MASCOT, THE SMALL MOBILE ASTEROID LANDING PACKAGE ON ITS PIGGYBACK JOURNEY TO 1999 JU3: PRE-LAUNCH AND POST-LAUNCH ACTIVITIES

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Since December 2014 the Japanese spacecraft Hayabusa2 is on its journey to asteroid (162173) 1999 JU3. Like its famous predecessor it is expected to study and return samples from its target body. This time, the mother spacecraft has several small passengers. One of them is a compact landing package called MASCOT (Mobile Asteroid surface SCOuT), which has been developed by the German Aerospace Centre (DLR) and the Centre National d'Etudes Spatiales (CNES). Once having been released from its mother spacecraft's cradle, MASCOT will descend to the asteroid and after a few bounces will come to rest at a certain location on the surface. Sitting on the surface, it will perform its scientific investigations of the asteroids surface structure, mineralogical and physical properties, thermal behaviour and magnetic effects by using its suite of four scientific instruments: a spectrometer (MicrOmega, IAS Paris), a camera (CAM, DLR Berlin), a radiometer (MARA, DLR Berlin) and a magnetometer (MAG, TU Braunschweig). These payload operations are made possible by, amongst others, a clever thermal subsystem design specifically devised to cope with the contrasting requirements of cold cruise and hot on-surface operations and a primary battery optimizing mass versus energy output. A mobility mechanism realizes locomotion on the surface supported by an attitude and motion sensing system. An intelligent autonomy manager which is implemented in the onboard software can operate MASCOT when ground intervention is not available.

In a nutshell, with its many challenging technical hurdles that have been solved, the MASCOT lander can serve as a benchmark for extremely lightweight (10 kg), highly integrated mobile small body landing systems with onboard autonomy and high science output.
This paper will summarize the mission and system development. We will provide an overview of the final capabilities of the system as well as discuss the last challenging pre-launch activities and tests. Further a summary and an outlook regarding the already performed as well as upcoming post-launch activities will follow. Lessons have been learned and will be told to be ready for future upcoming missions for small solar system body exploration.

I. INTRODUCTION

MASCOT's development was from the very beginning a race against time. Passing the starting line in December 2011, when the interfaces with Hayabusa2 were frozen during its subsystem CDR, MASCOT was only at the beginning of phase B and since then constantly required to catch up with the mother spacecraft.[1] A system PDR in July 2012, a CDR in April 2013 and FAR in July 2014 can serve as interims, whereas the launch on December 3rd, 2014 is marking the finishing line as it can be seen in Fig. 1.

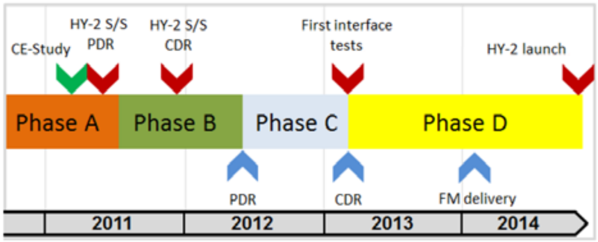

Fig. 1: MASCOT and Hayabusa2 history and schedule with major milestones[1]

Wining this race was only possible by optimizing the Assembly, Integration and Verification (AIV) program of MASCOT in order to save time. The result is called "Concurrent AIV" and differs from a classical sequential approach in that sense that testing activities were executed in a parallel manner while using multiple copies equipped with an as identical as possible set of subunits. This parallelization resulted in independent development tracks of Structural-, Thermal-, Software- and Functional Testing which shared their verification processes (see Fig. 2).[2]
Despite the fact that a methodology could be found which was consistent with the schedule constraints, MASCOT was not spared from facing issues which surfaced close to the finishing line. These issues came on top of the already foreseen pre-launch activities and resulted in an even more compressed test manifest. But also these last minute hurdles were found to be surmountable due to a performed paradigm change for late change requests. Found non-conformances and other issues were taken out of the main track in order to find solutions in parallel to the remaining ongoing integration and test activity. A special risk assessment and verification strategy was established for this purpose.[2]

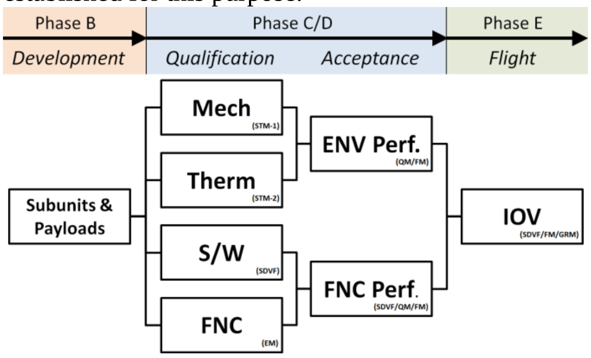

Fig. 2: MASCOT Concurrent AIV strategy [2]

In this light and having seen the hardware leave the launch pad one could think that the job is already done, but the opposite is true. Due to the short development schedule and the constrained project resources it was decided to postpone some of the test issues related more to characterization than validation until after launch. Those were all issues, which were deemed not critical for the launch of the hardware and which could be addressed by software updates or operational means during the cruise phase. Also, some of the last minute non-conformances which were identified as not launch-critical were deferred to post-launch activities. The result is a list of open points which requires further tests on ground as well as with the MASCOT flight model which goes clearly beyond the scope of standard operational activities. At the time of writing this paper, some of these post-launch actions are already closed, some will take more time.

II. MISSION OVERVIEW

Hayabusa2 is currently in the first year of a 3½ year long cruise phase. During this time MASCOT is stored on the –Y side panel and nominally off except for commissioning and periodic monitoring and calibration activities. Thermal control and power is provided by Hayabusa2 which allows MASCOT to save as much energy as possible for the on-surface operations as it contains only a primary battery. MASCOT's telemetry will be relayed to ground via Hayabusa2, and vice-versa. Following the arrival at 1999 JU3 in June 2018, Hayabusa2 will perform a global mapping. This phase is crucial for the characterisation of this C-type asteroid and for the landing site selection process of MASCOT, as a proper knowledge of the main properties, surface geology and thermal conditions is an essential input.[3]

The date of MASCOT's separation and landing is subject of an ongoing investigation, as several factors have to be considered.

The heliocentric distance of 1999 JU3 will increase as time progresses into the mission up to January 2019, when the asteroid reaches aphelion. Landing operations are not possible between October and December 2018 due to solar opposition. A cooler landing site can thus be achieved after opposition. Other factors such as equatorial vs. polar landing sites as well as the orientation of the rotational axis need also to be considered.

Concerning the separation time in the mission, a compromise needs to be found with respect to:

1. The time needed for global mapping, landing site selection and preparation of tele-command sequences,
2. a landing before or after a first sampling attempt of Hayabusa2, and
3. the desire to land at a cold landing site in order to avoid overheating.

Given the constraints in terms of time needed to map the asteroid, process the data, choose a landing site, and prepare sequences, it seems desirable to land shortly after solar opposition in January 2019, which would be after the first Hayabusa2 touchdown.

Prior MASCOT's deployment, Hayabusa2 will leave its Home Position at 20 km altitude and descent to 100 m. Triggered by the activation of a Non-Explosive Actuator (NEA), MASCOT will be ejected via a spring mechanism from Hayabusa2.

MASCOT's free fall to the asteroid surface will take about half an hour due to the weak gravity field. Communications to Hayabusa2 will be maintained throughout by omnidirectional antennae as there is no attitude control during this phase and MASCOT will likely rotate or tumble slowly. MASCOT is expected to take camera images of the asteroid and measure its magnetic field while approaching the surface.

After the descent Hayabusa2 will initiate a search for MASCOT using a camera and flash light. In the original operational concept Hayabusa2 was then foreseen to return to its home position of 20 km altitude. However, due to a reduced sensitivity of MASCOT's redundant transceiver which is one example of the aforementioned last minute hurdles, Hayabusa2 might be required to ascent only to 1.5-3 km altitude in order to allow MASCOT to establish a working and redundant RF-link with the mother spacecraft.

The highest priority for MASCOT after landing will be to determine its attitude and to upright itself in case it is not laying with the bottom plate on the surface as this is the required orientation to perform scientific measurements. According to the current operational baseline a separation and landing around local noon is desired in order to perform scientific tasks before nightfall and to transmit these data to Hayabusa2. As one asteroid day is nearly 8 hours long this means roughly 2 hours are left for this operation on the first asteroid day. Hayabusa2 will be nominally positioned around the sub-solar point which means that MASCOT will only be able to communicate with the mother spacecraft during daylight and that the telecommunications will be interrupted during asteroid night.

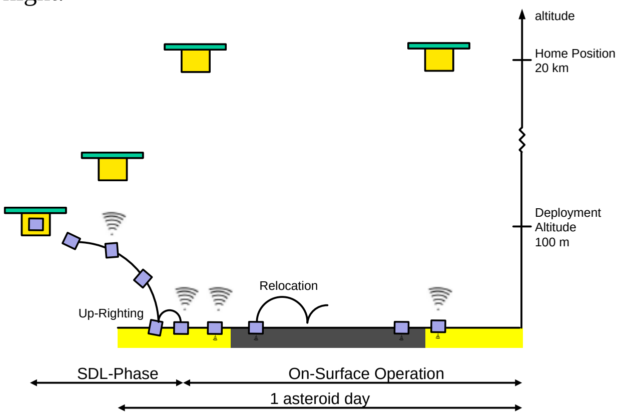

Fig. 3: MASCOT operational concept[3]

The full characterization of the first location is expected to be completed during the night. In the morning of the second asteroid day all relevant night-time data shall be transmitted to Hayabusa2, before MASCOT is supposed to hop to another site for further scientific measurements. This relocation manoeuvre will be realized by the same mechanism as used for the uprighting.

This mobility mechanism allows MASCOT to hop across the surface at a distance of up to 220 m. Nevertheless, the current operational baseline favours rather a short hop in order to land again during the same asteroid day, to take science measurements, and transmit all data before the beginning of the second night.

The expected lifetime of MASCOT is limited by the energy stored in its battery and is in the order of 10 hours.

During the on-asteroid phase, MASCOT will nominally only downlink information, due to the long turnaround times for ground intervention: 16 minutes per transmission, plus processing and decision time. As such, all nominal operations and a limited set of failure responses will be handled by onboard autonomy. This autonomy will be responsible for the scheduling of uplinks, determining any attitude correction manoeuvers and scheduling the science operations. In the event of contingencies which cannot be compensated by the onboard autonomy, ground support at the control centre at the DLR Microgravity User Support Centre (MUSC) in Cologne, Germany will have the limited capability to intervene.[3]

III. SYSTEM DEVELOPMENT

The development of MASCOT resulted in a space segment design which consists of the lander MASCOT and the Mechanical Electrical Support System (MESS).

Fig. 4: MASCOT Flight Model (Lander only)

The lander measures 0.275 x 0.290 x 0.195 m^3, has a mass of 9.6 kg and is divided into two segments: a warm compartment containing the electronics-box with the majority of MASCOT`s electronics, the battery package and the mobility mechanism, and a cold compartment housing the payloads. The four lateral external walls are covered with single layer aluminized Kapton (Single Layer Insulation - SLI), with the top surface being used as the main radiator.

The MESS consists of a mechanical framework which holds MASCOT in place during launch and cruise, a push-off mechanism to deploy MASCOT at the asteroid, an electrical connection to Hayabusa2 for providing power to MASCOT during checkouts and for the heater system. It also contains a calibration target shared by MARA and CAM, and a MESS antenna to allow RF communication with MASCOT during cruise. The MESS will remain attached to Hayabusa2 after the lander has been ejected.[4]

III.I Structure and Thermal

The development and verification of MASCOT’s primary structure and thermal subsystem are ranked among the most challenging technical tasks in this project.

The difficulties arose on the one hand from the requirements and on the other hand from the fact that there was no previous design which could be adapted in order to meet MASCOT’s mission needs. This led to a full prototype qualification program.

The aforementioned difficulties were confirmed when the first STM Model (STM-1) failed in its initial vibration test. In order to recover from this setback and to catch up with the original schedule, two identical models of the improved STM were built (STM-2.1 and STM-2.2) and used in independent mechanical and thermal test tracks. The fact that these models were identical in design allowed to consider both models to be mechanically qualified if only one model was tested in this regard and passed successfully the qualification test. The same approach was followed for thermal aspects.[2]

The development resulted in a primary structure based on an ultra-lightweight CFRP-foam sandwich frame which is in line with the strict mass requirements.

The structure itself reflects the configuration of the space segment and consists therefor also of two elements:

The highly integrated lander sandwich structure comprises of four external side walls; one internal vertical/middle wall, the base plate and a top-plate. The top-plate serves as MASCOT’s radiator, while the middle wall is used as the main load bearing path, with the separation mechanism introducing the loads into the overall structural framework. In order to support late-access activities, such as the installation of the battery, the radiator has been divided into a main and a sub-radiator, whereby the latter one is removable. For the solid CFRP framework structure of the MESS the same material as for the MASCOT lander’s sandwich face sheets was chosen (see Fig. 5). The CFRP struts are used again to cope with the launch loads. In order to decouple Hayabusa2 thermally from MASCOT during cruise and to provide thermal insulation of Hayabusa2 from space after MASCOT’s deployment, the entire volume created by the struts and filled during cruise by MASCOT is surrounded by Multi-layer Isolation (MLI).[4]

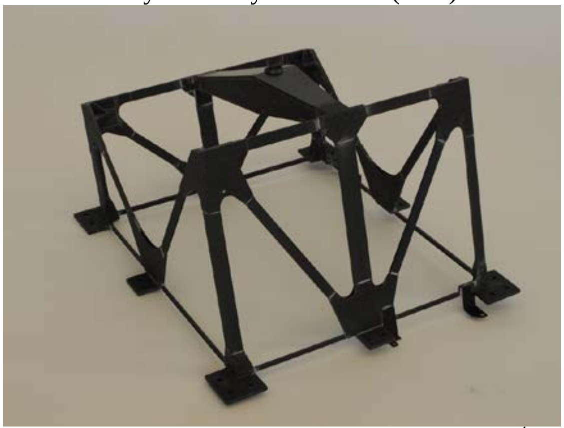

Fig. 5: MESS structure STM 2.2 (without MLI) [4]

During the development of the thermal subsystem it turned out to be very complicated to find and to qualify a design which can cope with a thermal environment which is changing with the mission phases and results in a wide range of temperatures, but is also in line with the mass and volume requirements. The performed design trades and analyses led to a semi-passive thermal control system, comprising of MLI, redundant heaters and 3D-heat pipes with variable thermal conductance properties.

During cruise MASCOT will be exposed to a cold thermal regime as it will be shadowed by Hayabusa2's solar panel for most of the time. As the S/S and P/L have to be kept within their non-operative temperature a redundant heater system provides heat to the battery, the electronics-box and MicrOmega as these S/S and P/L are the most temperature sensitive devices onboard of MASCOT. The SLI wrapping the lander module, the MLI covering the MESS and heat pipes, having very low thermal conductance will limit the heat transfer during this mission phase between MASCOT and external surrounding. The heaters will be powered by Hayabusa2 and operated only during the cruise phase. To have a high failure tolerance in this mission, the heater power of critical S/S is configured such that the nominal cruise duty cycle is low, thus allowing the use of a single heater in the event of failure. Before deployment or during cruise checkouts, the duty cycle will be increased to warm-up the components to reach switch-on temperature.

During the "separation-descent-landing"-phase as well as during the on-asteroid phase, the thermal regime will be due to the albedo of the target asteroid, a hot one. In order to prevent MASCOT from overheating, the dissipated heat in the electronics-box will be removed by a redundant set of high thermal conductive heat pipes which are connected to the main radiator, whereas the sub-radiator will remove the produced heat via four metal rods from the battery package, as MASCOT will run on its primary battery after separation.[4]

III.II. Power, OBC, Communication and GNC

For the development and verification of the software- and functional-heavy units, namely onboard computer (OBC), power control and distribution unit (PCDU), communications and guidance navigation and control (GNC) a double-track approach was found to be the best way to speed up software development, testing and debugging and through that to save time during integration and testing on system level.

The first track of this approach included the usage of a Software Development and Verification Facility (SDVF) which served as a testbed for MASCOT's onboard software development and allowed to perform subsystem software functional tests with Hardware-in-the-loop components.

The biggest advantage of the SDVF is its flexibility as it allows to connect all aforementioned units and P/L boards when they are available and to simulate their functions in case they are missing. The absence of a certain unit poses then no showstopper for the software development and testing.

On the second track a MASCOT EM was used for initial conducted EMC and RF transmission tests. The EM was equipped with a complete OBC, a PCDU, antennas, transceivers for communication and EM/QM electronic boards of all payloads.

The here presented approach allowed to find most of the problems on the interface and functional side of each subsystem prior to the final integration.[2]

The resulting design of the aforementioned units is summarized hereinafter.

Power Subsystem

In order to make efficient use of the given mass and volume and to have a sufficiently long on-asteroid lifetime to conduct scientific measurements it was decided to power MASCOT via the umbilical connector by Hayabusa2 during cruise and once separated from its mother spacecraft to rely on a primary battery package consisting of 9 LSH-20 cells in a 3s3p configuration. All power conditioning and distribution functionalities will be handled by the full redundant and single failure tolerant PCDU. Both units were developed and provided by CNES.

Onboard Computing

As the on-asteroid operating conditions remain hardly predictable and Ground Segment intervention is limited, MASCOT needs to perform its tasks highly autonomously in order to react and adjust its operations sequence. This has led to an onboard computer (OBC) design which is dual redundant and capable to deal with health checking and providing FDIR processes in the event of failure. Beyond that it is responsible for data collection, compression, storage and transmission. The OBC comprises of two CPU-boards (main and redundant) and two I/O-boards (main and redundant). The latter set of boards provides I/F to all of MASCOT`s S/S and P/L and is cross-strapped with the CPU boards. Equipped with a NAND FLASH mass memory the OBC is capable of storing over 2 Gbit of scientific data.

The required level of autonomy will be achieved by the “MASCOT Autonomy Manager” which is running as an application on the OBC. Its main functions are to provide a timer and sequencer for coordinating the timeline of events, to prioritize stored data, initiate site changes and to enact attitude corrections.[4]

Communication

The communication between MASCOT and Hayabusa2 is realized during the cruise and on-asteroid phase via an UHF link.

MASCOT is equipped with two patch antennas, one on the top plate and one on the bottom, thus ensuring quasi-omnidirectional coverage. A third antenna is installed on the MESS which is connected via a RF-cable to Hayabusa2 and allows MASCOT to communicate via its top-plate antenna with its mother spacecraft during cruise. All three antennas as well as the corresponding RF-cables and couplers are provided by CNES.

Once separated, Hayabusa2 will switch from the attenuated MESS antenna to the un-attenuated “Onboard-MINERVA-Equipment-Antenna” (OME-A) in order to establish a link to MASCOT and to compensate the increased distance between the two spacecraft.

Inside MASCOT a redundant set of JAXA-provided Child-Communication-transceivers (CCOM) is used to communicate with its counterpart - the Parent-Communication transceiver (PCOM) - on board of Hayabusa2 based on a half-duplex communication and time division multiple access (TDMA) methods. The whole inter-spacecraft communication chain is shown in Fig. 6.

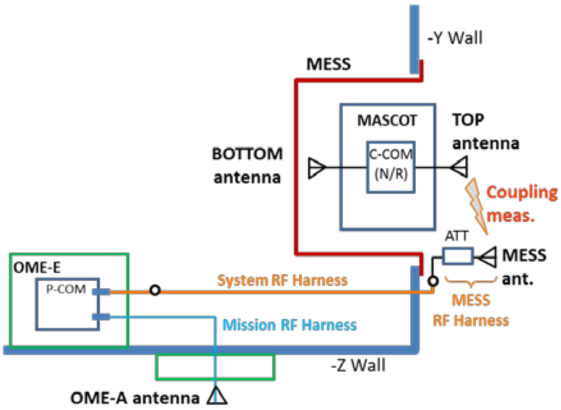

Fig. 6: RF communication chain between MASCOT and Hayabusa2

A maximum uplink rate of 37.037 kbps to Hayabusa2 allows for a considerable amount of housekeeping and science data to be sent. Payload packets will be prioritised in the uplink to ensure that the maximum amount of science data is received on Earth.

GNC (Attitude determination)

In order to determine MASCOT’s motion state and orientation on the asteroid surface, a GNC subsystem based on five optical proximity sensors (OPS) and six PCB-mounted photoelectric cells (PEC) was selected. In addition to that a set of newly developed thermal orientation sensors is onboard for demonstration purposes. This sensor-suite is capable of providing reference information from the local surface topology and solar direction respectively, whereby the information is passed through a filter to determine which side of MASCOT is pointing to the surface.[4]

III.III. Mechanisms and Connectors

Beyond the main units whose development was already described before, it was also required to develop and qualify certain subunits namely mechanisms and connectors as there was little heritage which could be leveraged here. The qualification of these subunits led to an additional test-track layer which came on top of the four already described main test-threads. The resulting design of the most prominent subunits is described hereinafter.[2]

Umbilical Connector

An umbilical separation connector which has some heritage from Rosetta and Philae has undergone an extensive qualification program including environmental and functional unit level tests to assure proper functionality of this mission critical component. The umbilical connects MASCOT electrically through the MESS with its mother spacecraft. The connector design is based on a MIL standard Matrix KJ connector with spring-loaded pins and concave platinum counter faces on the opposing sides (see Fig. 7).

Fig. 7: Umbilical Connector (Flight Model)

Preload-Release-Mechanism

A Preload-Release-Mechanism (PRM) was developed in order to reduce the preload of 2.5 kN which was required to keep MASCOT in place during launch but could lead to a too high ejection velocity during separation. A too high velocity could cause MASCOT to bounce off the asteroid. The PRM is composed of two thermoplastic disks which deform when heated to relax the spring tension and allow a preload reduction down to 200 N. As the activation of the PRM and the resulting preload reduction are highly temperature sensitive activities, numerous tests were performed to characterize its behaviour prior activation on the MASCOT FM which was successfully performed during MASCOT's calibration in September 2015.

Separation Mechanism

A separation mechanism using a compressed spring and a V-shaped push-off plate was developed and qualified in several drop-tower campaigns in order to allow MASCOT to be safely ejected from the MESS / Hayabusa2. Safe means here at a velocity of 0.05m/s. A Non-Explosive-Actuator (NEA) which will release the spring propelled separation mechanism is part of MASCOT, but controlled by Hayabusa2.

Mobility

Once having arrived on the surface of 1999 JU3, MASCOT will rely on its mobility mechanism to upright itself in the event that it lands on any side other than the baseplate and to change the location on the asteroid surface via hopping. As the gravitational conditions on the asteroid can be hardly replicated on Earth, the principle functionality of the mobility mechanism was verified through a zero-g flight test campaign for the uprighting and through numerical simulations for the hopping.

The resulting design consists of an internal excenter mass that is rotated to cause a reactive force and apply jerk to the overall MASCOT. The acceleration and deceleration as well as the start and stop positions of the excenter arm are controlled parameters which are used to execute short flips for the uprighting with a low force implied and long distance hops to change the location with a strong force implied. Imperfections in the underlying soil and an off-axis alignment will ensure that 6-degree rotation is possible. The radial components of any uprighting/hopping velocity will be restricted (by command) to less than half the escape velocity of the asteroid to ensure safe operation.[5]

IV. PRE-LAUNCH ACTIVITIES

IV.I. Planned Activities

The planned pre-launch activities can be divided into the “Hayabusa2 Level Acceptance Tests”, the “Late Access Activities”, the “Final Integration and Flight Simulation Test” and the “Launch Campaign”.

Hayabusa2 Level Acceptance Tests

Originally the MASCOT FM was foreseen to join Hayabusa2 Level Acceptance Tests from the very beginning. However, due to some delays on the FM track, the EQM which successfully passed cruise thermal vacuum, shock and vibration, conducted and radiated electromagnetic compatibility (EMC) and full functional tests of all subsystems and instruments, was assigned to join Hayabusa2 on the first part of its acceptance test program until the FM became available. The EQM participated in the thermal vacuum and communication tests together with its mother spacecraft.

End of June 2014 the MASCOT FM arrived in Japan and replaced the EQM for the second part of the acceptance test program which at that point in time foresaw an acoustic and sine vibration test as well as further communication and flight operation tests.

Late Access Activities

After having passed the acceptance tests, MASCOT FM was demounted from Hayabusa2 and entered the late access activity phase which included an EMC and RF Coupling-test. Beyond that the battery was supposed to be replaced against the flight version and a magnetic signature determination was also on the task list.

The EMC test on the FM was performed in an abbreviated manner as the electrically fairly similar EQM had already undergone an unexpectedly successful EMC campaign including bonding, isolation, inrush current, conducted and radiated emission (CE, RE) and conducted and radiated susceptibility (CS, RS) tests. In order to maintain the overall schedule especially at this point in time, and due to the fact that usually CS and RS are viewed as too risky for FMs and therefore only done if there are significant deviations in CE and RE, it was decided to perform only the latter. The MASCOT FM passed as successfully as the EQM. Ensuring a safe operability of the mother spacecraft was paramount for the definition of this minimum set of requirements.

Due to the absence of a specific license our team was required to perform this test in a modified anechoic chamber. The modifications were related to grounding and cleanliness issues which were addressed by an EMC invisible tent and a dedicated grounding for MASCOT.

The same modified facility was then also used for the RF coupling test in which the antenna behaviour was characterized for comparison with the simulated link budget.

For the CE part of the tailored EMC test campaign as well as for the low and high power mode test of the CCOM's, MASCOT was moved to a Mu-chamber which is a radio and magnetic isolated clean chamber. But the main reason to put MASCOT into this chamber was to determine the magnetic signature caused by MASCOT and especially by its flight battery as measured by MAG.

So the swap of the battery was a prerequisite for this test and as already mentioned above a planned activity. However, as some issues were found with both of the flight like battery packages (FM and FS), the planned activity triggered some unplanned activities which will be outlined in the following chapter.

Prior to the final integration of MASCOT, more tasks were waiting for execution. Among them were the replacement of the outer walls made of SLI, the measurement of the final mass and the final centre of mass, the confirmation of the separation spring performance and its final adjustment, the cleaning and sterilization of the optical sensors and last but not least the removal of red-tag items as well as the connection of the safe-arm plug of the single-shot units.

On top of these planned tasks came again some unforeseen activities which will be presented in the subsequent chapter.

Final Integration and Flight Simulation Test

MASCOT and MESS were assembled and secured with the previously discussed preload, before the package was handed over to JAXA for final inspection, electrical check and integration to its mother spacecraft. On that occasion also a late change request from JAXA to adapt the Frame-MLI covering the protruding parts of the MESS and to relocate the grounding plate was fulfilled.

Shortly after that, MASCOT was prepared to participate in the Hayabusa2 Flight Simulation and Operations Test. The purpose of this test was to demonstrate that all spacecraft components are compatible with the bus system after final assembly and to give first cross-reference data for the launch check-out and the early operation phase in space. As this activity foresaw an ignition test of all spacecraft pyro-technical units, a reasonable solution for MASCOT was required, as the amount of remaining NEA's was constrained and an activation of the MASCOT built-in NEA was not acceptable as it is a single shot device whose replacement requires the total de-integration of the lander. The solution found was a representative NEA-simulator (in terms of current level and blow time performance) using specifically selected commercial break fuses and flight-like QM and diagnostic EM units. In order to assure a high representativeness of this simulator, its behaviour was cross referenced with data from previously performed drop-tower tests.

Launch Campaign

The shipment of Hayabusa2 and MASCOT to the launch site marked the beginning of the Launch Campaign. On Tanegashima Island MASCOT received its final software update prior launch via an external test connector while powered by the mother spacecraft. Another RF test between MASCOT and Hayabusa2 was performed, whereby MASCOT was covered by a shield box due to RF license regulations. During this test a major non-conformance on the CCOM-Redundant was found which triggered another unplanned series of activities which will be detailed later.

Beyond that some other software related issues with the data transfer between MASCOT and Hayabusa2 caused by the OME-E were investigated. The problem was that the OME-E stopped MASCOT frequently from transmitting data to the mother spacecraft, when the OME-E struggled to transfer the received data from its buffer to Hayabusa2 main storage. This resulted in packet loss and an effectively lower data rate. As this was a problem which could be addressed via a software update it was agreed to investigate this more in detail after launch.

After a final health check MASCOT's good performance was confirmed and Hayabusa2 and its small passenger was placed on the rocket adapter and declared ready for launch.[2]

IV.II. Unplanned Activities

The aforementioned battery issue surfaced just prior to the MASCOT FM joining the acceptance test program of Hayabusa2. The comparison of the thermal test results of the MASCOT EQM and FM indicated that the heat transfer within the battery package in the QM battery (which was tested on the MASCOT EQM) differed from the FM and FS battery, whereas the FM battery was supposed to fly. Although identical in design, this non-similar thermal behaviour required further investigation in order to select a battery package with an acceptable thermal performance for flight. A thermal imaging test provided the desired characterization and led to the decision to install the FS battery on the MASCOT FM during the late access activities. The obtained results allowed also to define temperature set points for the battery heaters in order to stay within the non-operating temperature limits during cruise and provided enough data to define a pre-heating strategy prior separation.

Another thermal related non-conformance was found with the MicrOmega heater on the MASCOT FM. The measured duty cycle deviated from the specified one which indicated that either one heater circuit was damaged or that the wiring of the redundant heater was mixed-up during integration. If not corrected, this could have led to a violation of the lower non-operational temperature limit during the cold cruise phase and in the worst case to a damaged or even lost payload. As a de-integration and return to the manufacturer was not in line with the overall schedule a pragmatic solution was required. Measuring the heater resistances under ambient temperatures was not an option, as the redundant heaters were protected by thermostats which close the circuits only below -30°C. The only practical way to solve this problem was to reach that temperature. But cooling only the thermostats or the unit would have resulted in a non-acceptable contamination risks due to condensing droplets. Insofar it was decided to put MASCOT into a climate chamber with a defined dew-point. In order to address the cleanliness requirements MASCOT was isolated by a sealed clean bag which was flushed with pure nitrogen. The performed test confirmed the mixed-up wiring theory and led to a straight-forward corrective action.

The second MicrOmega-related unplanned activity stemmed from the fact that the FM-harness which connects the systems electronics with the sensor unit, differed in shape from the one used on the MASCOT EQM, so that it came very close to MARA's field-of-view (FOV). As this overlap would have resulted in an unacceptable reduction in scientific output on MARA side, a pragmatic solution was again required. The solution came in the form of an adjustable connector saver which could move MicrOmega's connector and attached harness out of MARA's FOV. As the implementation of such a saver posed no risk for the structural integrity of the lander, the manufacturing was kicked-off and the connector underwent an abbreviated functional, cleanliness and outgassing program.

Another connector-related unplanned activity was caused by the fact that a termination plug (a green tag item), short circuiting the open lines of MASCOT's test connector (which is even accessible when the lander is attached to its mother spacecraft), failed to arrive in Japan. Launching without this plug was not an option as the OBC could then not make use of its redundant signal paths to MAG and MARA. The refurbishment of an available EM terminator on-site with flight-like material brought the desired solution in this case.

During one of the final communication tests on the launch site a significant sensitivity reduction of the CCOM-Redundant was found. The reduction is so severe that a landed MASCOT cannot communicate any more via its CCOM-Redundant with a Hayabusa2 in its home position. The options which were on the table were anything but attractive. A replacement of the CCOM-Redundant would have taken 6 weeks as a refurbishment by JAXA would have been required and would have resulted in an unacceptable launch delay and possible target asteroid change. An expert team formed by JAXA, DLR and CNES representatives conducted a workshop on this non-conformance and agreed that a further degradation of the CCOM-Redundant is not expected as the cause of this reduction in sensitivity was very likely a onetime event which was a too high input on the receiving channel during one of the previous tests. As the CCOM-Main was still working without a single flaw it was decided to give a recommendation for the planned launch and to fly MASCOT, as it is.[2]

It was also agreed to use primarily the CCOM-Main during cruise and to consider the CCOM-Redundant only as a backup. The PCOM on Hayabusa2 side will be operated in the low-power mode. In case the CCOM-Redundant should be needed, the PCOM would be switched into the high-power mode to allow a reception by the CCOM-Redundant. This critical switch-over would then be handled by a command from ground. For the on-surface phase again the CCOM-Main is considered as the primary means of communication. However, in case MASCOT would need to rely on its CCOM-Redundant, it is currently under investigation to lower Hayabusa2's altitude from 20 km to 1.5-3 km in order to improve the link budget by shortening the distance.

V. POST-LAUNCH ACTIVITIES

V.I. In Space

The launch of Hayabusa2 with MASCOT aboard occurred on December 3rd, 2014, 04:22 UTC. Delayed by only 3 days due to bad weather conditions at the Tanegashima launch site, the launch itself was flawless (see Fig. 8).

Fig. 8: Launch of Hayabus2 with Mascot on December 3, 2014, from Tanegashima Space Centre, Japan.[2]

While MASCOT was off during the launch and early orbit phase (LEOP), only the expected activation of the Hayabusa2 controlled Heater Control Element (HCE) indicated that MASCOT was still properly connected via its umbilical with its mother spacecraft.

In order to get a comprehensive picture of MASCOT's health state a dedicated in-flight health check (HC) was planned for December 16, 2014 (see Table 1).

Ops	Activity	Date	Start/Stop [UTC]
#1	Health Check #3	16.12.2014	13:20 to 15:23
#2	Health Check #4	18.06.2015	07:59 to 11:42
	RF test	19.06.2015	07:45 to 12:31
#3	Calibration	17.09.2015	05:11 to 22:15
	PRM activation	17.09.2015	21:42 to 21:54

Table 1: Overview of MASCOT operations since launch

The objective of this test was to activate each P/L and S/S and through that to obtain some house-keeping (HK) telemetry in order to conclude on the health state of the system.

The shown performance during this test led to the conclusion that MASCOT's overall health state is nominal.

Almost all P/L and S/S responded as expected. Only MAG recognized some external disturbances caused by the presence of the mother spacecraft, but not a single contingency request was raised.

The data transmission performance to Hayabusa2 improved compared to the situation on ground and also the CCOM-Redundant has shown no further degradation once arrived in space. Nevertheless it was decided to perform a dedicated RF test to get a better understanding on the link budget side as well as on the functional side.

The next opportunity to do that was end of June 2015. As MASCOT spent 6 months in hibernation mode a pre-heating of the system was required in order to reach the switch-on temperature of the OBC inside of the electronics-box. For this purpose the temperature set points of the HCE were changed on June 16 from -33 and -28°C to -10 and -5°C (HCE-A/B). The temperature increased as expected and MASCOT could be activated on June 18 for another in-flight health check.

During this test all P/L and S/S were activated again and showed nominal performance based on the data which could be successfully transmitted to ground as the OME-E struggled massively under the amount of data packages which queued up on MASCOT side for transmission. The reason for the lower data transmission performance was that the OME-E was not operated in mode 4 as during the HC in December 2014, but in mode 3. The difference between these modes is that mode 4 allows a faster data transfer from the OME-E buffer to Hayabusa2 storage than mode 3.

Beyond that the amount of transferable data was higher compared to the December 2014 HC as e.g. the PCDU data acquisition frequency was increased in order to cover the power data during the CAM operation.
The second part of this operation foresaw on June 19 a dedicated RF test in which the settings on the OME-E / PCOM on Hayabusa2-side and for the CCOM on MASCOT-side were varied in order to characterize the RF link performance in space. For this purpose the OME-E selected not only the MESS antenna to communicate with MASCOT, but also the OME-A antenna. Also the PCOM was operated in low as well as the high power mode. On MASCOT side the CCOM-Main and CCOM-Redundant were used and both operational frequencies (958.5 and 954 MHz) were tested.
The only parameter which was not changed was the CCOM power mode, which was required to stay at the lower level throughout all test cases in order not to harm the PCOM at this short distance.
The used antenna on MASCOT side was selected automatically by the OBC based on the Received Signal Strength Indication (RSSI) value. Throughout all cases the top antenna was selected.

The only forbidden test case was to operate the PCOM in high power mode in combination with the healthy CCOM-Main as this could have resulted in a likely damaging of this unit at this distance.

In total 11 different test cases were investigated and unveiled some surprising results.
It was already expected to establish a working link between the CCOM-Redundant which has a reduced sensitivity and the PCOM, when it is operated in a high power mode. So the successful demonstration of this link was not a surprise. What was more surprising was the fact that a working link could be established between the OME-A antenna and MASCOT's top antenna. Furthermore, the measured RSSI values were in all tested cases higher than the ones which were measured while the MESS antenna was used. This means MASCOT has two means of establishing a RF link during cruise which is in other words an unexpected additional form of redundancy.
The reason why this behaviour was not found earlier and a MESS antenna was foreseen in MASCOT's design is mainly due to the fact that not all minor details which can potentially affect the propagation of electromagnetic waves can be taken into account in RF link simulations. Beyond that it has to be mentioned that there was never an opportunity to perform a RF link test aboard Hayabusa2 in an anechoic chamber.

In consequence of the superior performance of the RF link with the OME-A antenna, it is currently under investigation whether it makes sense to use the MESS antenna during the upcoming operations during cruise. But during separation it might be required to rely again on the MESS antenna as the anticipated movement of MASCOT through the near-field of the OME-A could result in harmful high received signal power. This issue is also currently under investigation.
After the successful completion of the RF test MASCOT was shut-down and brought again into the hibernation mode.

On September 17 and 18 two slots were foreseen in which MASCOT could be operated.
After the required pre-heating, MASCOT's instruments were calibrated and the PRM was successfully activated. The analysis of the downloaded calibration data is still ongoing.

From now on MASCOT will be checked every 6 months until Hayabusa2 arrives at 1999 JU3 in summer 2018. The next operational activities in this series will include a software update for MASCOT's OBC which is currently scheduled for the spring of 2016.

V.II. On Ground

Three months after the launch of the MASCOT FM, the MASCOT FS became available so that the list of open points from the pre-launch phase could be addressed.

Thermal - Open Points

Among the first tests was the TVAC-6 campaign in March 2015. The cruise phase, the arrival at the home position as well as the separation, descent and landing were simulated in this test.
The objectives of this test were to obtain all data for the evaluation of the healthiness of the currently applied pre-heating and long-term heating strategy of the battery, to improve the thermal modelling of the battery package, focusing in particular on the thermal gradient present between each battery cell and last but not least to obtain all the data which were required to finalize the thermal model of MASCOT.
The performed test confirmed that the currently applied heating strategy (usage of temperature set points) on the FM is in line with the thermal requirements. Beyond that it was possible to demonstrate that an operational sequence for MASCOT could be defined in which the spacecraft would not risk to overheat while Hayabusa2 would

perform its descent down to MASCOT's separation altitude.
In the future it is also under investigation to perform another TVAC test in which the on-asteroid phase would then be simulated.

Battery-related Activities

In order to allow the MAM to operate MASCOT in an energy-saving manner and through that to perform as many scientific measurements as possible, and to know how much energy is left in MASCOT's battery, an algorithm for the determination of the remaining energy is under development and shall be uploaded with the OBC software update as soon as available.
As the cell performance is depending highly on the thermal environment and the applied discharge current a proper thermal-electrical characterization of the cells is mandatory.
For this purpose battery discharge tests were already performed, but as it turned out the dependencies are more complicated than previously thought, so more tests are required.

These tests will also help to define a de-passivation strategy for the battery package onboard of MASCOT. As the amount of flight-like batteries is limited a test battery will be built in order to support these various tests.

This battery shall also be used to power MASCOT in a functional test in which the on-asteroid phase will be simulated. The purpose of this test is to unveil any kind of battery driven non-conformance which might be addressed by operational means.

In case the detailed analysis of this yet to be performed functional test on the MASCOT FS and/or the already performed calibration on the MASCOT FM should unveil any kind of EMC-related problem, it is planned to perform a third EMC test with the MASCOT FS in order to characterize this problem and to find operational and or software-driven solutions as the flight hardware cannot be changed anymore.

FDIR-Implementation and End-to-End-Tests

In parallel to these tests the definition of FDIR-cases on system level was continued, but is still not finished. Also the discussion with the scientists regarding the functionalities which are currently implemented in the MAM led to some additional review demand which will very likely lead to some software change requests.

Last but not least a proper End-to-End test has to be performed in order to give the confidence that MASCOT will know what to do and how to do it once it has left its mother spacecraft and reached the asteroid surface. In order to support these activities it is also foreseen to build a dedicated MASCOT Ground Reference Model (GRM).

Communication-Issues

The data transmission issues between MASCOT and Hayabusa2 will hopefully be overcome soon by a long-awaited software update for the OME-E which will increase the variable buffer within the OME-E. In parallel the need to address the reduced sensitivity issue on the CCOM-Redundant by operational means will be investigated among the project partners.

VI. CONCLUSION

The MASCOT-Project taught us that it is possible to develop a highly integrated asteroid lander with unique capabilities in less than 2½ years.
In principle the concurrent AIV strategy which we followed in this project could also be applied in other interplanetary projects in order to increase the efficiency and to reduce the duration of the project implementation phase.

However, it has to be clearly stated that this strategy is not free of side effects and it needs certain organizational prerequisites in order to being successfully applied. This means firstly a team culture which is characterized by an open, solely engineering-driven, solution oriented mind-set, where mutual trust is omnipresent and hierarchy thinking is limited to a minimum. Examples for the aforementioned side effects can be found in MASCOT's pre-launch phase when problems appeared which were solely caused by the limited time as e.g. the MicrOmega heater mix-up. Although it was possible to overcome the majority of these problems and to clear the way to the launch pad, the list of required post-launch activities on ground is a clear indicator that in such a fast paced high performance project the work does not end with the lift-off of the spacecraft. As such a significant amount of the personnel which was working prior launch on the project is also bound afterwards for a longer duration compared to projects with a longer development time.

Despite these lessons, MASCOT's in-flight health condition as observed during its first health checks and calibration is as pristine as its performance is flawless and leaves us optimistic for the activities to come. Here it seems increasingly likely that MASCOT works so well not despite the timelines on and the ways in which it was built, but because of them: As early as possible, as broadly scoped as possible, and usually highly parallel testing of the most 'real' (i.e., flight-like) hardware and software available was required and performed throughout, for more than 2½ years of a barely 3 years long AIV phase.

Beyond the concurrent AIV methodology, the lander concept itself could become an "Export-hit" as it is from the mass and volume requirements a very attractive P/L for any small-body-mission. Therefore it is not a surprise that MASCOT-derived lander concepts are currently under consideration for upcoming asteroid missions.

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