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MASCOT – a Mobile Lander on-board Hayabusa2 Spacecraft – Operations on Ryugu

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Abstract

MASCOT ('Mobile Asteroid Surface Scout') is a 10 kg mobile surface science package part of JAXA's Hayabusa2 sample return mission. The mission was launched in December 2014 from Tanegashima Space Center, Japan. The Hayabusa2 spacecraft reached the target asteroid in summer 2018. After a mapping phase of the asteroid and a landing site selection process the MASCOT lander was deployed to the surface on the 3rd of October 2018. MASCOT operated successfully for about 17 hours on the surface of Ryugu. It performed three relocation manoeuvres and one "Mini-Move" and returned 128 MBytes of data.

MASCOT has been developed by the German Aerospace Center (DLR) in cooperation with the Centre National d'Etudes Spatiales (CNES). The main objectives were to perform in-situ investigations of the asteroid surface and to support the sampling site selection for the mother spacecraft. These objectives could be reached successfully.

On 6th December 2020 (JST) Hayabusa returned successfully asteroid samples to the Earth.

Keywords: (Hayabusa2, MASCOT, Asteroid, Landing, Surface, Ryugu)

Acronyms/Abbreviations

CNES = Centre National d'Etudes Spatiales
DLR = Deutsches Zentrum für Luft- und Raumfahrt e.V.
HY2 = Hayabusa2
FD = Flight Dynamics
FoV = Field of View
GNC = Guidance, Navigation & Control
IAS = Institut d'Astrophysique Spatiale
JST = Japan Standard Time
MAM = MASCOT Autonomy Manager
MARA = MASCOT Radiometer
MASCam = MASCOT Camera
MASMag = MASCOT Magnetometer
MCC = MASCOT Control Center
MMEGA = MicrOmega
MASCOT = Mobile Asteroid Scout
SSOC = Sagamihara Space Operations Center

1. Introduction

Hayabusa2 is a spacecraft, developed and launched by the Japan Aerospace Exploration Agency (JAXA) dedicated to investigate the asteroid Ryugu and return samples back to Earth [1]. After launch on December 3rd, 2014 from the Tanegashima Space Center, with an H2A rocket, it went on its cruise to the C-type asteroid (162173) Ryugu (earlier designation was 1999JU3). The spacecraft reached the target asteroid in summer 2018 and returned the collected samples to Earth on the 6th of December 2020 (JST).

Hayabusa2 is based on the highly successful Hayabusa mission, which was the first spacecraft that returned samples from an asteroid to Earth (launched in May 2003 to asteroid (25143) Itokawa). Certain aspects of Hayabusa2 are modified as compared to its predecessor, including the addition of a small lander MASCOT as science payload.

The MASCOT/Hayabusa2 mission started a new generation of space missions, in a new frame of cooperation, coupling intimately remote sensing at a macroscale, in-situ characterization at a microscopic scale, and return samples for refined laboratory analyses.

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 was to perform in-situ investigations of the asteroid surface, provide ground truth and to support the sampling site selection for the mother spacecraft.

MASCOT is a mobile surface science package with a mass of about 10 kg [2],[3]. After arrival at the target asteroid (162173) Ryugu a detailed mapping phase was performed and the landing site of MASCOT has been selected [9]. The deployment of MASCOT to the asteroids surface was planned for the beginning of October 2018. After its deployment MASCOT investigated the asteroid surface in detail. Two relocation manoeuvres, selfrightening and a so-called "mini-move" were performed. MASCOT survived two asteroid nights and performed its planned measurements. The scientific results of MASCOT combined with those from the instruments aboard the Hayabusa2 mother spacecraft as well as the returned samples shall allow a comprehensive understanding of asteroid Ryugu and the role of primitive asteroids during the history of the solar system.

2. Mascot Lander System and Payloads

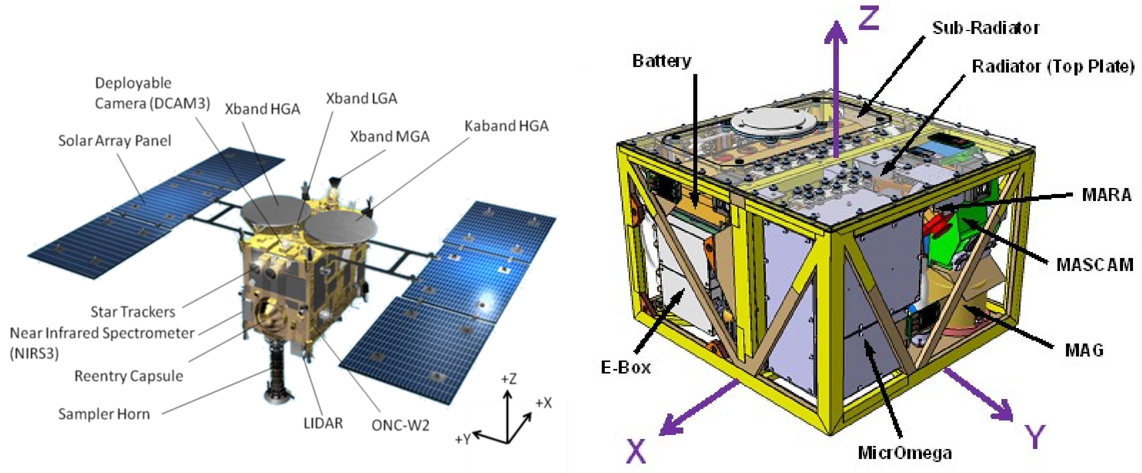

Figure 1: Left: Overview of Hayabusa2 spacecraft [4], Right: Schematic of MASCOT lander

MASCOT supports four scientific instruments a wide-angle camera, a hyperspectral infrared microscope, a radiometer and a magnetometer (see Figure 1). The camera (MASCam) provided the ground truth for the orbiter remote sensing observations, for measurements by the other lander instruments (radiometer, spectrometer), and the orbiter sampling experiment, by characterizing the geological context, mineralogy and physical properties of the surface (e.g. rock and regolith particle size distributions)[4]. The MASCOT camera observations, combined with the MASCOT hyperspectral microscope and radiometer spectral observations, have been designed to cover a wide range of observational scales and to serve as a strong tie point between Hayabusa2's remote sensing science (10^3 - 10^{-3} m) and sample science (10^{-3} - 10^{-6} m)[5]. The radiometer (MARA) determined the surface brightness temperature, the thermal inertia of the surface material and the spectral slope in infrared [6]. The MARA radiometer's FoV has been designed and calibrated to be within the camera's FoV such that the effects of grain size and boulders in the field of view can be disentangled from the thermal measurements. The magnetometer (MASMag) observed the magnetic field profile during descent and bouncing and for the determination of any global and local magnetization of the asteroid [7]. The hyperspectral IR microscope (MicrOmega) is an instrument for the investigation of the composition of the asteroidal surface at grain scale: in terms of minerals (pristine, altered), ice/frosts, and organics and characterize the microscopic structure of the soil [8].

MASCOT was powered by a primary battery which enabled it to investigate the asteroid surface for up to two asteroid days. MASCOT was further equipped with a mobility mechanism for selfrighting and relocation on the asteroid surface. Due to its shape (compare Figure 1) and the absence of a dedicated landing gear, it was not predefined which side would face the asteroid once MASCOT came to rest. The GNC sensors would determine the orientation of MASCOT relative to the asteroid surface and the mobility mechanism used to upright MASCOT in its default measurement orientation. The communication of MASCOT to Earth took place via Hayabusa2 spacecraft as a relay. It is worth noting that because the Hayabusa2 spacecraft was located near the sub-Earth point during the MASCOT mission, contact of MASCOT to the spacecraft was only possible during the asteroid day times.

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. Therefore, MASCOT was equipped with the MASCOT Autonomy Manager (MAM), a state machine which scheduled the different MASCOT operations depending on the detected situation, such as:

- Detection of separation from HY2 spacecraft
- Descent of MASCOT
- MASCOT rest on the surface and its orientation towards it

- MASCOT uprightening to its nominal measurement orientation
- Scheduling of science surface activities
- Day/night detection
- Trigger for MASCOT relocation
- Schedule the MASCOT end-of-life activities

Out of the four instruments aboard MASCOT, MASMag and MARA were permanently switched on and taking measurements. Different settings were adjusted on event by the MAM. The Camera and MicrOmega activities are defined in separate sequences which were scheduled by the MAM on event.

2. Mascot Cruise Phase

Between the Hayabusa2 launch in December 2014 and the approach to asteroid (162173) Ryugu, MASCOT has already performed a large number of operations in space. The main objectives of these operation activities were health status checks of the MASCOT bus and instrument in-flight calibrations. 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 during cruise phase. Additional objectives were to test HY2 and MASCOT interaction as well as preparation tests for the on-asteroid phase. Table 1 shows a chronological overview of MASCOT in-flight activities during the cruise phase.

Table 1: MASCOT In-Flight activities during cruise

Activity	Date	Activtiy	Date
MASCOT Health Check	Jun 2015	**MASCOT Instrument Calibration #2**	Nov 2016
HY2-MASCOT Communication Check	Jun 2015	**MASCOT Health Check**	May 2017
MASCOT Instrument Calibration #1	Sep 2015	**MASCOT Software Upload**	July 2017
PRM activation (launch lock)	Sep 2015	**MASCOT Health Check**	July 2017
CAM data download	Jan 2016	**MASCOT On-Asteroid Sequence Test**	Aug 2017
MASCOT Health Check	Jul 2016	**MASCOT Instrument Calibration #3**	Nov 2017
Data Transfer Test (On-Asteroid Spacecraft configuration)	Jul 2016	**MASCOT On-Asteroid MAM test**	Nov 2017
MASCOT Thermal Evaluation	Jul 2016	**Data Transfer Test (On-Asteroid Spacecraft configuration)**	Dec 2017
HY2-MASCOT Communication Check	Oct 2016		

All telecommands and activities performed in flight and later on the asteroid have been validated beforehand at the MASCOT ground reference model at the MASCOT Control Center (MCC). The telecommands were uplinked to MASCOT from SSOC (Sagamihara Space Operations Center) via the Hayabusa2 orbiter. Hayabusa2 was used as relay for MASCOT telecommands and telemetry throughout the whole mission. Commanding, telemetry processing, evaluation and status assessment of MASCOT was jointly performed in cooperation with all partners JAXA, CNES and DLR in the respective control centers together with IAS and TU Braunschweig. The real-time monitoring of the in-flight activities took place at the MCC while a MASCOT liaison was present at SSOC.

The MASCOT health checks performed in flight showed a nominal status of MASCOT system and instruments. In-flight calibrations of the instruments have been performed to provide the opportunity to monitor instrument performance throughout the cruise phase until the target asteroid was reached.

3. Landing Site Selection

The landing site selection process for MASCOT has been performed in close cooperation with JAXA, as it was not only dependent on input from the instruments of the Hayabusa2 main spacecraft, but also interconnected with the delivery sites if the MINERVA II landers and the selection of the sampling sites [9].

The selection of the MASCOT landing site, a complex process, involving many actors, had to be carried out within about one month, to make use of the data, received after arrival at the asteroid, and being ready for lander delivery in October 2018. In order to be prepared to perform the process in such a short time, it was exercised two times, about a year before the actual events took place.

A major role played the CNES flight dynamics team, analyzing the separation-descent and landing process, including various bouncing scenarios by Monte Carlo analyses [9,10].

For the landing site of MASCOT several constraints had to be taken into account:

a) Operational constraints: guaranteeing daylight for 50% to 70% of the asteroid rotation period, allowing communications link with the main spacecraft and considering thermal restrictions.

b) Constraints imposed by the Hayabusa2 spacecraft: the main S/C had to stay near the subsolar point and had time constraints related to the use of various Grounds stations on Earth. No overlap between sampling sites and MINERVA II or MASCOT landing sites was acceptable (to avoid the risk of confusion between lander and target marker).

c) Scientific constraints: due to a relatively homogeneous surface of Ryugu, there were no areas explicitly favored. Nevertheless, scientific relevance of the candidate sites was discussed.

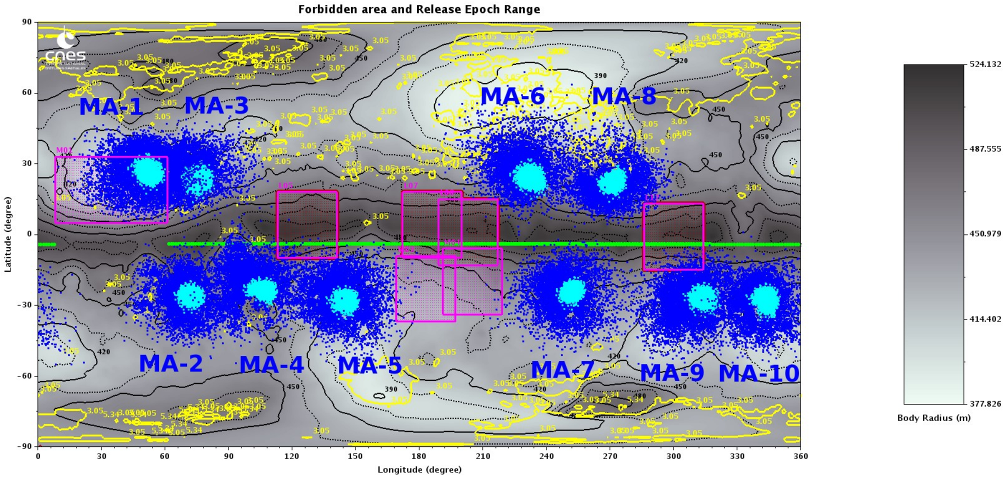

Figure 2: The possible landing sites of MASCOT determined by the flight dynamics team [9]. The light blue areas are possible first contact points of MASCOT with the surface of Ryugu (CP1). The dark blue areas are the possible settlement points for Mascot after bouncing (SP1). The pink squares were potential activity areas for HY2 spacecraft [credit Jaxa].

After analyzing 10 candidate sites, in an iterative process during a team meeting in Toulouse, on August 14th, 2018, one site (MA-9) was selected as most favorable from MASCOT side. This site has been confirmed by JAXA during the HJST (Hayabusa2 Joint Science Team meeting), August 17th in Sagamihara and was finally adopted for the successful delivery on October 3rd.

4. Mascot Deployment Strategy

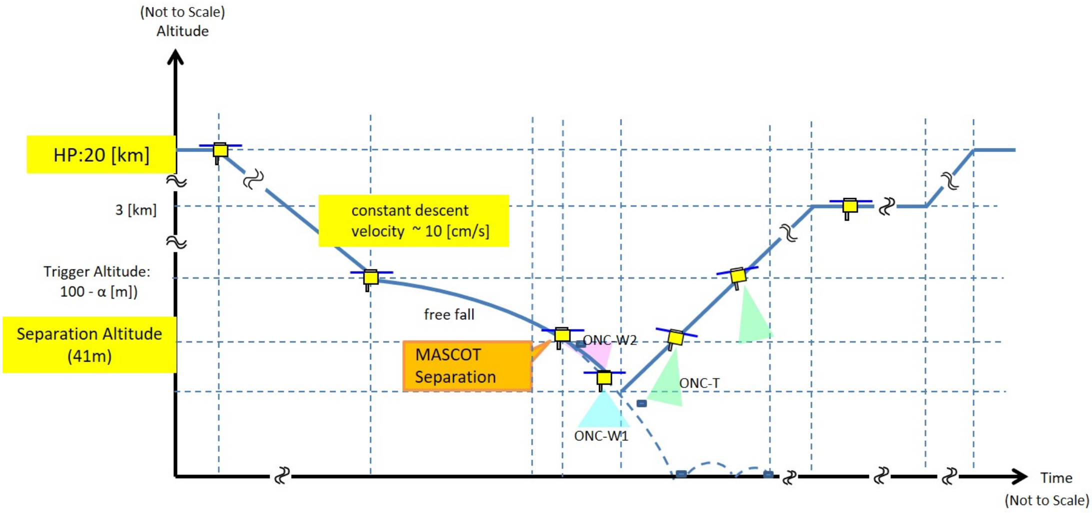

Figure 3: Schematic image of MASCOT Deployment [4]

For MASCOT deployment HY2 spacecraft slowly descended from its home position at 20 km above the asteroid's surface and released MASCOT at about 41 m (Figure 3) altitude. The lander performed a free-fall down towards the asteroid surface, touchdown and bounced over the Ryugu surface till it came to rest. After The MASCOT release the HY2 spacecraft ascended to an altitude of 3 km and hovered at this altitude during MASCOT operations. During the descent phase and especially after the separation of MASCOT the HY2 spacecraft took pictures with its on-board cameras to track the pass of MASCOT and to support the localisation of MASCOT on Ryugu's surface.

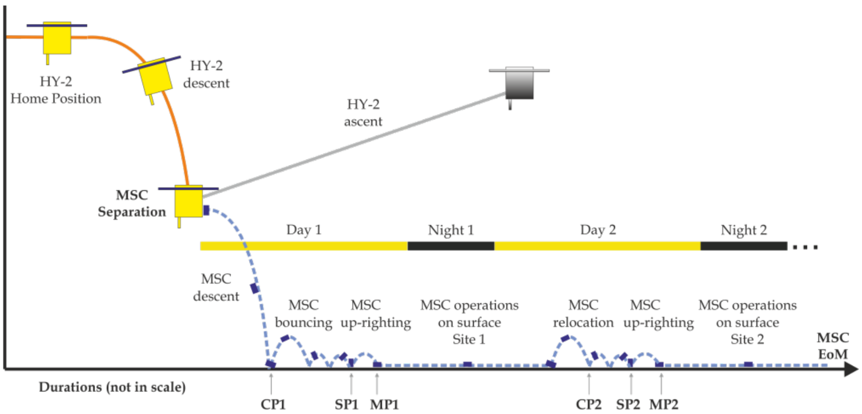

Figure 4: Sketch of MASCOT and Hayabusa-2 relative movements after separation

MASCOT landing trajectory prediction and optimization had to take into account the fact that the lander had no anchoring mechanism and was thus expected to bounce on the asteroid surface and possibly stop far from its first touchdown point. This is indicated in Figure 4, where CP1 denotes the first contact point and SP1 the first settling point. MP1 denotes the first measurement position. The simulated trajectories resulting of the Flight Dynamics dispersions analysis are essential inputs to tune at best 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 operations [9].

The deployment concept of MASCOT with its bouncing profile did not allow precision landing on a predefined landing spot but did result in a spread-out landing area instead [10]. This implied that the final settling longitude and latitude could only be predicted with a certain probability. The exact asteroid daytime to start the MASCOT surface operation was not known beforehand and also the exact duration of day and night at the actual resting point had some uncertainty. The planning of MASCOT on-surface operations thus had to rely on minimum and maximum assumptions for the different MASCOT phases like bouncing or surface illumination cycles.

5. Mascot Landing Preparation and Separation

The general on-asteroid strategy of Mascot was planned long in advance during the cruise phase. The science sequences were planned, prepared and intensively tested on ground. All sequences needed to be prepared beforehand, as ground interactions with MASCOT were limited. The planning needed to be focused on robustness with the aim to maximize the science return during the limited lifetime of MASCOT. The measurements needed to be timed for an optimal usage of the link budget from MASCOT to the Hayabusa2 spacecraft, so that the data could be stored on-board the HY2 spacecraft before the battery of MASCOT was depleted. As described above the settlement spot of MASCOT could not be predicted precisely, which lead into an uncertainty for the duration from settlement until first sunset, but also in the day/night time duration. The number of attempts and thus the duration to achieve self-righting also could not be predicted precisely beforehand, introducing an additional timing uncertainty relative to the day/night transition as well as loss and reacquisition of signal of the link to HY2.

The landing site was selected about six weeks before the separation of MASCOT took place. The time between the confirmation of the landing site and the real separation of MASCOT was used to finalise the parameter settings of the payloads and subsystems for the conditions of the targeted landing site. Final tests of the sequences were performed by the operations team at the ground reference model and the final command products were prepared.

The MASCOT separation took place on the 3rd October 2018. The overall activities in space started already days beforehand with preparation activities.

6. MASCOT Landing and On-Asteroid (Ryugu) Phase

The In-flight preparation of the MASCOT Ryugu phase started about 1 week before the separation took place with the upload of the final command sequences for the separation and the on-asteroid phase. These command sequences contained already the final adaptations for the selected landing area.

The final MASCOT switch-on took place on the 29th September 2018 while HY2-Spacecraft was still hovering at its home position 20 km above Ryugu's surface. The activities for MASCOT separation started with the final step for the primary battery depassivation followed by a MASCOT system and payload check. Afterwards MASCOT was not switched off but stayed in idle mode coming along with small activities and checks still powered via the main spacecraft while the HY2 spacecraft started its descent to the targeted release altitude of MASCOT about 40 – 60 m above the asteroid surface,

Prior to the separation the battery was heated to its targeted release temperatures. The MARA instrument was switched-on about 3 hours before separation to adjust the temperatures to its set points. The magnetometer was also switched-on this time to monitor the separation itself and the descent of Mascot to Ryugu's surface.

The MASCOT battery switches were closed shortly before separation. From the moment of separation until the end-of-life MASCOT was powered by its own battery.

MASCOT separation took place on 3rd October 2018 01:57:20 UTC in an altitude of about 41 m above Ryugu's surface. It required about 4,0 +/- 1.5 sec for MASCOT to leave its support structure (MESS) inside HY2 spacecraft.

30 sec after MACOT separation the HY2 spacecraft started to ascent to an altitude of about 3 km above Ryugu's surface. HY-2 spacecraft continued to stay at this altitude of 3 km until the end of MASCOT mission and returned afterwards to its home position [3].

During MASCOT descent MASCam, MASMag and MARA performed measurements. The cameras abord the HY2 spacecraft took pictures in parallel in order to track the pass of MASCOT.

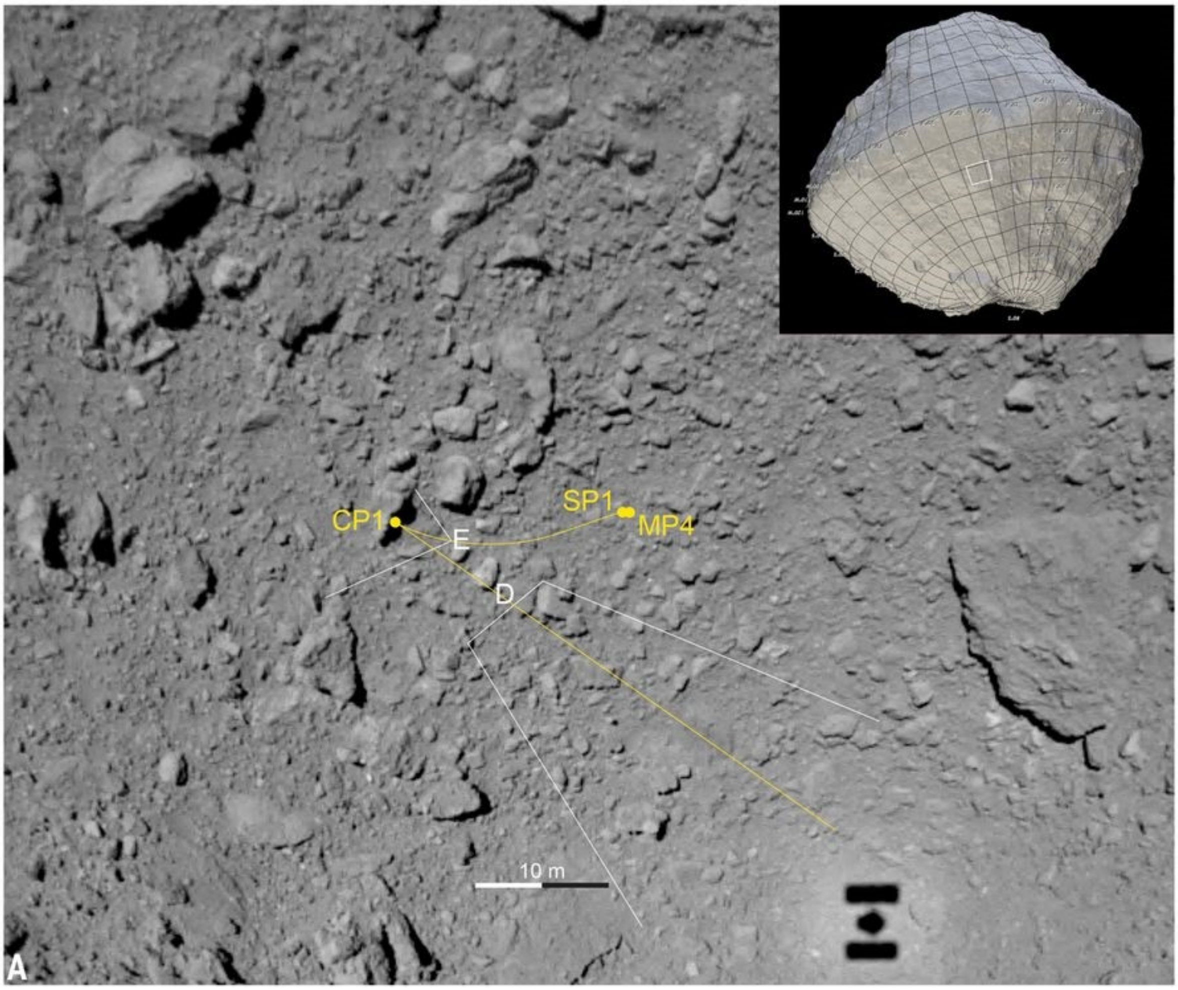

Figure 5: Reconstruction of MASCOT trajectory towards and on Ryugu, Yellow: MASCOT descent and bouncing trajectory [11]. Image of Hayabusa2 ONC camera.

The first contact of MASCOT with the surface of Ryugu occurred 05:51 [mm:ss] after separation. MASCOT bounced over Ryugu's surface for further till it came to rest. The analysis of Jauman et al and Scholten et al [11,12] showed that the first contact of MASCOT with Ryugu was the shadowed side of a bolder. With combination of the MASCOT images and the HY2 images it was possible to reconstruct the bouncing pass of MASCOT on Ryugu (Figure 5). After its settlement MASCOT performed a selfrightening manoeuvre to get into its measurement orientation towards the asteroid's surface and the MAM started the first MASCOT surface science sequence (Figure 6). Actually, the GNC system on-board MASCOT detected the orientation wrong for this first measurement position, likely due to the very rough terrain around MASCOT [3]. MASCOT was in this phase upside down oriented but performed constantly its measurement. MASCOT entered in this orientation the first asteroid night in which no communication between spacecraft and lander was possible. With the help of the system and payload data the upside-down orientation could be determined on ground by the MASCOT team. While MASCOT was still on the night side of Ryugu ground commands were sent to the mother spacecraft to force a MASCOT relocation followed by the start the second science cycle to not waste time on the asteroid and to avoid overheating of the MicrOmega bottom side. MicrOmega had just cooled down during the asteroid night while facing to the sky. When MASCOT appeared back in the line of sight to HY2 spacecraft and the commanding link was re-established the respective commands were sent to MASCOT from HY2 spacecraft and the relocation manoeuvre was performed. MASCOT performed a hop of about 70cm and came to rest in its nominal measurement orientation. The second science measurement cycle was started by the MAM. This second measurement cycle continued during the second asteroid night of MASCOT. All planned measurements could be conducted including also the night MARA and MASCam measurements.

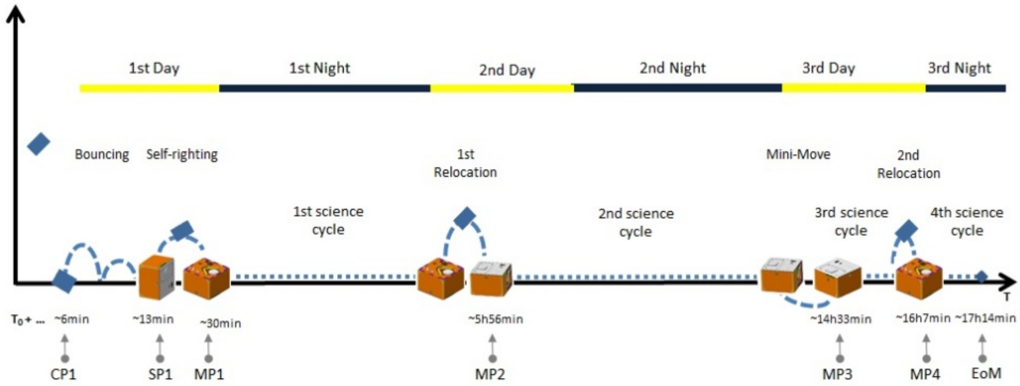

Figure 6: The schematic MASCOT mission timeline starting from release at T_0 until its End of Mission [11].

The next intended move of MASCOT was performed after the second science cycle had finished, a so-called MASCOT Mini-Move, 3.6 cm around its z-axis. This slight orientation change of MASCOT was planned to get a slightly different FoV on the same area to allow stereo imaging of the measurement site and attempting also to get different target material into the FoV of MicrOmega.

MASCOT operated meanwhile on the 3rd asteroid day on Ryugu. Before MASCOT entered the 3rd night on Ryugu a last relocation manoeuvre was commanded from ground, attempting to get to another site of the surface. The manoeuvre ended again in an upside-down orientation, and MASCOT entered in this orientation the third night on the asteroid. During this third night the battery of MASCOT depleted. No further signals from MASCOT were received on the next morning. However the lifetime of MASCOT was near the absolut maximum according to the expectations with more than 17 hours of runtime (Table 2).

Table 2: Main events of MASCOT separation, descent and operation on Ryugu's surface, see also [3]

Time [UTC]	Event	MASCOT Operation
		MASMag and MARA are on before separation
01:57:19	NEA firing by HY2 spacecraft	MASMag detects separation
01:57:20	Hayabusa detects disconnection of Mascot	MASCOT moves out of the MESS
01:57:23	MASCOT descent start towards the asteroid.	Hayabusa2 released MASCOT with a velocity of ~5.9 cm s^{-1} [11]
01:59:47		MASCam started to acquire descent and bouncing images
02:03:14	The first impact of MASCOT with Ryugu (**CP1**) detected by MASMag followed by a bouncing phase.	
02:12:27		MASCam acquired last descent and bouncing images
02:18:51	MASCOT reached its first settlement point (**SP1**)	
02:20:31		MASCOT started to upright, GNC recognized in motion
02:34:20	MASCOT reached its first measurement point (**MP1**).	Start of the 1st science cycle by MAM

03:13:12*	End of 1st day and start of 1st night on Ryugu.	
07:18:28		A ground command has been sent to HY2 spacecraft to interrupt its science measurement and force the lander to relocate
07:50:04		MASCOT start for 1st relocation (MAM state). Relocation forced by ground command
07:51:38*	End of 1st night and start of 2nd day on Ryugu.	
08:27:51	MASCOT reached its second measurement point (**MP2**).	The GNC sensors confirmed the correct orientation of the lander and the 2nd science cycle was started.
10:52:06**	End of 2nd day and start of 2nd night on Ryugu.	
11:16:53		MASMag has been turned off.
15:27:11*	End of 2nd night and start of 3rd day on Ryugu.	
16:28:29	MASCOT at its third measurement point (**MP3**)	MASCOT started "Mini-Move" maneuver and initiated its 3rd science cycle once on MP3
18:05:41	MASCOT reached its 4th measurement point (**MP4**)	MASCOT performed a 2nd relocation once at MP4 executed measurement of MASCam, MicrOmega and shortly MASMag.
19:03.57	End of mission (EOM): reception of last MSC HK packets (final link break by horizon occultation).	

(*) Uncertainty of several 10 sec because of sensor reading interval
(**) OBC event packet

7. MCC – Ground Segment

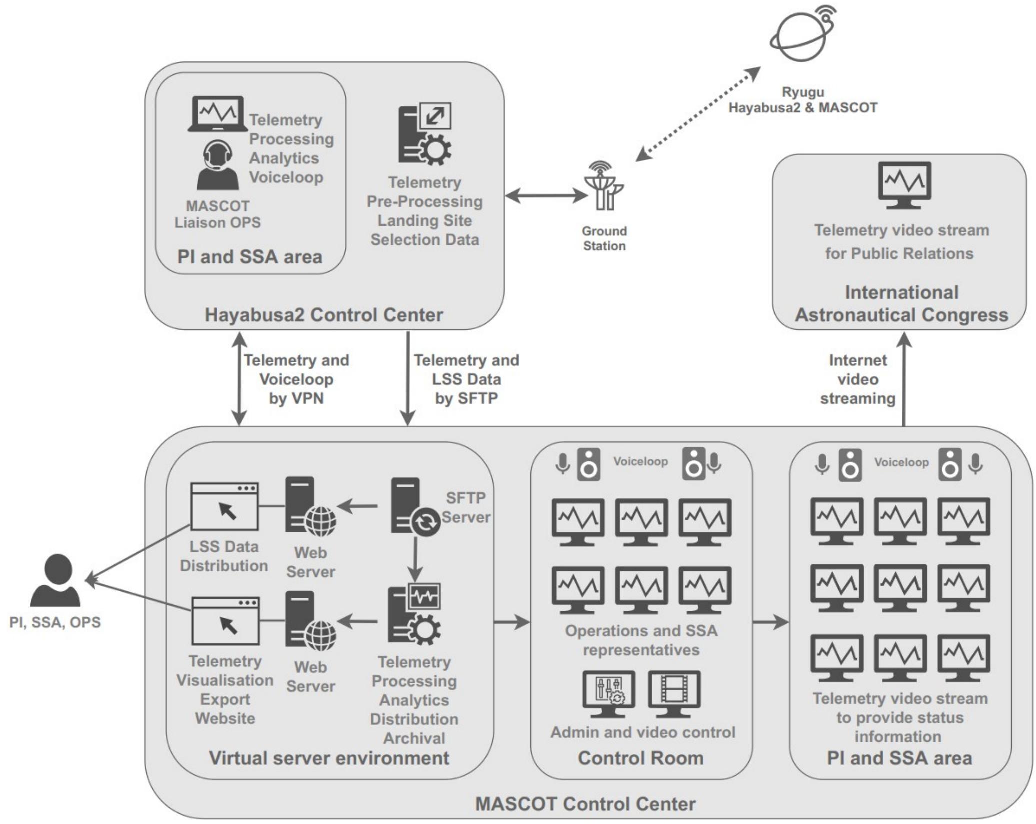

Figure 7: Scematic on MCC setup, interfaces and data flows during MASCOT operations on Ryugu

Operations were performed at the MASCOT Control Center (MCC) located at DLR, Cologne and with a liaison operator at the Hayabusa2 Control Center (SSOC) in Sagamihara. To include the scientists and engineering community as well as the public at the IAC in Bremen during the landing and operational phase several distributions of telemetry and data products have been established. The main operations were performed by MASCOT operators and subsystem authority representatives in the control room. A liaison operator was located in Sagamihara to be a direct person of contact in any case of connection loss to the MASCOT Control Center. An expertise center was also equipped in CNES premises to support analyses for the landing site selection, with processing capacities dedicated to trajectories commutations and to 3D visualization.

7.1 Telemetry and Landing Site Selection Data

Reception
The telemetry and Landings Site Selection data were received by a server at ISAS that periodically extracted MASCOT relevant and Hayabusa2 related Telemetry from the complete set of Hayabusa2 data sent to Earth. This process ran automatically and produced several growing files that where incrementally received by using the Secure File Transfer Protocol (SFTP) based on Secure Shell (SSH). MASCOT telemetry was provided as a plain CCSDS file and Hayabusa2 telemetry consisted of text files with comma separated values (CSV). The reception rate of MASCOT and Hayabusa2 Telemetry could be freely adjusted up to a rate of one retrieval per minute.
The Landing Site Selection Data was a data set of several types of information. It consisted of data products from all instruments of Hayabusa2. The products were on a scientific level and therefore of standard file types like images, tables, text, video and other. The way of transport was the same as for the telemetry, but updates where made on weekly basis or on request. Because of the large number of files (39280), folders (577) and the accumulated size of 140 GB a synchronization on file and folder basis was used to only transmit new and changed files and folders

during a weekly update. Given the time constraints, the expertise center located in CNES had a direct access to the ISAS server to directly retrieve the data necessary for the time-consuming trajectories optimization and to directly deliver to the Hayabusa2 team the operational data expected, such as the optimized position for the MASCOT release.

Distribution
MASCOT and selected, MASCOT relevant Hayabusa2 telemetry were processed by the MASCOT telemetry servers and could be accessed and used by the clients in in the control room. The plain telemetry was also accessible by the liaison operator in Sagamihara. The operator was equipped with a mobile telemetry server and client to be able to perform the same operations as in the control room. The MASCOT telemetry servers were also capable to provide telemetry data in visualized and exportable formats on a web site. The MASCOT community was able to receive their needed data in pre-configured exports as soon as they were received and processed. So the community was able to follow and analyze their instrument or system and contribute operations with current information. Additionally to the client and web based access to the processed telemetry two video streams of selected information were produced. One stream was available in the main scientists and engineering area of the MASCOT Control Center and the second one was published on an internet service to be shown at the International Astronautical Congress (IAC) that was held in Bremen during the landing of MASCOT.
Landing Site Selection Data was synced to a Data and Document Management Server of the MCC and available via a web site to all involved parties of the MASCOT project.

7.2 Co-location of the liaison operator and communication

The liaison operator at the Hayabusa2 Control Center in Sagamihara was able to interface personally to the Hayabusa2 operators and had a vital role in the communication of the two control centers. To provide the liaison, the control room and the scientists and engineering area with direct information a voice-loop was used. All involved parties were able to speak to each other no matter of the location of individual. Telemetry and the voice-loop was transported to the liaison by using a Virtual Private Network (VPN) tunnel between the MCC infrastructure and the operator's equipment in the Hayabusa2 Control Center.

8. Summary

The MASCOT mission on Ryugu lasted more than 17 hours. This duration exceeded the expectations. MASCOT was successfully separated from the mother spacecraft. The descent to Ryugu's surface went as expected and could be reconstructed with the data and pictures of MASCOT itself and of HY2 spacecraft. The payloads could perform the main measurement requests or even exceed these.

The Mascot mission was prepared beforehand in great detail taking into account energy and link budgets. The unknown terrain and uncertainties of final settlement location of MASCOT needed to be considered for the planning scenario and sequencing. The planned activities of MASCOT were robust against the uncertainties faced by the unknown world of Ryugu.

Because of the rough terrain the MASCOT subsystems received wrong determinations of the lander's orientation towards the surface at the beginning of the mission but these could be corrected from ground. The autonomy concept of MASCOT worked out in general with small interactions from ground.

The team experienced an exciting phase with MASCOT inside the Hayabusa2 project starting with the design; launch and cruise phase and culminated in the successful operation on Ryugu [3].

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