking into account the MASCOT attitude off ground and on ground.

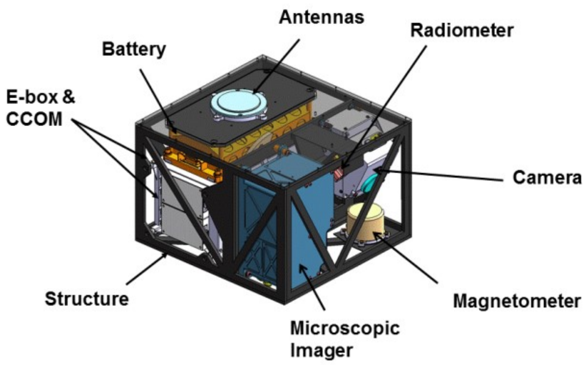

Figure 1: MASCOT Flight Model

Communication subsystems in details

Even if the communication system is not highlighted like the scientific payloads, it is at the heart of the mission success.

It has to be designed to answer the needs of communication during the cruise that lasts several years and during the mission with radically different conditions (distance, attitude).

Contrary to Philae, the umbilical physical link between Hayabusa-2 and MASCOT could not be used to setup communications during the cruise. The transmission had then to be done by radiofrequency. A dedicated system with one specific antenna (MESS antenna) on Hayabusa-2 allowed establishing the link when MASCOT was still attached. For the mission, another antenna was foreseen (OME-A), mounted on the face that will be facing the asteroid.

On MASCOT side, there was no attitude control integrated in prevision of the descent and the landing. But the need for communication implied that the radiofrequency link should not be interrupted at the separation from Hayabusa-2. The best idea to ensure a continuous communication regardless the probe attitude is to use omnidirectional antennae on opposite sides of the probe so that a 4π-steradian coverage is available. MASCOT has thus two patch antennae mounted, one on top and one at the bottom of the body.

Two transceivers, for redundancy, were mounted on Hayabusa-2 and MASCOT. They are linked to the antennae through couplers on MASCOT and through a switch on Hayabusa-2. On MASCOT side, a receiving sensitivity degradation has been monitored on one equipment during the AIT. A hierarchy has then been decided with a definition of a main and a redundant equipment. Priority was always given to the main transceiver.

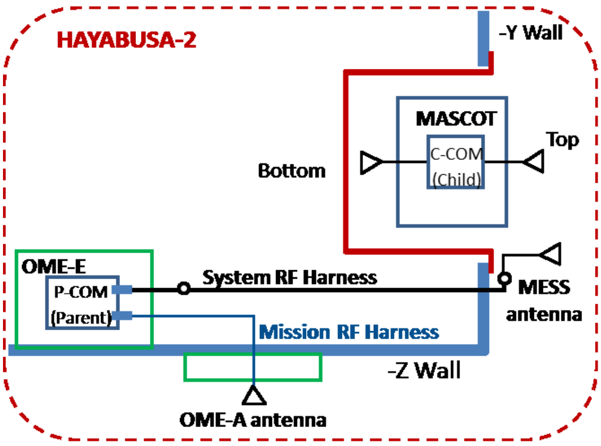

Figure 2: Global communication architecture

Both transceivers offer two RF power modes (low at -10 dBm and high at +30 dBm) to be used according to the situation, during cruise with a very short and constant distance between the two probes or during the mission with an increasing distance after separation. They used UHF frequencies and are compatible with two frequencies (954 and 958.5 MHz). The waveform for Command and Telemetry links is BPSK with convolutional encoding for Telemetry link.

The communication is based on half duplex link with Time Division Multiple Access (TDMA). Within a TDMA slot which lasts 27.648 ms, a slot (6.144 ms plus 1.216 ms of guard time) is attributed to commands transmission (HY2=>MSC) and another (17.408 ms plus 2.88 ms of guard time) for telemetry reception (MSC=>HY2). The data formatting allows for commands the transmission of 6 user data bytes + 6 control data bytes which gives a useful data rate over the TDMA slot of 6[byte]/27.648[msec] = 1.736[kbps]. For telemetry, the formatting allows 128 user data bytes + 8 control data bytes which gives a useful data rate over the TDMA slot of 128[byte]/27.648[msec] = 37.037[kbps]. These values reflect the theory but in reality the useful data amount to be transmitted varies and so the useful data rate. Typically, when only housekeeping telemetry needs to be sent the data rate is lower than when science data are transmitted.

The transceivers were provided by JAXA and are similar to the ones used in the Minerva landers. Thus, all the communications with the landers were ensured by the same equipment.

The overall architecture is given on Figure 2 and MASCOT communication system architecture on Figure 3.

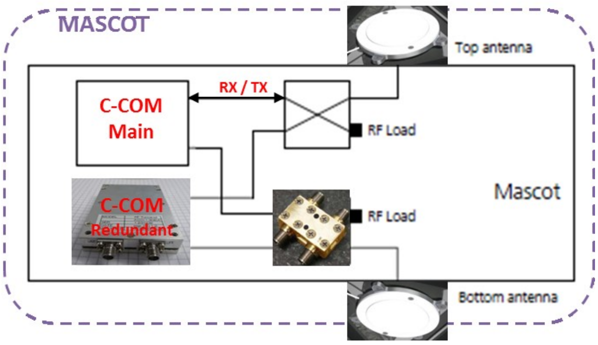

Figure 3: MASCOT communication system architecture

Communication subsystem management

With this designed system the communications were possible for several physical configurations but there is still a brick missing in that wall, how do you automatically command the transceivers and antennae switches in order to ensure a continuous link taking into account lander attitude and possible equipment anomalies or failure? The answer is onboard intelligent algorithm.

The connection-oriented communication protocol between the active MASCOT transceiver and HY2 ensures the delivery of CCSDS packets in both directions, by automatic retransmission in case of errors.

The protocol has been designed by DLR and Telespazio and has been tested multiple times with fine adjustments according to the observations obtained during the cruise tests. It uses many parameters values, available in the MASCOT housekeeping telemetry, data filtering, to smoothen the high variations and noise, and thresholds to take decisions. Most of the complexity lied in the adjustment of these thresholds. In order to add more complexity, the behavior of both MASCOT transceivers were not similar, in particular for the receiving sensitivity. The adjustments had to be custom for each transceiver.

The protocol was in charge of several vital functions for the mission:

- Receive CCSDS TC packets and forward them to the data handling software.
- Receive CCSDS TM packets from the data handling software and transmit them to the active transceiver for downlink to the orbiter.
- Periodically acquire the COM HK data and calculate the specified derived parameters.
- Monitor RF link availability and telemetry flow.
- Autonomously manage the RF power mode and the antenna selection.
- Autonomously manage the subsystem anomalies and transceiver redundancy.
- Implement high level procedures and commands to manage the subsystem.
- Manage the Umbilical interface, used during ground operations, ensuring no conflicts with the RF link channel.
- Estimate the TM bit rate and the TM packet rate transmitted through the active TM interface.

Different versions were tested directly during the cruise and a final and stable version was downloaded a few months before the landing. Analysis of the performances is given later in the paper.

COMMUNICATION LINK VALIDATION

The communication link between Hayabusa-2 and MASCOT was an international partnership. The transceivers and the HY2 antennae were provided by JAXA, the MSC antennae, the link budget computation and validation were CNES responsibility and the communication protocol and system validation DLR responsibility. All the activities involved a dozen engineers and managers.

This paper focuses on the activities engaged during the 2 years before the landing. At this time, only software adjustments were conceivable. The main task was the link budget validation and onboard protocol validation.

Link budget validation

The link budget validation was CNES responsibility but directly involved JAXA and DLR members for the HY2 and MSC parts. The link budget was obviously already computed at the moment of the probe launch in 2014 but some parameters needed to be better characterized in particular the antenna pattern of the mission antenna (OME-A) mounted on Hayabusa-2. It is single-strand helix with SMA connector.

If the antenna gain was already known of the antenna alone, the axial ratio has not been measured and the overall performance on structure neither. The antenna was surrounded by several appendices on the panel and some masks and interferences were expected after simulation analysis (see Figure 4).

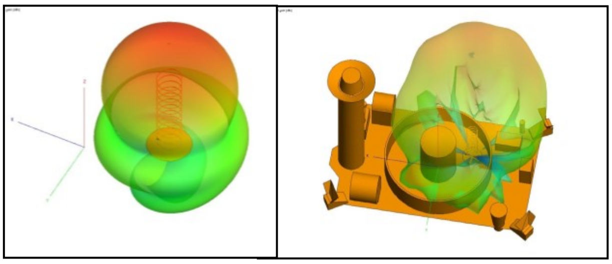

Figure 4: OME-A pattern simulations, standalone and on-structure

CNES launched an activity of on-structure antenna characterization in 2017 implying the availability of an OME-A spare antenna, of a scale-1 mock-up representative of the HY2 Z-panel where the OME-A was mounted and of the CNES anechoic chamber which has a reservation schedule of several months even years according to the tests duration.

The convergence of these three constraints has led to a week of tests at the end of January 2018.

The antenna was first measured alone to characterize the spare model and allow comparison with the on-structure measurements. It was then mounted on the metallic mockup with representative appendices. The overall structure measured 185 cm by 112.5 cm by 104 cm for a total weight of roughly 50kg. The antenna base was covered with MLI for a better representativeness (see Figure 5).

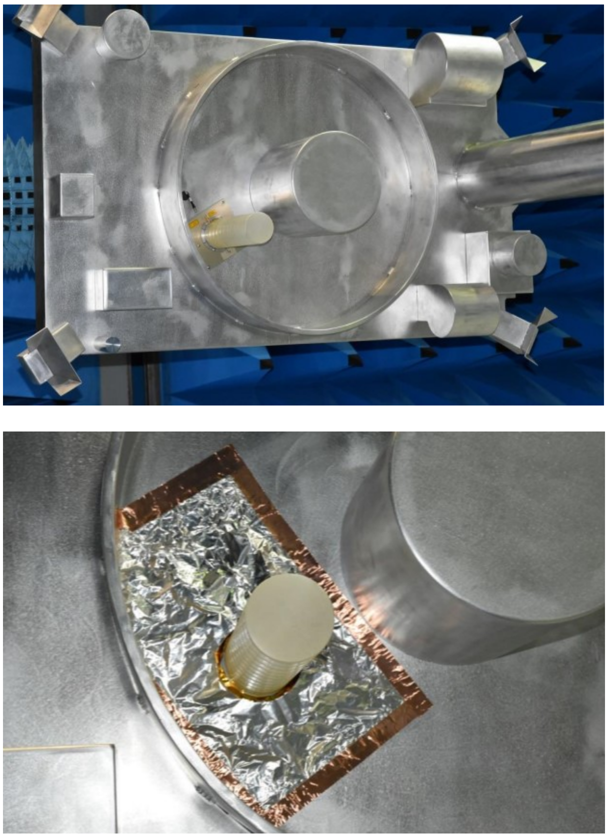

Figure 5: OME-A spare on Z-panel mockup

The measured radiation patterns were considered correct in both left hand ad right hand polarizations, despite the presence of numerous appendices around the antenna on mockup. The results enabled a more precise knowledge of the link budget between the orbiter and the lander, and thus a better analysis mission for the landing.

Communication protocol validation

As already indicated, the communication protocol has seen several versions during the cruise and a validation in real conditions was proposed by CNES in 2016 to confirm the final configuration. The test setup was more complex than the OME-A measurement. The idea was to emulate a complete bidirectional radiated link at distances and with MASCOT attitude (tumbling) foreseen for the mission.

Equipment for emulation of HY2 and MASCOT sides were needed. JAXA provided the same OME-A antenna than for the antenna pattern characterization and the HY2 emulator rack. DLR provided the spare of MASCOT with representative communication equipment and electrical architecture as long as monitoring equipment. CNES had the responsibility of setting up the tests and in particular finding the best way to emulate the variable distance foreseen during the mission.

In light of the total equipment mass and needed power emulating HY2 side (~100 kg) and the need of an operator to make it work, the only solution offering variable distances and flexibility was to use a helicopter.

The next step was to find the place where to make it fly. As the antennae will radiate RF power in the air during the tests, a coordination with the French regulation authority for electronic communications (ARCEP) and the French national agency for frequency regulation (ANFR) was requested. Indeed, the frequencies used for the intersatellite link are in terrestrial telecom bands and transmissions in these bands are regulated. An analysis of potential interferences for mobile customers was carried out and coupled to the selection of an area with helicopter provider, low density population, easy access by road and open field to limit multipath interferences. The optimization offered at least one solution, at the airdrome of Pamiers at less than 2 hours driving from CNES site in Toulouse. The tests were foreseen for a week during Winter 2018 (end of February).

The helicopter emulated Hayabusa-2 while the spare model of MASCOT was disposed on the tarmac of the airdrome. The OME-A was mounted at the bottom of the helicopter cabin (Figure 6) and the equipment rack was connected to the helicopter electrical system. The electrical needed power implied to have the engine started to switch on the equipment, the internal battery being insufficient, adding some complexity to the implementation.

Figure 6: OME-A antenna mounted at the bottom of helicopter cabin

An inertial central was installed in the helicopter with a GNSS receiver in order to precisely know the distance between MASCOT and the helicopter.

On the ground, MASCOT spare model was connected to the monitoring system which was apart to limit the interferences (Figure 7). As for the mission, the communication was at the initiative of HY2 side.

After verification of the overall setup and good health tests of the equipment, it appeared that the HY2 emulator was not able to provide the expected RF power which impacted the test plan and schedule.

Some calibration tests were performed at different altitudes starting from 50 m up to 3500 m. The same parameters than during the mission were monitored on both sides of the link and, in particular, the ones giving information on the link budget quality such as the received power indicator.

Both RF power modes were used during the tests in order to determine the limit of capacity of the low power mode and verify the protocol in both configurations.

Figure 7: MASCOT spare model and monitoring system during helicopter tests

Once communication link was established and validated at different altitudes, a phase test with MASCOT tumbling could started. At this moment, no tumbling dynamic was available for the descent and the foreseen rebounds on the ground of Ryugu. Some empiric tumbling was thus manually carried out (all the directions and for several rotation speed). The acquisition of signal, the useful data rate and the selected antenna parameters were closely monitored to verify the transition between the antennae and the continuity of communication.

The antennae switched followed with consistency the attitude applied to MASCOT. The useful data rate showed some decrease during the tumbling but went back to nominal after each stabilization. The decrease was not expected in particular during the mission and was attributed to some limitation of the test setup on HY2 side.

Some link interruptions were observed but, once again, it was attributed to the test setup after analysis of the parameters.

The overall telemetry analysis of these tests showed that the protocol behavior was nominal in the mission configurations and brought some confidence for the coming mission on the asteroid. These tests were the last planned activity susceptible to bring updates to the final onboard configuration which was set up during Summer 2018.

PREPARATION FOR SEPARATION

The MASCOT mission was planned for early October 2018. The operations planning before and after separation is described with more details in other publications [7][8].

This paragraph will focus on the communication subsystem preparation.

Communication subsystem configuration

The strategy for communication subsystem use during the operations was defined in the weeks before the separation.

One major topic was the RF power mode switchover from low to high after separation. This subject became more complex from the moment when the difference of receiving sensitivity between the transceivers was noticed. Indeed, at short distances, the low power mode is used to remain in the tolerated received power range of the transceivers. Exceeding the maximal value could be destructive for the amplifying technology in the receiving chain of the transceiver. This was, by the way, the most probable cause of sensitivity loss of one of the receivers. When the distance increases, a switch to high power mode allows pursuing the communication. If both receivers worked identically the question of the power mode transition would have been simpler as the impact would have been the same for both. But, with a receiver less sensitive than the other, the distance range where it can be usable for communications is different from one another. If full redundancy is required during the whole mission, there must be an intersection of both operational ranges. In other terms, the switchover to high power mode in order to cope with the less sensitive receiver must not endanger the nominal receiver.

In order to define a strategy, a flight dynamics simulation of MASCOT after separation was needed and provided by CNES Flight Dynamics team. It allowed simulating the link budget in favorable and worst cases in order to determine the distance and time ranges for the decision. Moreover, the strategy must cope with failure cases, data volume transmission optimization and the lifetime of MASCOT on batteries.

For Hayabusa-2 side, the strategy was to command the power mode switchover after the confirmation of separation has reached the Earth. Thus, the risk of blinding the MASCOT receivers in case of separation failure was avoided. For MASCOT side, the strategy was to automatically switch after a timeout because separation would be confirmed onboard by several measurements and the continuity of RF transmission was a priority. The timeout was decided taking into account the link budget analysis mentioned above.

The mission antenna (OME-A) on Hayabusa-2 was chosen to be used even before the separation. The link budget when still attached and just after separation was good enough to make that choice and thus avoid a switch command during the mission taking unnecessary risk of interrupting the link. On MASCOT side, the antenna choice was let to the decision of the autonomous protocol.

Hayabusa-2 manoeuver for MASCOT mission

The separation was planned on October 3rd, 2018 and implied a complex approach manoeuver for Hayabusa-2 with progressive descent with propulsion, descent in free fall, release of MASCOT, propulsion for ascent while maneuvering to scan the landing site and stabilization at an altitude of 3 km during the whole MASCOT mission (see Figure 8). The operations started several days before the separation date and several gates with Go/NoGo decisions were on the path. They were all successfully validated and the final go for separation was given around 1:00 AM UTC on October 3rd. At this moment, Hayabusa-2 still was descending toward Ryugu. The one-way travel time for sending commands from the Earth or receiving telemetry from Hayabusa-2 was 18 min so any commanded action needed roughly 40 min to be acknowledge in the control center.

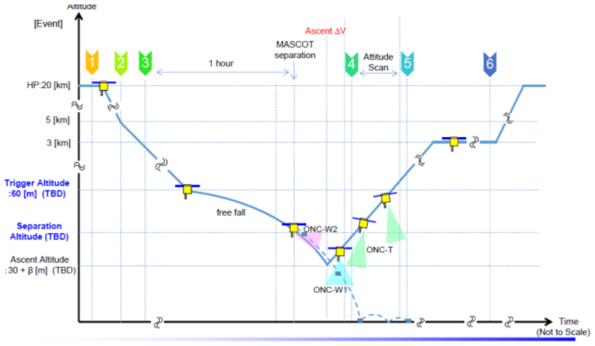

Figure 8: Hayabusa-2 manoeuvers around MASCOT separation

SEPARATION, DESCENT AND LANDING FROM THE COMMUNICATION SUBSYSTEM POINT OF VIEW

This paragraph will focus on the communication subsystem during the Separation, Descent and Landing (SDL) phase of the mission and the information that can be derived from its telemetry analysis.

It may be interesting to indicate that the only accessible communication subsystem telemetry for analysis by CNES and DLR during the operations was the one from MASCOT. It was recorded on MASCOT then transmitted to Hayabusa-2 for relay toward the Earth and routing up to the MASCOT Control Center. The equivalent telemetry generated in Hayabusa-2 for the communication subsystem was directly sent to JAXA and was not available. The analysis is thus made from only one side of the pipe which is more challenging.

Another challenge was the telemetry sampling frequency. Each subsystem and scientific payload provides housekeeping telemetry to be sent back to Earth with limited resources and prioritization. The highest the sampling frequency, the best for analysis but it does not cope with the resources constraints. A choice has to be made on the adequate sampling. For communication subsystem it was every 16 s. It means that phenomena with frequency higher than 1/32 Hz cannot be seen or are badly sampled. Typically, antennae switchovers can occur, at most, every 5 s so they do not all appear in the telemetry if the algorithm run at this speed.

From the MASCOT communication subsystem point of view, the main source of information to understand the different events from the separation to the stabilization on the ground is the Received Signal Strength Indicator (RSSI) which is, as the name suggests, directly related to the RF power received by MASCOT transceivers.

Separation

The separation command was run on Hayabusa-2 at 01:57:20 UTC when the probe was below 60 m from the asteroid surface and the confirmation was monitored in the telemetry of the GNC sensors (guidance, navigation and control) 22 s after.

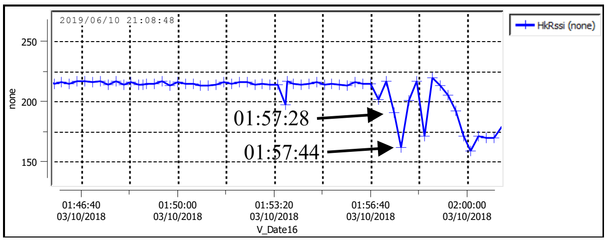

Figure 9: MASCOT RSSI at separation

The sudden RSSI variations shows the moment, in the limit of the frequency sampling incertitude, when the separation occurred, i.e. between 01:57:28 and 01:57:44 UTC.

Descent and first touchdown

After separation, the descent toward the asteroid was planned to last roughly 7 min before a first touchdown and multiple anticipated rebounds on the ground. During the descent, a tumbling of MASCOT was expected leading to variations in the RSSI values and possible antenna switchovers depending on the tumbling.

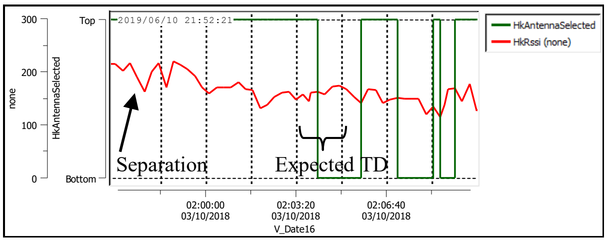

Figure 10: MASCOT RSSI after separation

RSSI variations are visible and also an average decrease which can be related to the increasing distance between HYA and MSC during that phase. There are no antenna switchovers until 02:04:08 UTC, being close to 7 min after separation, and then several after that time. No-switchover indicates that the separation was smooth and the tumbling slow before the first touchdown. An event must have started the antenna switchovers phase, certainly the first touchdown.

Rebounds and stabilization

A phase of rebounds was expected before stabilization on the ground. The uncertainty on the duration was very high because of the unknown ground nature and presence of boulders and their size. It was simulated between 3 and 104 min depending on several scenario configurations. A good indicator of the end of the rebound phase is the stabilization of the communication on one antenna which seems to happen around 02:10:32 UTC on Figure 11.

The RSSI during the rebound phase shows variations with reduced amplitude and a constant average value. It is delicate to find an interpretation of the variations due to the low sampling frequency.

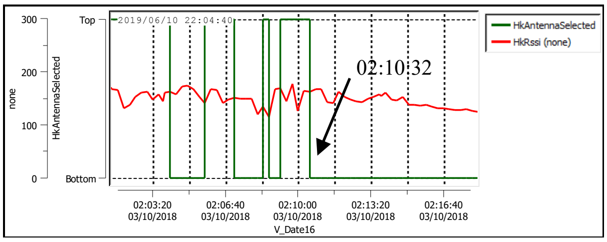

Figure 11: MASCOT RSSI after touchdown

The stabilization phase lasts several minutes after the antenna switchover as visible in the RSSI variations stabilization in Figure 12. After 02:15:04, the RSSI is uniformly decreasing meaning MASCOT is now at rest on the ground with bottom antenna used for link establishment revealing that MASCOT is certainly upside down.

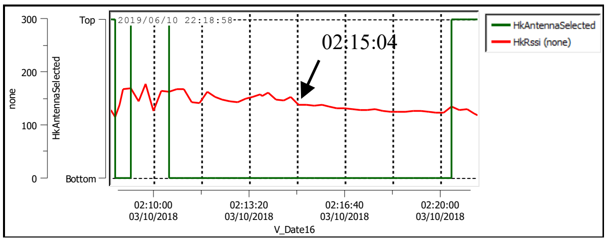

Figure 12: Final MASCOT stabilization on the ground

Upright

In operation preparation, it was anticipated that MASCOT could land upside down and a dedicated manoeuver was set to be automatically run after stabilization detection. It uses the upright mechanism called Mobility. The upright phase is visible in Figure 13, starting around 02:20:24 UTC and ending after 02:26:16 UTC.

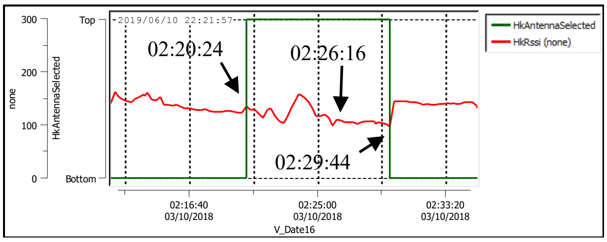

Figure 13: MASCOT upright

The top antenna is solicited for link establishment and RSSI shows high variations and then stabilization which was the expected behavior for that type of move. Unfortunately, the upright seems to make MASCOT landing upside down again. The RSSI associated to the top antenna is low and close to the threshold triggering the antenna switchover which happens at 02:29:44 UTC. The following RSSI increase indicate that the bottom antenna is the best solution for link establishment and that MASCOT is definitely upside down again.

The automatic science sequence was already running onboard at that moment and first results collected, pictures mainly.

RF power mode switch

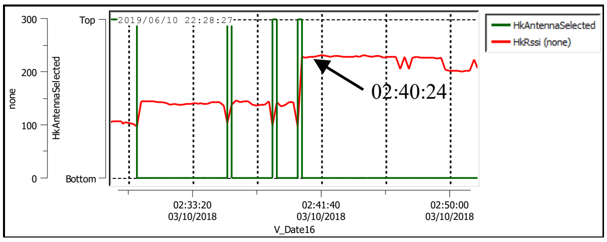

Figure 14: RF power mode transition

The transition between low and high power mode for Hayabusa-2 transmitter is visible in Figure 14 at 02:40:24 UTC. In Hayabusa-2 telemetry, the transition was tagged at 02:41:24 on HY2 UTC.

End of day 1

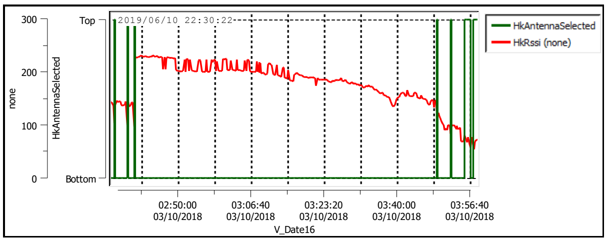

Figure 15: End of day 1

There was no move of MASCOT during the remaining time of day 1. The whole sequence planned was run even with the upside down attitude. The slow RSSI decrease is due to the geometrical variation between HY2 and MSC. The recorded RSSI values indicate a very good link budget with a strong received signal from Hayabusa-2 during the pass. At the end of the day, the decreasing RSSI triggers the antennae switchover algorithm. The last value indicating an RF link was recorded at 03:49:28 UTC so day 1 lasted ~1h52m.

Synthesis

The first satisfaction about SDL phase was the continuity of the RF communication with a telemetry bit rate constantly higher than 0 and no link interruption detected (Lock statuses at 1 all the time, Figure 16). It means that the autonomous onboard protocol worked perfectly even during the rebound phase. The highest bit rate values correspond to science data download while the lowest correspond to housekeeping telemetry.

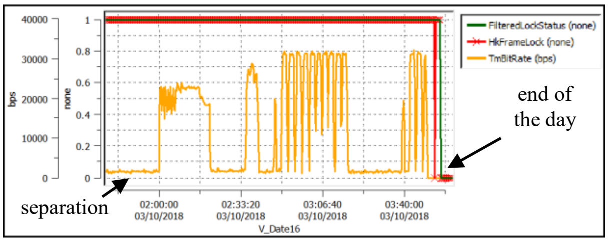

Figure 16: TM bit rate and lock statuses during day 1

The Table 1 summarizes the analysis of the SDL phase from the communication subsystem telemetry and compares the results to the final events sequence that was determined using all the available telemetries from scientific payloads and subsystems.

Table 1: Synthesis of the Separation, Descent and Landing phase analysis from communication subsystem telemetry compared to actual events time

Event	Time occurrence through COM TM analysis (UTC)	Final retained time occurrence (UTC)
Separation	Between 01:57:28 and 01:57:48	01:57:44
First touchdown	Before 02:04:08	02:03:05
Stabilization: end of fast bouncing	Around 02:10:32	02:10:26
Stabilization: at rest on the ground	Around 02:15:04	02:14:17
Upright: start	Around 02:20:24	02:20:31
Upright: end	Around 02:26:16	02:27:01
HY2 high power mode	Around 02:40:24	02:41:24 (HY2 UTC time)
End of transmission	03:49:36	

It is interesting to notice that most events are discernible by analyzing a few parameters only from the communication telemetry. It can provide a good first understanding of the on-going events with a good level of confidence with some incertitude on the time due to the frequency sampling.

Night 1 and Day 2 on Ryugu

After several discussions including mission management and scientific teams, it was decided to make a new upright attempt with Mobility at the beginning of day 2 and to start again the initial science sequence of day 1.

During the night the MASCOT 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 (Figure 17). The night 1 lasted ~5 hours.

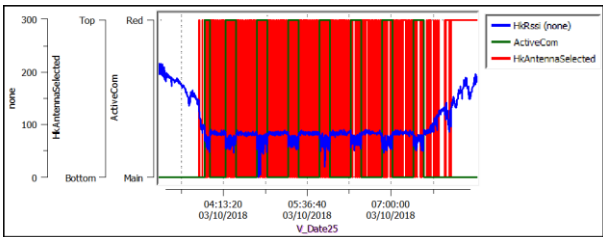

Figure 17: Communication TM during night 1

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 upright attempt was commanded at the beginning of the day and is visible in the antenna switchover, from bottom to top, visible in Figure 18.

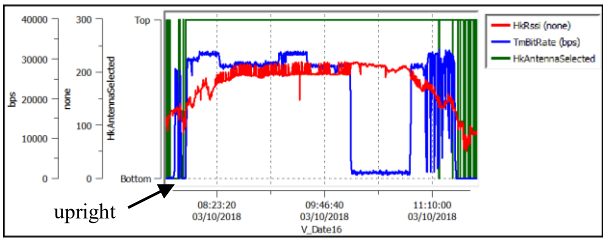

Figure 18: Communication TM during day 2

The day 2 was nominal for the RF link with a typical average RSSI variation related to geometrical variation between HY2 and MSC. No link interruption was noticed until the end of the day. Day 2 lasted ~3h38m, from a communication point of view. The night was longer than the day on the MASCOT landing site.

Night 2 and Day 3 on Ryugu

The second night was similar to the first one in terms of RF activity but with a shorter duration of 4 hours and 6 minutes.

Day 3 was expected to be the last and some MASCOT moves were discussed to expand the scientific harvest. First, a mini-move (at 16:29:09 UTC) implying a very short movement on the ground while keeping the same MASCOT attitude. It was close to a vibration making a mobile phone moving on a table. Then, a bigger move in order to change MASCOT location on the asteroid (at 18:03:56 UTC).

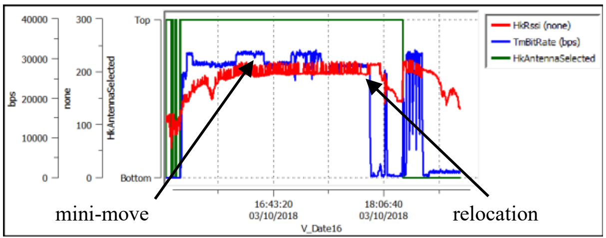

Figure 19: Communication TM during day 3

The mini-move had no impact on the RF link while the relocation had an influence on the RF path leading to a decreasing RSSI over the next 15 minutes after the move. An antenna switchover occurred (from top to bottom) indicating that MASCOT attitude has changed and that bottom antenna was a better choice for maximizing the link capacity. Incidentally, the TM bit rate increased after the antenna change, 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, making the total duration of MASCOT mission exceeding the 17 hours. 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, far from the world excitation in the face of this new great adventure, joining its companion Philae in the History of space exploration.

CONCLUSION

This article intended to highlight the MASCOT mission from the point of view of its communication subsystem. The telemetry analysis allows understanding the different phases of the mission and in particular the critical Separation, Descent and Landing phase. It was thus a reliable source of information during the operations. The RF link between Hayabusa-2 and MASCOT behaved nominally during the whole mission and demonstrated the capacity of maintaining the communication even in challenging conditions with lander tumbling. The mission feedback will be very precious to prepare the space exploration future.

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