Going Beyond the Possible,
Going Beyond the "Standard" of Spacecraft Integration and Testing!

– A Summary of the DLR Mascot AIV Activities within the Hayabusa2 Project from the First Unit Hardware Test to Final Check-out before Launch –

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Mascot, a small 11 kg Asteroid Lander on-board JAXA's Hayabusa2 space probe, was launched on December 3rd, 2014. To catch this particular launch opportunity its development timeline needed to be heavily compressed so that current and well established verification processes could not be followed in order to finalize the project in the given time. Applying a unique mix of conventional and tailored model philosophies it was possible to dynamical adapt the test program to accomplish for the shortest planning and a suitable weighing of costs and risks. A strategy of Concurrent AIV helped to identify and mitigate design and manufacturing issues and shortened the test timeline further from a general 4-5 year phase to 2½ years. This paper provides a summary of the performed Mascot development process and its verification strategy which goes beyond the possibility of today's *Standard* of Spacecraft Integration and Testing.

Key Words: Mascot, Hayabusa2, Asteroid Lander, Concurrent AIV, Late Change Requests

Introduction

As today's projects increase quickly in complexity and development times are shortened to save budgets, schedules become so compressed, and resources are so constrained, that the corporate goal of such projects is to overcome impossible odds and to achieve miracles.[1)] The DLR Mascot project, a small 11 kg Asteroid landing package on-board JAXA's Hayabusa2 space probe launched on December 3rd, 2014, had such constraints (Figure 1). Selected at a time when its conceptual design and scientific payloads had not been fully defined; with the carrier spacecraft already in its critical design phase having most of its interfaces fixed; only 2 years left until a proposed final delivery of the flight unit; and no heritage to use off-the-shelf equipment directly, a full prototype design of a miniaturized asteroid lander to an unknown target became necessary.[2,3)]

Generically, choosing the right verification process is crucial and driven by risk tolerance. Less verification implies but does not necessarily create more risk. More verification implies but does not guarantee less risk.[4)] Though according to the standards currently in use, like the one from the European Cooperation for Space Standardization (ECSS) or from the NASA Technical Standards Program (NTSP), such a plan would have been classified as impossible and would have been cancelled due to lack of available schedule time. However, as performed and shown in the Mascot project an alternative answer would be to leave the comfortable zone of the known standards, reiterate the given requirements and establish a tailored standard which achieves both, enough confidence in the products performance as well as finding the shortest planning including a suitable weighing of costs and risks.

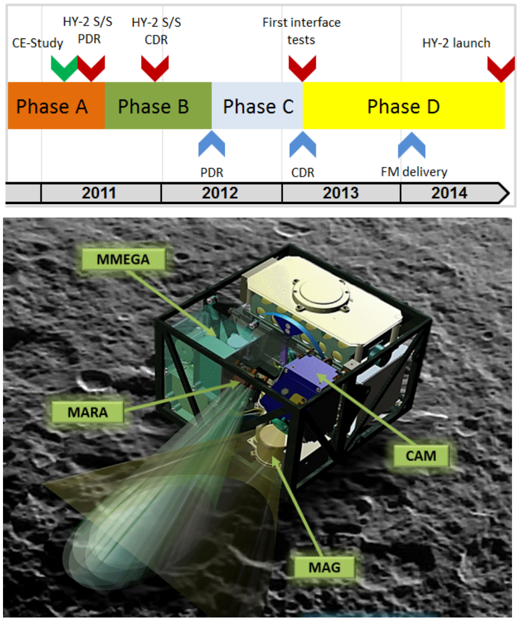

Fig. 1. Top: Mascot project timeline with major milestones; Bottom: Artists impression of the landed Mascot on the surface of 1999 JU3 indicating the operation of its four payloads; Camera (CAM); Radiometer (MARA); Magnetometer (MAG); Microscope (MMEGA).

1. Concurrent AIV

To realize the Mascot project its Assembly, Integration and Verification (AIV) program had to be optimized. It could not follow a classical sequential approach, in order to allow for appropriate margins. The heterogeneous maturity levels have led to the tailoring of a mixed model philosophy of the subunits into an adaptable overall Hybrid Approach.[5)] Furthermore, the project incorporated parallelization of testing activities using multiple copies with subunits compiled to be as identical as possible for the purpose of the test and a high rate of flexibility in its development process to quickly react on delays due to non-conformances on systems, units, parts and facilities. This in turn created independent unique test threads only joining their dependencies at key points where optional other roads could be chosen. Like Concurrent Engineering, a methodology based on the parallelization of engineering tasks nowadays used for optimizing and shorten design cycles in early project phases, we introduced the term "Concurrent AIV" to express the simultaneous running test and verification activities.[6)] In effect, the development tracks of Structural-, Thermal-, Software- and Functional Testing got their own independent routes sharing their verification processes (Figure 2).

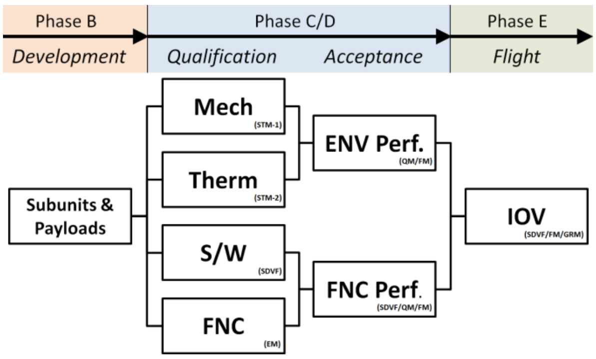

Fig. 2. Mascot Concurrent AIV strategy

Also, certain flexibility between these 4 major threads allowed for in-parallel subunit testing. This included test models reorganization, refurbishing and re-assigning previous models for other verification tasks if appropriate, skipping test cases, parallel testing of similar or equal models and for some equipment and components allowing the qualification on a higher *Mascot System Level* (Table 1).

Table 1. Mascot System Level Hierarchy

1	Hayabusa2 Spacecraft Level
2	Mascot System Level
3	Mascot Module Level
4	Mascot Equipment Level
5	Single Component Level

The challenges in creating parallel development lines were found in team and facility resources where these were not readily and on-demand available. This philosophy is also more complex as it requires the overview of the development process of the mother spacecraft, the ongoing progress on system level as well as the insight in all payloads and subsystems. This was handled by splitting the tasks on more Systems Engineering and AIV responsible personnel and performing regular consolidation gatherings between these key players including also the Project Management and Product Assurance, in order to keep the project sorted and on course. These gatherings were held daily, strictly limited in time and based mainly on current test schedules and observed non-conformances. This allowed the core team to quickly react on critical matters saving valuable time usually lost easily in hierarchy driven management decision processes (see for reference – Obeya, Toyota Production System).

1.1. Structural Integrity and Thermal Concept Testing

The two most challenging hardware verification tasks on *Mascot Module Level* were the development and qualification for its primary structure and its primary thermal concept. In order to meet the strict mass and volume requirement an ultra-lightweight CFRP-foam sandwich frame was designed for Mascot's Landing Module (LM) and a solid CFRP truss frame for its Mechanical and Electrical Support System (MESS), which remains on the Hayabusa2 spacecraft after separation. The thermal design, since Mascot will separate from its mother spacecraft, was required to have a robust system which can withstand a wide range of temperatures during the different mission phases like "Cruise Phase", "Separation-Decent-Landing" and "On-Asteroid Operation". For this, a semi-passive thermal control was selected including Multi-layer Isolation (MLI) and redundant heaters to keep all subsystems and payloads within their non-operative temperature during cruise and a redundant set of 3D-heat-pipes to remove all excessive heat from the sensitive electronics. Due to its compact size and highly integrated nature, the thermal performance is highly dependent on the structural design and vice versa. A small change in one area can have a significant impact in the other. However, neither of these two aspects could take advantage from a previous design, which led to a full prototype qualification program. A first STM model (STM-1) intended to qualify first the structural design, however, failed its initial test. As a consequence, the remaining timeline did not support for sequential structural and thermal testing. In order to keep the verification time short and to test both areas as close to each other as possible, two identical models of the iterated and improved STM were produced (STM-2.1 and STM-2.2) which could run completely independent qualification activities (Figure 3).

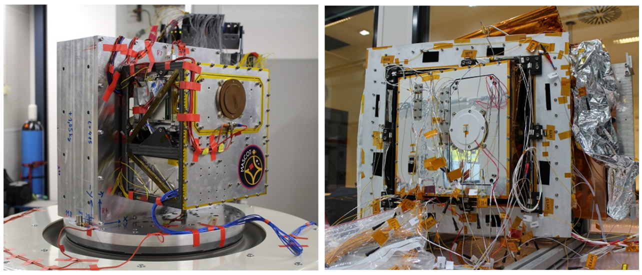

Fig. 3. Left: Mascot STM-2.1 during Random Vibration Test; Right: Mascot STM-2.2 during Cruise-Phase Thermal Vacuum Test.

Due to similarity in design, by testing one sub-aspect (e.g. structure) at one model, meant verification of this aspect in the other model as well but without the need for actual testing.

1.2. Software and Functional Testing

A Software Development and Verification Facility (SDVF) was created to establish a general test bed for Mascot onboard software development and subsystem software functional tests with real hardware-in-the-loop electronic (Figure 4, left). The facility can be connected to an electrical interface unit for the system electronic boards including backplane, science payloads (P/L) boards, onboard computer (OBC) and power control and distribution unit (PCDU). The SDVF can therefore simulate certain spacecraft components by software simulation and at the same time supports physical connection by their hardware interface to the available hardware at that point in time. This way, every payload and subsystem can freely do debugging tests with the OBC which can take longer time when done independently or sequentially. E.g., the OBC can be connected to the SDVF simulating the other system elements which can later be added piece-wise whenever hardware becomes available; or the other way around, the OBC is simulated by the SDVF for the other already available hardware. The SDVF is also capable of simulating all Hayabusa2 spacecraft functional units completely in software i.e. the OBC and other subsystems. This boosts up significantly the speed of software development and testing. It enables software development and testing to be done from any computer anywhere without dependency on the availability of hardware. In a final step, the real OBC board could be integrated running in real-time manner and verifying Mascot's functional performance. These functional tests did run continuously until functional performance of all real hardware electronic boards were approved and the cards could be implemented into the Mascot EQM. With this approach, most of the problems on the interfaces of each subsystem were found before the final integration. This significantly reduced integration problems and troubleshooting time during the later *Mascot System Level* integration and testing.

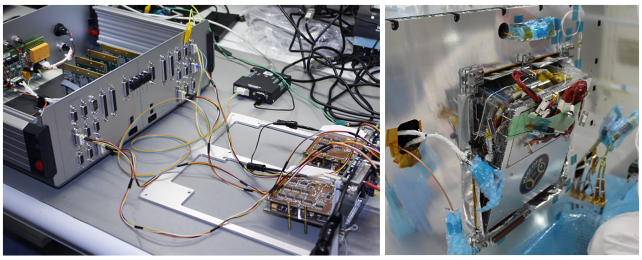

Fig. 4. Left: Mascot SDVF electrical interface unit during conducted EMC test including On-Board Computer and Power Distribution and Control Unit; Right: Mascot EM mounted to Hayabusa2 during Initial Integration Test verifying mechanical interfaces as well as basic communication and subunit performances.

Aside from the SDVF, a separate Mascot EM was built having functional communications equipment including OBC, PCDU, Antenna, CCOM units as well as EM/QM electronic cards of all payloads (Figure 4, right). This model was used for initial conducted EMC and RF transmission tests. Furthermore, using a mock-up structure resembling Mascot in form and fit this EM could also support parallel functional testing as well as initial mechanical interface tests on *Hayabusa2 Spacecraft Level*. Here, some of the subunits were either replaced by mass dummies to suit the overall weight and handling or simulated by load resistors to test the current drains.

1.3. Subunit Development and Interface Testing

As mentioned above, most of the equipment and components of Mascot were full prototypes or having only minor heritage from previous projects (e.g. more in circuit design than in hardware shape and form). The main subunits and other non-electrical interfaces which had to be developed and qualified along the main system were the Umbilical Separation Connector, the Preload-Release (Launch-lock Mechanism), the Separation Push-off Mechanism, the Depressurization Stability, the 3D-Heat-Pipe Performance and the Structure-Thermal Interactions. For these tests, if appropriate and available, the systems STM units were refurbished and reused, which ensured a direct relation to the final flight system. In total more than 40 additional *Mascot Equipment Level* test campaigns were performed. With the already in parallel running 4 main treads (Figure 2) these subunit tests added an additional layer of test activities. As a consequence for peak times, more than 10 different test campaigns had to be performed independently and at the same time. This excludes any test performed by the Payloads or other subsystems provided by the collaborating partners and contractors during subunit development. However, the Mascot team performed countless unit debugging tests with these systems to help fix electrical and software interface problems including campaigns with Power Supply, RF-Communication, Mobility Mechanism, GNC and the 4 scientific payloads; the Camera, the Radiometer, the Magnetometer and the Hyperspectral-Microscope (Figure 1).

1.4. Environmental und Functional Performance

After the concurrent qualification program of the systems main modules the process could enter the systems acceptance phase. Environmental Performance was tested with a full qualification program of the EQM and an abbreviated acceptance program with the FM. Both units, running their tracks in near-parallel activities, gave also the possibility to verify the systems Functional Performance in its respective launch and cruise conditions (Figure 2).

The EQM successfully performed its program for cruise thermal vacuum, shock and vibration, conducted and radiated electromagnetic compatibility (EMC) and full functional tests of all subsystems and instruments. After some small refurbishments the EQM was shipped to Japan to undergo the first part (thermal vacuum) of the *Hayabusa2 Spacecraft Level* acceptance tests, testing also basic communication with the mother spacecraft. During this period late change request from the Hayabusa2 team to make modifications on the systems frame-MLI and the repositioning of the main grounding plate were discussed and which were agreed with the Mascot team to be implemented with the soon to arrive FM (Figure 13).

The FM meanwhile went through its abbreviated *System Level* acceptance tests including vibration and cruise thermal vacuum. Some acceptance and calibration tests needed to be skipped or shifted to a Late Access opportunity in order to deliver the FM in time to take the place of the EQM and finalize the second part of the *Hayabusa2 Spacecraft Level* acceptance program (acoustic and sine vibration as well as communication and flight operation tests).

Since the EQM and the FM (Figure 5) performed near-parallel activities before being shipped only 3 months apart, comparing the thermal test results of both programs revealed some unexpected findings. There were differences in reaching steady state conditions with the used QM+FM Battery units. Although identical in design, indications were strong of an insufficient insulation. Since for flight there was still the decision to be made to use either the FM or the FS Battery, uncertainty about this non-similar thermal behavior had to be understood.

Moreover, the necessary heater power for the Microscope's duty cycle was found to be different than specified. This indicated that either one heater circuit was damaged or that there was a mix-up with the wiring of the redundant heating circuits during integration. Analyses from the measured values during the *FM System Level* thermal vacuum test (the Mascot EQM only used a non-functional STM unit of the Microscope) as well as from documentation were not conclusive.

Apart from the heater wiring, the Microscope's FM harness, connecting the systems electronics with the sensor unit, showed also physical differences with the one used for the EQM. The connector design, though manufactured with flight standards, was not a well fit with such a compact system design. As an example, no single connector back-shell was used inside Mascot due to volume constrains. As a consequence, one of the Microscopes connectors came very close to the field of view (FOV) of the Radiometer. Verification by CAD and additional 3D measurement verified an offset, which led to adapt the Radiometers stand-offs position in order to reduce the risk of an actual overlap. However, the real connector could not be modeled in CAD and the final verification needed to be made with a dedicated FOV-device during the late access activities (section 2.4).

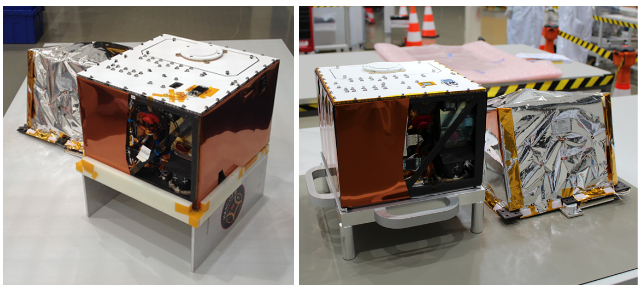

Fig. 5. Mascot EQM (left) and Mascot FM (right) after their respective final assemblies.

1.5. Paradigm Change for Late Change Requests

To perform a concurrent strategy as described above already took some adjusted mindset from a standardized sequential approach, or even from a generalized hybrid approach. The findings during the system's acceptance phase, which can be seen as a direct consequence of such a hard tailored approach, needed another and more dramatic paradigm change as engineering changes at this stage can put high risk to other subsystems, the whole lander system itself and even to the main satellite.

In order to still stay within the limited schedule the found non-conformances and indications for other issues were taken out of the main track to find solutions in parallel along the remaining integration and test time. The remaining campaigns were continued, but leaving an opportunity to make necessary changes at a later point in time. For this purpose, a special risk assessment and verification strategy was established (table 2). If all the points in the list could be answered with a "yes", also a late change on the FM just before final integration into the satellite was acceptable. To really go for such a no-frozen-design approach takes some adjustments in the normally applied and used to absolute-minimized-risk oriented verification ideology. Those adjustments need to be and are not limited to: common sense and engineering experience as a driver for quick decisions inside the core team; allowing the communication of experts (even from different organizations) directly between each other with no hierarchy implied bottlenecks; lean documentation with no formal document style and no extensive signature loops; including subcontractors as project partners to understand the need to implement small changes even at later stages; Quality Assurance shall be seen as a subsystem and not just as a pure control entity (it builds the interface to established processes and guidelines, but in a way that these can be adjusted whenever necessary). One also has to overcome the responsibility question – rather than asking "who did it?", focusing on "how can it be solved?".

Table 2. Criteria list for implementation of late change requests

#	Criteria	Yes/No
1	is it critical for the affected subsystem to either endanger overall mission success or the value of scientific output?	
2	is it not possible to solve the problem by an operational back-up or alternative strategy?	
3	can it safely be tested/implemented or can further precautions, which are acceptable in terms of time and budget, significantly reduce the risk?	
4	is it non-critical for the main spacecraft or other lander subsystems?	
5	can success criteria be simply formulated and can they quickly be tested?	
6	are test facilities, experts and other personnel available?	
7	can a common agreement be found quickly between the system experts and the principal investigators?	

2. Late Access Activities

After the final environmental acceptance test on *Hayabusa2 Spacecraft Level*, the Mascot FM was demounted from its carrier to undergo some last refurbishments to be readied for launch. This possibility was used also to perform some acceptance tests on *Mascot System Level* which had to be skipped earlier. The time off the main spacecraft, however, was short and the remaining activities had to be performed under heavy time constrains.

2.1. EMC and RF Coupling

A test for Mascots' compatibility to Electromagnetic radiation (EMC) was performed already on the Mascot EQM including bonding, isolation, inrush current, conducted and radiated emission (RE, CE) as well as conducted and radiated susceptibility (CS, RS), The FM, though almost identical to the EQM, had not seen this test. To make sure the FM does also fulfill a minimum set of requirements to ensure operational safety of the main spacecraft an abbreviated test was agreed (CE and RE only). At this stage CS and RS was not performed as it was decided to be too risky for Mascot and would also not usually be done for FMs. In order to perform this test without a specific license this test was performed in an anechoic chamber at ISAS. Usually used as an antenna test range for antenna development tests, this chamber had to be slightly modified for the Mascot needs. A dedicated grounding for the test area was manufactured and installed as well as an EMC invisible tent was constructed in order to stay within acceptable cleanliness levels. In addition, Mascot was tightly wrapped in foils to be able to keep the clean room chain during transport and positioning. Further small modifications ensured a grounded and well isolated test bed. The transformation of an antenna test range to an adapted EMC chamber was completed and the required RE measurements could be performed. Here also the coupling of Mascot's communications antennas could be tested which gained the first cross measurements of the simulated link budget.

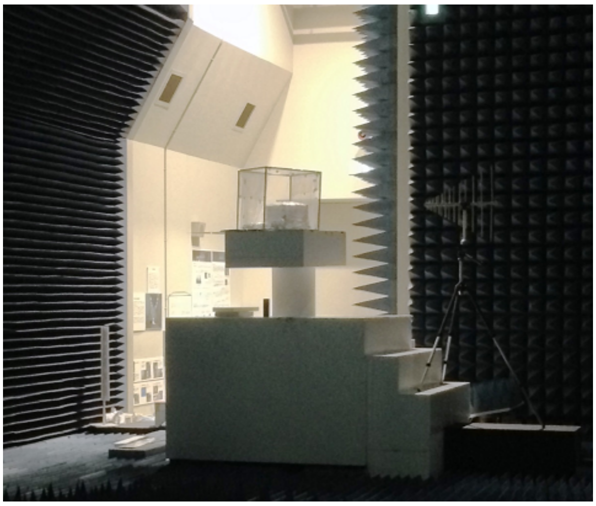

Fig. 6. Mascot FM during EMC radiated emission test inside JAXA's anechoic chamber at ISAS Sagamihara

The following day, Mascot was transported to the Mu-chamber (a radio- and magnetic isolated clean chamber also available in ISAS), where the CE part of the agreed abbreviated EMC test could be finished. Here also the low and high power mode of the two Japanese child communication modules (CCOM's) inside Mascot could be tested.

2.2. Battery Performance and Magnetic Signature

In the meantime, the final decision for the flight battery had to be taken. As mentioned above, the battery units varied slightly in their thermal behavior. To get a better understanding of this a dedicated thermal IR imaging test campaign for the FM+FS Battery was conducted. With the detailed thermal conduction behavior it is possible to define temperature set points for the battery heaters in order to stay best inside the non-operating temperatures during cruise and also to define a preheating strategy before separation in order to extract as much energy out of the cells as possible. With a current best estimate of order of 10 hours non-rechargeable battery life on the surface every single minute can have a significant impact for the scientific operation.

Apart from the thermal behavior also the magnetic cleanliness of these two units had to be verified, which otherwise could have had a significant impact for the Magnetometers performance. Since the Mascot FM was undergoing the conducted EMC test inside the Mu-chamber, the IR-tested battery models were integrated after one another and dedicated measurements with the Magnetometer got clarifications for the batteries magnetic signature.

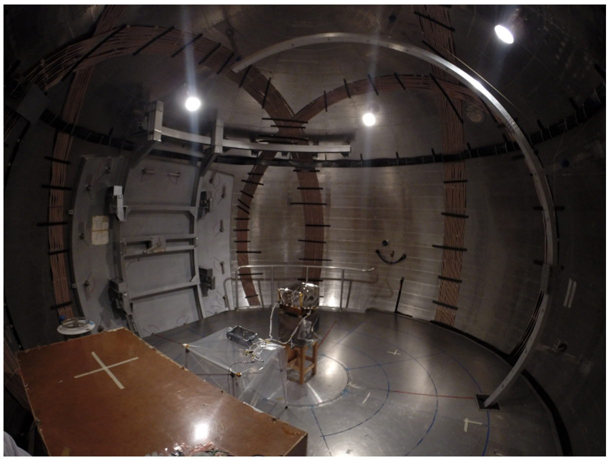

Fig. 7. Mascot FM during magnetic cleanliness test inside JAXA's Mu-chamber at ISAS Sagamihara.

2.3. Search and Rescue

As mentioned above (section 1.4), during the last thermal vacuum test of the FM, the necessary heater power for the Microscopes duty cycle was found to be different than specified. Further investigation of this non-conformance indicated a mission critical situation for this instrument as a too low power output of the heating system would lead to severe damage during the relative cold cruise conditions. Disassembling the entire payload and sending in back to the manufacturer was not possible due to the tight schedule. A simple measurement of the heater resistance was also not possible, as the redundant heating circuits were protected by thermostats which close the circuits only at a defined temperature of -30°C. Access to these thermostats was not possible and putting the unit or only the thermostats in such a temperature regime (e.g. by local cooling) without a controlled overall environment could have endangered other sensible instruments inside Mascot as neither cleanliness nor possible condensing droplets from surrounding moisture could be predicted. A small task force developed a quick and subtle strategy to put Mascot in a controlled climate chamber with controlled dew-point and where the low temperature requirements could be achieved. However, according to standardized verification processes such a method and at this point in time would have been non-negotiable. Mascot would have needed either to take the risk of losing one of its four instruments during cruise or would have needed to call a launch delay of the Hayabusa2 mission.

The solution to this problem was found once more in the good cooperation with the Hayabusa2 team being able to negotiate critical issues in a practical orientated best engineering sense. With a quick and thorough risk assessment (see table 2), the confirmation to use a suitable and available chamber, taking extra cleanliness and condensation precaution by sealing Mascot inside a clean bag and flushing it through the entire process with high purity dry nitrogen, the system and the payload teams could agree on this test. After a cooling/drying phase for about 4h in the chamber going from room temperature to -35°C at a rate of 15°C/h, the thermostats switched and the measurement of the heating circuits, which were extended and routed to the outside of the chamber, could be performed. The heater lines were indeed mixed-up which resulted in a higher heater resistance that very likely would have led the Microscope to see damaging low temperatures during cruise. The chamber was heated-up slowly back to room temperatures, Mascot was removed from the chamber and its protecting bag and a concluding inspection and functional performance test showed no alterations and a fully functional system.

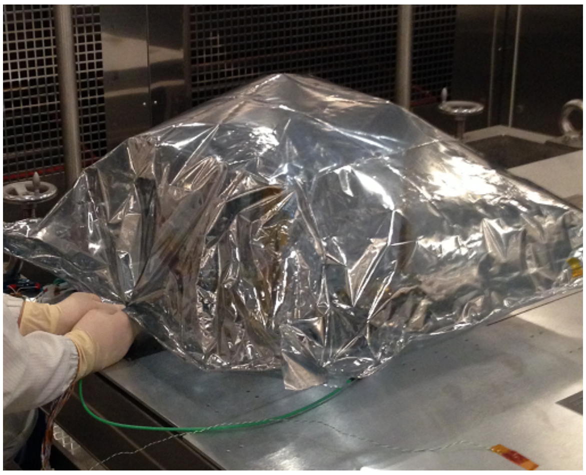

Fig. 8. Mascot FM during preparation for its low-temperature test inside JAXA's climate chamber at ISAS Sagamihara.

As mentioned in section 1.4, the final verification of an unobscured FOV of the Radiometer needed to be performed. For this, the Radiometer team had provided a simple conical hold-on element representing the combined FOV of the 6-sensor detector. Three of these cones with different opening angles provided a range in order to quantify the impact if present. The fit-check revealed indeed that a small overlap still exists for one of the sensors. Taking a possible emissivity effect of the connector into account, which heats up by direct sun illumination during the day, the relative low temperature measurements of the surface during night would have been undetectable in the noise produced by the connector. Since only 2 of the 6 Radiometer sensors detect low temperatures during the night, losing this sensor element meant losing a significant portion of the anticipated science data.

Yet again the team was required to establish a task force in order to find an answer if this could be changed without putting too much risk for the system and the other instruments. The solution was a simple adjustable connector saver which could move the Microscopes connector and attached harness out of the Radiometers FOV. All points from the established late change strategy presented in section 1.5 were answered with yes. The problem produced a severe impact for the science data and it was not possible to address this with an operational adaptation. Such a saver could be easily implemented without endangering the system or other instruments and it could be easily tested with a functional test and another FOV check after installation. There was no harm for the spacecraft nor did such a small element meant any harm for the structural integrity. The required experts in Europe could start immediately with the manufacturing and there was enough time to at least undergo a minimum standard of a functional, cleanliness and outgassing program. Interestingly enough, the most critical part was the required shipping time and the question if this connector would make it in time before Mascot had to be installed back on Hayabusa2.

Shipping time did indeed prevent another green-tag item from being ready. A termination plug, short circuiting the open lines of Mascot's single external accessible data connector used for hardwired commanding during ground tests, did not manage to find its final destination. Without a proper termination plug, however, the on-board computer could not make use of its redundant signal path. The risk assessment list was carefully answered and it was agreed to refurbish an available EM terminator on-site with available flight-like materials into an FM (Figure 9).

Fig. 9. Mascot termination plug; Left: EM, Right: FM (refurbished EM)

2.4. Final Integration and Flight Simulation Test

During the last few days before final integration a still very tight task list had to be executed including the already defined refurbishment tasks as well as the additional hardware changes necessary due to the results of the search and rescue findings. The tasks included amongst other small adaptations the exchange of the final selected battery and the exchange of the outer walls with a fresh set of single layer isolation. The communication elements were connected and secured. The final mass and the final center of mass were measured. The performance of the separation spring was confirmed and the mechanism was adjusted accordingly. Instruments and specifically the optical sensors of the Camera and the Microscope were cleaned, sterilized and inspected one last time. The refurbished termination plug as well as the just in time arrived adjustable connector saver were installed (Figure 10 and 11), with a short functional test giving confidence of the systems full performance.

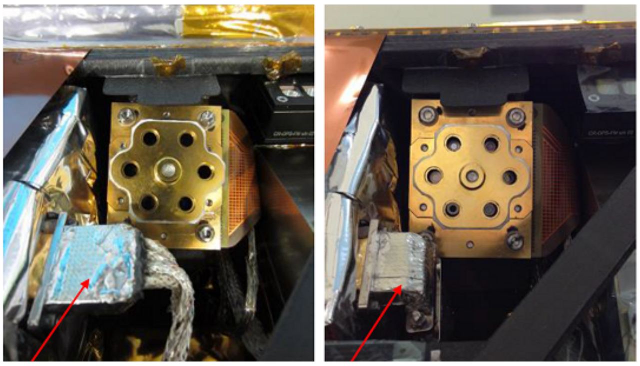

Fig. 10. Implementation of the adjustable connector saver. Left: before installation; Right: after installation.

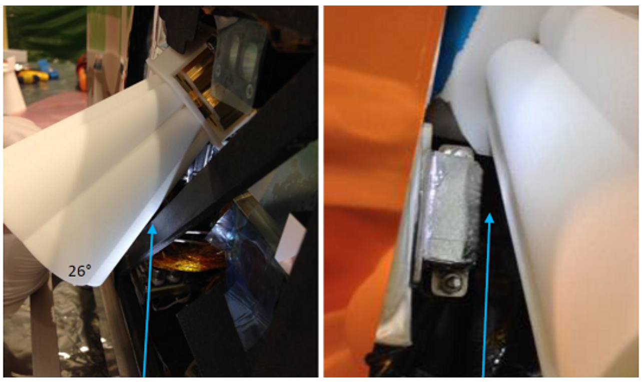

Fig. 11. Verification of an unobscured FOV for the Radiometer.

Finally, the protective covers for the instruments and other red-tag items including the safe-arm plugs of the single-shot units were removed. Mascot and its supporting frame were assembled and secured with the defined preloaded acting as launch lock. Mascot was then handed over to the Japanese integration team for final inspection and electrical checks after which it was cleared to be put back on its carrier satellite. In addition, adaptations to the Frame-MLI and the grounding plate position (see section 1.4) were applied, for which the solution could also be agreed with the satellite team. Once back on the spacecraft; Mascot was prepared for the Hayabusa2 Flight Simulation and Operations Test showing compatibility of all spacecraft components with the bus system after final assembly and giving the first cross reference measures for the launch check-out as well as for the early operations phase in space after launch. This included also an ignitions test of all spacecraft pyro-technical units. For Mascot, this was handled with a cost effective on-side built simulator using commercial break fuses (representative in current level and blow time performance) as well as flight-like QM units and diagnostic EM units of separation-related Mascot circuitry. The similarity of the fuses was cross referenced with actual data of the QM separation units from previous microgravity separation tests. This test ensured functionality of the spacecraft ignition circuits, while avoiding an unintended firing of the non-replaceable, single-shot separation unit build within Mascot.

After this last test campaign at the assembly side in Sagamihara, Japan, and just before shipment to the launch side the first official press conference gave the Japanese public the first opportunity to have a close look at the spacecraft which soon would be send on its long journey. Since Mascot vanishes from view, when the solar arrays of Hayabusa2 in their launch configuration are folded carefully over Mascot, the Mascot EQM was prepared and positioned next to the main spacecraft (Figure 12).

Fig. 12. Mascot EQM during Hayabua2 press release.

3. Launch Campaign

Mascot and Hayabusa2 were shipped to the launch site, where they could perform further necessary test together. Mascot did get its final software update before launch via its external test connector (for flight closed again with the termination plug) while being attached to and powered by the satellite spacecraft bus.

An RF test was required in order to validate the wireless communication between Mascot and Hayabusa2. However, as a necessary license to perform such a test on the used frequency bands was not yet active, the satellite team had prepared a dedicated Mascot shield box which could be placed directly in front of the satellite engulfing Mascot and its communication antenna. During this test, the team learned about a significant sensitivity reduction of the redundant child-communication module (CCOM-red) inside Mascot which meant that the satellite could not communicate any more with a landed Mascot on the surface when after separation returning to its home position. Removing Mascot from Hayabusa2, re-opening it and exchanging the redundant CCOM unit was unfortunately not possible any more for the upcoming launch date (refurbishment for Mascot with a new CCOM unit would have taken 6 weeks). During a dedicated workshop with the combined teams from JAXA, DLR and CNES a mitigation strategy was assessed. Thanks to the flexibility of the Mascot system and its SDVF enabled the team to quickly construct and test this mitigation solution and to install it in Mascots' start up routine setting. During cruise, the spacecraft would communicate only in low-power mode and in addition, an operational scenario was agreed for a situation when the main CCOM unit would stop to operate during surface operation. Here, the spacecraft would lower its altitude to a minimal range which needs to be investigated by the teams with further ground-based tests during cruise.

Other technical problems with certain parameters regarding the data transfer between Mascot and Hayabusa2 were addressed and tested intensively during the last days before launch. The final fixes and updates will be followed by regular software updates during the 4-year cruise flight. Finally, Mascot performed its final health check before Hayabusa2 was moved onto the rocket adapter, showing the instruments and other subsystem in good working condition, after which Mascot was cleared for launch.

Fig. 13. Final hands-on activities on the Mascot FM including securing the shifted grounding plate, Frame-MLI adaptations and re-installation of the termination plug.

Conclusion

Delayed only 3 days by weather, the small asteroid lander Mascot was launched aboard the Japanese Hayabusa2 asteroid sample-return mission on December 3rd, 2014, 04:22 UT, within the first interplanetary launch window (Figure 14). Their target is the near-Earth asteroid (162173) 1999 JU3. The fully autonomous Mascot carries four asteroid science instruments, orientation sensors, and an up-righting/relocation mechanism within a shoebox-sized 10 kg spacecraft. Mascot is a fast paced high performance project, developed under strict constraints of volume, mass, available personnel, budget, and accessible infrastructures, to a timely deadline of a celestially fixed launch date. With a model philosophy tailored 'live' at *System Level*, it integrates a unique mix of conventional and tailored model philosophies at units level. A dynamically adapted test program using a Concurrent AIV strategy kept project risk within acceptable bounds and shortened the system level AIV phase from the typical 4 to 5 year to 2½ years within a project timeline of 3 years focused on the specific launch opportunity. The Mascot team has successfully completed approx. 30 *Mascot System and Module Level* tests, more than 50 additional *Equipment Level* tests (excluding payloads) as well as approx. 10 test campaigns on its carrier satellite Hayabusa2. This culminates in almost 100 different test campaigns performed in roughly half the time allocated for such a prototype project which would have followed a standardized way.

Mascot provided useful lessons in assembly, integration, testing and its related management that could be applied to increase the efficiency and decrease the lead time of future interplanetary projects from concept to launch.

Fig. 14. Launch of Hayabus2 with Mascot on December 3rd, 2014, from Tanegashima Space Centre, Japan.

Acknowledgments

The authors would like to acknowledge the significant contribution from all members of the ***Mascot Project Team*** as well as the ***Hayabusa2 Project Team***.

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