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ON TIME, ON TARGET – HOW THE SMALL ASTEROID LANDER MASCOT CAUGHT A RIDE ABOARD HAYABUSA2 IN 3 YEARS, 1 WEEK AND 48 HOURS

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ABSTRACT

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. Their target is the near-Earth asteroid (162173) 1999 JU_3. The fully autonomous MASCOT carries four asteroid science instruments, orientation sensors, and an uprighting/relocation mechanism within a shoebox-sized 10 kg spacecraft. Though only an instrument-sized lander, its complexity is comparable to a similarly equipped standalone 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 programme using Concurrent Assembly Integration and Verification (Concurrent-AIV) kept project risks 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. Here, MASCOT benefited from a preceding phase of a range of lander concept studies at the DLR Bremen Concurrent Engineering Facility since 2008. Within the 3 years project timeline, from the first integrated breadboard model (½ year after first unit-level hardware breadboarding) the MASCOT team has successfully completed approx. 30 MASCOT system level tests, more than 50 additional subunit 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. These lessons may become vital when the first sizeable Earth-impacting asteroid is discovered *before* its terminal dive.

Currently, the MASCOT Flight Spare is planned to be used as Ground Reference Model and to continue functional and environmental testing on system level

throughout the first half of 2015. It will be joined by still to be (re-)built partial hardware models for software and operations development. Also, some subsystem test campaigns necessary for optimized operations planning are ongoing or are being planned. All these expand the experience base for future MASCOT activities, and ultimately, for the few precious hours on the asteroid surface of the Flight Model – the one out there of the many.

Introduction

MASCOT always was [0] and still is a fast paced project. Its development took place within strict constraints of volume, mass, available personnel, budget, and accessible infrastructures, always facing a celestially fixed launch date as the ultimate deadline. During the development of MASCOT, out of necessity we developed the Concurrent Assembly Integration and Verification (Concurrent-AIV) approach which allowed the project's participants to compress a 2½ years AIV phase within a project timeline of 3 years focused on this specific launch opportunity. MASCOT provided many useful lessons in this time with the potential to increase the efficiency and to decrease the lead time of future interplanetary projects from concept to launch. These lessons may become vital when the first sizeable Earth-impacting asteroid is discovered *before* its terminal dive. They can also serve as inspiration and pathfinders for other projects to be realized under similar constraints or with the desire to accomplish things more efficiently and to reach goals faster.

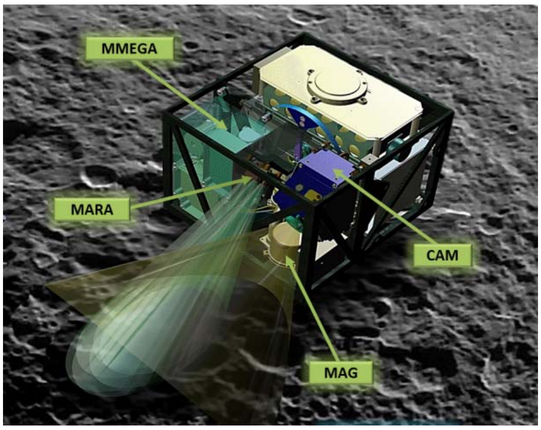


Figure 1L: MASCOT STM-1 on display at the ILA Berlin Air Show 2012 showing the moment of separation from HAYABUSA2

Figure 1R: Artists impression of the landed MASCOT on the surface of 1999 JU_3 indicating the operation of its 4 payloads.

THE MASCOT APPROACH

Following an invitation from JAXA to join in the follow-up mission of the first asteroid sampler HAYABUSA, MASCOT was selected at a time where its final conceptual design, including its scientific payloads, had not yet been fully defined. The tight schedule, tightly defined envelope, and strict margins policy were challenges during the development at all levels. Science payloads, bus subsystem units and overall system design had to be derived from what was available off the shelf at the project partners' in very heterogeneous maturity levels ranging from concept study to flight heritage hardware. As shown in Figure 2, MASCOT was in the beginning behind the main spacecraft schedule, but due to the early delivery date of the FM the project development cycle needed to be shortened. In other words, the MASCOT development was required to constantly catch up with the master timeline and finally overtake it [1].

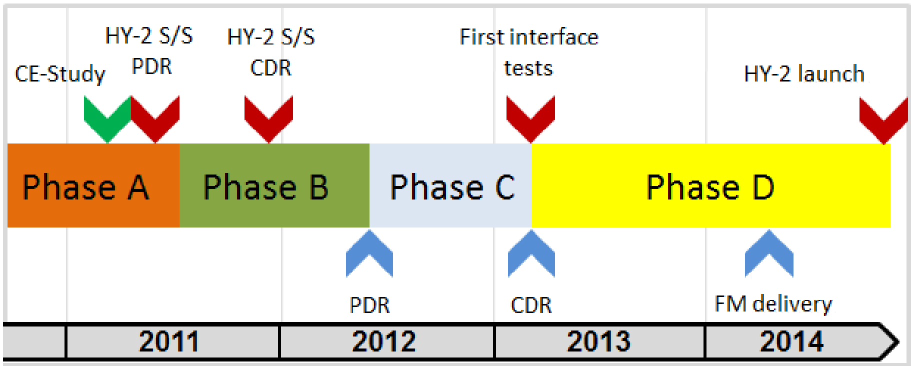


Figure 2: MASCOT project timeline with major milestones

MASCOT entered the realm of hardware with the first unit breadboarding in June 2011, over half a year before formal go-ahead. It passed HAYABUSA2 subsystem CDR in December 2011, and an internal system PDR in July 2012. The final go-ahead was given after passing the internal system CDR in April 2013. The MASCOT flight model was delivered in June 2014 for launch in December 2014. The tight schedule, due to a launch date fixed by celestial mechanics, was one of the major challenges during the MASCOT development not possible with the current established verification strategies, but with a controlled Death March [2].

The test philosophy of MASCOT applied a Hybrid Approach with a mixture of conventional and tailored model strategies. This approach is common practice in scientific robotic missions [3] but the specific MASCOT model philosophy went even further. The project started with a baseline on the Classical Approach (STM, QM and FM) to ensure a minimum number of physical models required to achieve confidence in the product verification with the shortest planning and a suitable weighing of costs and risks. But this approach was adapted on a case by case scenario, where the model philosophy evolved along the verification and test process depending on the particular system and subsystem readiness.

The heterogeneous maturity levels have let to tailor a mixed model philosophy of the subunits into an adaptable overall development strategy. More specifically, the project incorporated parallelization of testing activities using identical copies 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 many simultaneous running test and verification activities (Figure 3). In effect, the development tracks of Mechanical, Thermal, Software and Functional Performance testing got their own independent routes sharing their verification processes.

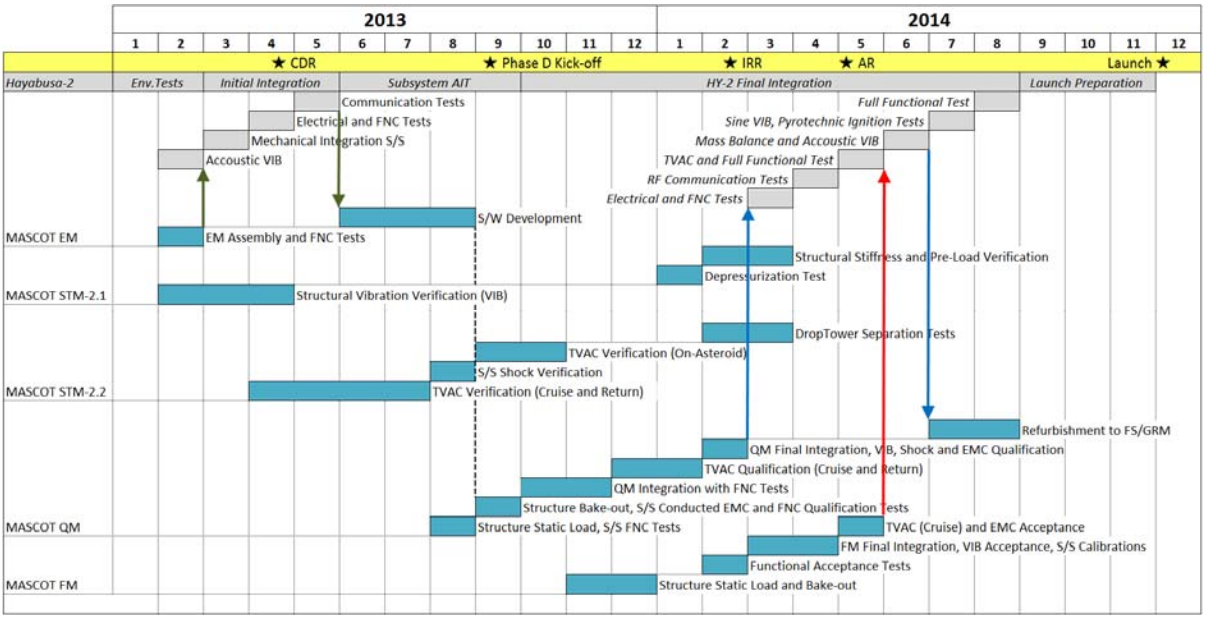


Figure 3: Concurrent-AIV schedule as performed in the MASCOT project.

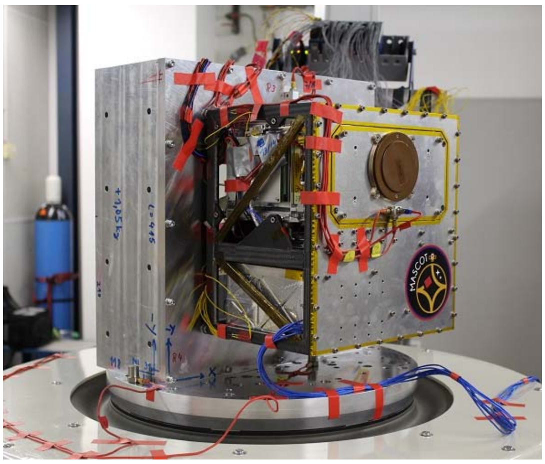
According to this concurrent process, almost all environmental and functional tests including subsystems could be performed on EM and STM level which effectively reduced potential delays. In addition, both these final threads (QM and FM) were sharing again their verification processes. The QM endured all environmental qualification tests at DLR herewith validating parts of the FM which in turn did its final mechanical and electrical acceptance on HAYABUSA2 system level, hereby reducing again required project timeline. Knowing the advantages of this novel approach, the challenges in creating parallel development lines were found in team and facility resources if these are not readily and on-demand available. In addition, 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 player including also the Project Management and Product Assurance, in order to keep the project sorted and on course. During the QM/FM timeframe, 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 decision processes.

PROGRAMMATIC THOUGHTS FACE REALITY!

The applied approach, as described above, was dynamic and evolved while the project progressed. The test philosophy was adapted on a case by case scenario, which effectively reduced the overall development time. However, the situation was complicated since for the verification of the main spacecraft, MASCOT had to take part in certain verification activities on HY-2 system level. In addition to the already parallelized MASCOT test threads, these tasks where scheduled as well in parallel, which introduced a dual-track test scenario. To cope this situation, duplicate or reduced models where built as “built to purpose and schedule”. Nevertheless, this was used as an advantage to shorten the verification process for MASCOT by skipping some safety driven *high-priority-tests*, which were later performed on the HAYABUSA2 system level track. The MASCOT track could therefore also incorporate *low-priority-tests*, mainly driven by the scientific instruments.

Mechanical and Thermal Testing

The development was focused around the systems main structure which comprised the MASCOT Landing Module (LM) the Mechanical and Electronic Support System (MESS), which is the main interface to HAYABUSA2remaining at the spacecraft after separation, and the common electronic box (Ebox), which is an integral part of the LM structure serving also as interface for other subsystems like the mobility unit, the battery and the communication modules. The development status of these three elements defined the overall maturity of each MASCOT model. The first model to demonstrate structural performance (STM-1) comprised units of the aforementioned three elements LM, MESS and Ebox, including mass dummies of the single heaviest subsystems, namely the payloads, the battery and the mobility unit. Unfortunately, the model did not sustain the loads and structural damage was severe.



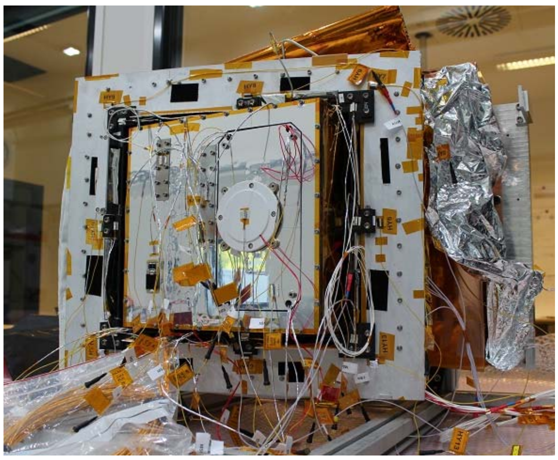


Figure 4L: MASCOT STM-2.1 during Random Vibration Test

Figure 4R: MASCOT STM-2.2 during Cruise-Phase Thermal Vacuum Test.

Due to the fact that structural integrity could not been approved early and the project schedule was too short to account for successive structural and thermal verification, two identical models of the iterated and improved STM-1 were produced (STM-2.1 and STM-2.2) which could run completely independent paths of structural and thermal qualification activities (Figure 4). 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 testing. For the next vibration campaign with qualification levels, which verified also the frequency response and load levels of all subunits, the STM-2.1 was integrated with the now available P/L, battery and communication STM subunits as well as an EM mobility unit. To shorten subunit test schedules, this test gave also the first possibility for subsystems electronics, if ready, to be integrated into the Ebox to qualify for structural integrity on MASCOT system level.

While the STM-2.1 underwent the structural verification path, the STM-2.2 unit was prepared for thermal verifications of the Cruise Phase as well as for the Return-to-Earth Phase. Therefore, shortly after the vibration campaign of STM-2.1, P/L's and other subunits were re-used and quickly advanced to be thermally representative, including dummy heat pipes, main and sub radiator, optical face sheets, multi-layer insulation as well as controlled heaters. After successful test of the return and cruise phase configuration the setup was changed to the third and final On-Asteroid Phase, whereas this test was again a reduced dress rehearsal for the later QM test which included full functional subsystems and payloads. Both STM-2 units after completion of the structural and thermal path were used as qualification test bed of other critical system elements, in example the separation mechanism (Figure 5), preload release, umbilical connector and depressurization as well as P/L FOV alignment tests.

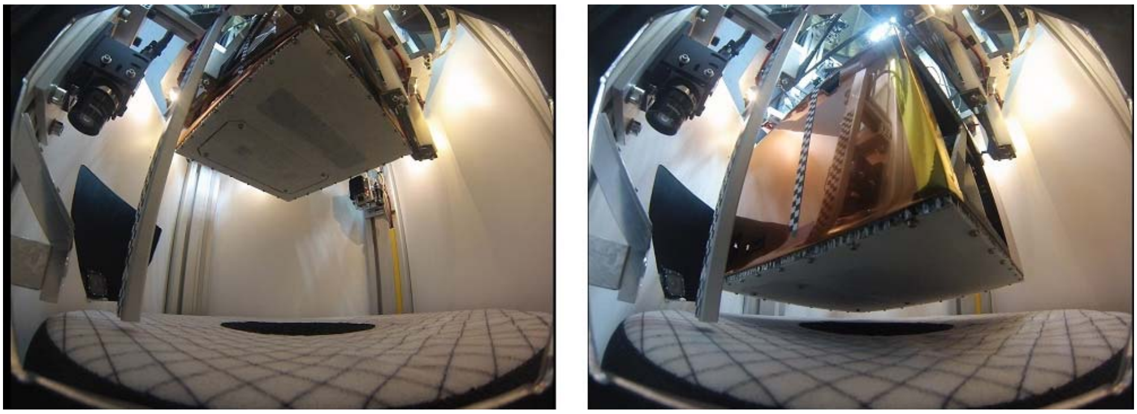


Figure 5: Separation sequence of MASCOT in microgravity during drop tower experiments.

Software Development and Functional Performance Testing

In addition to the physical MASCOT models a Software Development and Verification Facility (SDVF) was created to establish a general test bed for Mascot onboard software development and individual instrument and subsystem software functional tests with real Hardware-in-the-loop electronic (Figure 6L). This device builds the electrical interface for the system electronic boards including backplane, P/L boards, onboard computer (OBC) and power control and distribution unit (PCDU). The SDVF can therefore simulate certain spacecraft components and their interface by software connected with the only available hardware to be tested at that time. This way, every payload and subsystem can freely do debugging tests which can take longer time independently. In example, the OBC can be connected to the SDVF simulating the other system elements, which could be added piece vise when the hardware electronic becomes available but also the other way around where the OBC remains simulated by the SDVF. In a final step the real OBC board could be integrated running real EM boards and verifying MASCOT's functional performance (Figure 6R). 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 QM (Figure 8). With this approach, most of the problems on the interface and functionality of each subsystem were found before final integration. This reduced dramatically integration problems and troubleshooting time throughout the entire development.

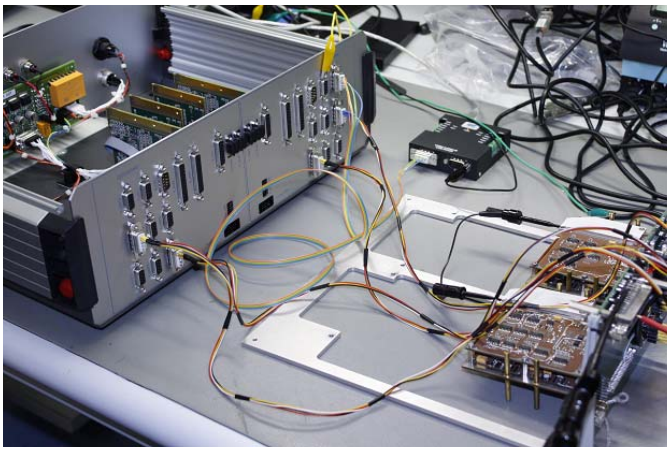
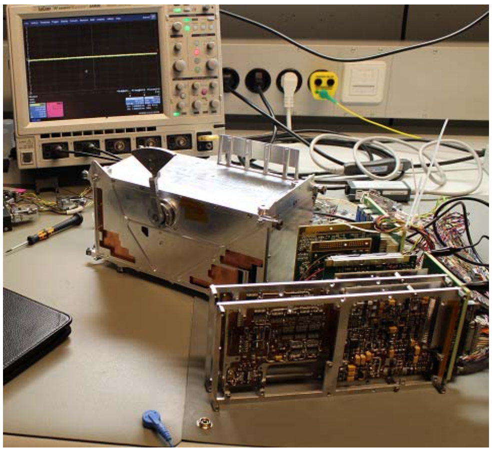



Figure 6L: MASCOT SDVF during conducted EMC tests including On-Board Computer (OBC) and Power Distribution and Control Unit (PDCU).

Figure 6R: Software verification test of the MASCOT mobility motor and its control unit.

For the first electrical performance on HAYABUSA2system level a separate EM was built with a mock-up structure resembling MASCOT in form and fit as well as having EM functional communications equipment including OBC, PCDU, Antenna and CCOM (Figure 7). Other subunits were either simulated only by load resistors to test the current drains or replaced by mass dummies to suit the overall weight and handling of MASCOT as a whole. Prior to shipping, an EMC conduction test on the Ebox, including BB/EM/QM electronic cards of all P/L, as well as an initial RF Test had shown basic functional performance.

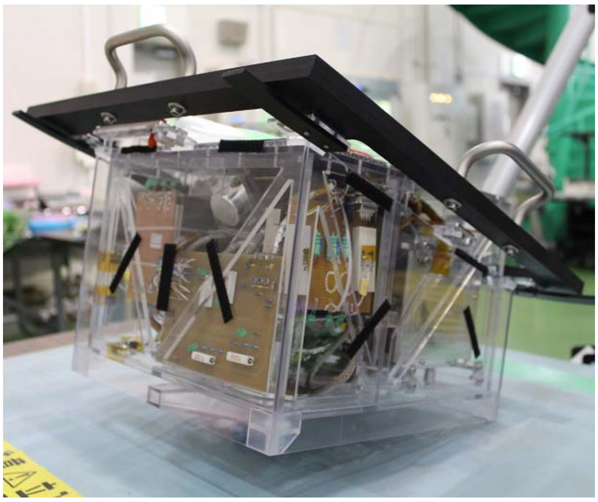
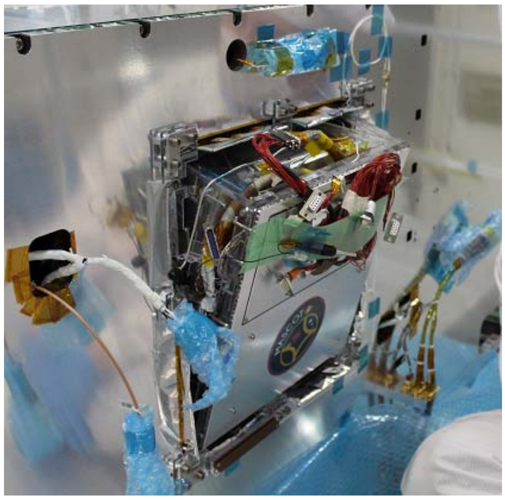
 

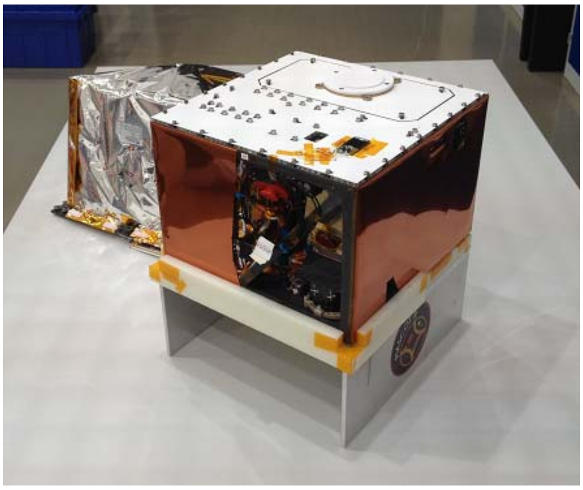
Figure 7L: MASCOT EM as used during the first functional tests at JAXA/ISAS verifying basic communication and subunit performances.

Figure 7R: MASCOT EM mounted to the Hayabusa2spacecraft during Initial Integration Test.

Final Acceptance Testing

The qualification program included static load tests, full random vibration and shock tests, thermal vacuum tests of all major mission phases (Cruise Phase, On-asteroid Phase and Return-to-Earth Phase), conducted and radiated electromagnetic compatibility (EMC) tests, full functional tests (FFT) in table top configuration as well as fully implemented into the MASCOT system. After the MASCOT QM had passed successfully this program with a mix of integrated STM, EM, EQM, and QM payloads and subsystems (Figure 8), it was shipped to Japan to join the mother spacecraft for its own final environmental test. In the meantime, the flight model (FM) of MASCOT, including all FM units, was prepared for an abbreviated acceptance test program, including vibration, thermal vacuum cruise phase, EMC tests as well as calibration campaigns for payloads and instruments. After completion, the MASCOT FM was sent to Japan only 3 months after the QM. At this point, MASCOT overtook the HAYABUSA2development progress and the dual-test track of MASCOT and HAYABUSA2merged.

The QM was returned to DLR and refurbished to the Flight Spare unit, which after successful launch of HAYABUSA2will be used as Ground Reference Model.



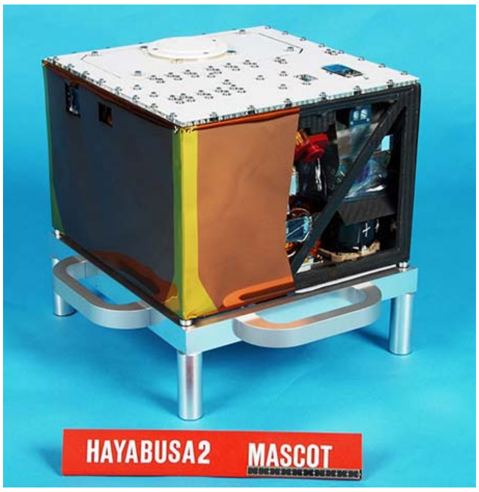


Figure 8L: MASCOT QM after passing successfully its Thermal Vacuum and Random Vibration test.

Figure 8R: MASCOT FM after final assembly and shortly before final integration into Hayabusa2

APPLICABILITY OF CONCURRENT-AIV TO PLANETARY DEFENCE

Planetary defence missions serve to characterize or deflect a specific small solar system body (SSSB) which has been recognized as a likely threat or confirmed as an impactor. Consequently, at a point in time when such a mission would first be seriously considered, the determination of the heliocentric orbit of its target object would already have been refined to an accuracy that is sufficient to make a positive prediction of Earth impact, an extremely close Earth passage, or a highly likely keyhole fly-by leading to a threatening resonant return to Earth further in the future. As target Earth is of typical planetary size and its orbit is as well known as those of the other planets, the orbit determination accuracy required to decide conclusively that a SSSB is a serious threat is comparable to the orbit determination accuracy required or given for the target objects of planetary science missions. (cf. e.g. [4][5])

Hence, it is instructive to compare the combined schedules, project timelines and interplanetary cruise phase of Hayabusa2 and MASCOT towards arrival at (162173) 1999 JU_3 with those of other interplanetary rendezvous missions involving SSSBs and with the precision orbit determination histories of their respective SSSB targets. Ideally, those would include all historic orbit determinations from the date of their respective discovery to the arrival of the spacecraft and the following mission milestones at the target, to compare the historic accuracy with the best results currently available. Prominent examples are Rosetta/Philae, Stardust/NExT [6][7][8], Deep Impact/EPOXI [9][10], Deep Space 1 [11][12][13], or Dawn; and their respective target objects 67P/Churyumov-Gerasimenko, 81P/Wild, 9P/Tempel (9969) Braille, 19P/Borelly. Excluding direct Hohmann transfer planetary missions which are intended to land on or orbit their target and at least in the case of Mars follow a more or less regular synodic launch window schedule, all rendezvous missions require planetary fly-bys, usually multiple, and/or substantial on-board propulsion capability. Thus, missions to more distant planets are also of interest for this comparison, such as MESSENGER, BepiColombo, Galileo or Cassini/Huygens and the unique case of AKATSUKI on its new post-Venus-fly-by and resonant return trajectory.

If an appropriate time difference is applied to match SSSB orbit determination history and spacecraft development timeline, all these can also be compared to the discovery and precision orbit determination histories of (Potential Hazardous Asteroids) PHAs which have been considered as potential impactors at some point following their discovery, or to carefully end-to-end modelled fictional scenarios. Well covered objects suitable for this purpose include but are not limited to (99942) Apophis [14][15], (101955) Bennu (formerly 1999 RQ_{36}) [16][17], and (29075) 1950 DA [18], or the fictional 2013 PDC and 2015 PDC scenarios provided for this conference. For objects like Apophis which have subsequently been shown to pose no significant threat the date of the turn-over point at which the predicted impact probability stagnated at a few % or began to fall again may serve as the reference date for the kick-off of intense and detailed mission studies. In the case of a confirmed impactor the probability of impact would steadily continue to rise towards 100%. The commitment of significant resources to a planetary defence mission would most likely occur later, e.g. at a few 10's% probability of impact for a characterisation mission and probably only at significantly above 50% probability of impact for a serious attempt at deflection. (cf.[19]). The time interval from the kick-off of dedicated studies to the point of firm commitment to major expenses can presently only be estimated from fictional impactor scenarios such as the 2013 PDC and 2015 PDC scenario provided for this conference. A reasonable approach would be to assume the abovementioned study kick-off milestone occurs at the historic peak estimate of probability of impact for the object most widely considered as a threat and which has indeed kicked off a lot of characterization and mitigation mission studies, Apophis. [15] This places the study kick-off threshold at a level of impact probability of order a few %. Then, the time it takes for a fictional scenario to evolve from the point in time at which it passes this level of impact probability to reach the characterization mission and deflection mission thresholds of impact probability determines the spacecraft hardware design kick-off milestones.

In the event of a recognized threat on this scale it is not unlikely that suitable ongoing interplanetary probe projects would be redirected to address the threat as soon as possible. Then, spacecraft probably not from the outset designed to visit a SSSB would have to be modified by adding in-situ exploration capabilities such as are implemented for HAYABUSA2 by MASCOT. The complexity of the likely necessary planetary fly-bys required to match the target object's eccentricity and inclination, launch opportunities would be strictly limited to one target object, unlike for most SSSB science missions, and they would become favourable in intervals of the object's synodic cycle with Earth. As typical NEA synodic cycles are of order 3 to ~10 years, the time remaining to the next favourable launch window would most likely be very similar to the combined HAYABUSA2 and MASCOT project timeline. Also, since the target object would obviously not have been selected for a low delta-V accessible orbit, the mission design will most likely be heavily constrained in mass and require substantial on-board propulsion capability. Seen in this light and on the historical background of the first HAYABUSA's highly successful and exciting seminal mission to (25143) Itokawa and back to Earth, HAYABUSA2 with MASCOT aboard may also be seen as a first planetary defence spacecraft design and AIV practice mission.

Also, the increase of the number of landers and other task-specific separable sub-spacecraft from HAYABUSA to HAYABUSA2 is noteworthy. For the European AIM component [20] of the joint AIDA [21] mission currently being studied in detail, more than one lander and/or sub-spacecraft is currently envisaged. Since feasible interplanetary flight opportunities to a recognized threat SSSB might be very limited and also subject to launch payload mass constraint uncertainties, it would on the one hand be desirable to fly a number of landers to provide redundancy as well as broad characterization of the object and exclude misleading single-location peculiarities (cf. the GALILEO Jupiter atmospheric probe entry location likely having been such). On the other hand, the mass added by the pursuit of all these goals might be infeasible to launch to the target object. In this case, granularity of the landers component of the mission would be highly desirable, so that a prioritized selection could go along, as fully as possible making use of the available launch mass (cf.[22]). The approach of having, instead of one large and complex lander, a number of small landers [23] individually covering specific science tasks while covering many locations on the target SSSB by a common set of instruments at the same time also seems advantageous for planetary science missions as it would offer the opportunity to increase and broaden the science content as well as mission robustness in small increments following the development of trajectory and launch vehicle performance optimizations until relatively late in the project, or to adapt to these from one launch window to another. Expanding the concept of small sub-spacecraft towards the observation of dynamic phenomena as with HAYABUSA2's Small Carry-on Impactor (SCI) and deployable observation camera, DCAM3 [24], the Kinetic Impactor Demonstration Mission proposed in the framework of NEOshield carries several to fly in parallel and observe while the main spacecraft impacts the target [25]. This concept may also be considered for the DART component [26] of AIDA to help verify the modelling of impact processes [27][28] and in the context of space-borne hypervelocity impact experiments in general [29].

Such a varied payloads flotilla of small landers and sub-spacecraft could most likely benefit from MBSE-coordinated design [30] and advance the AIV schedule if a Concurrent-AIV approach is used, by offering synergetic gains through the higher number of bus-side units in circulation if a number of partially identical but differently instrumented landers is built in parallel. If it is envisaged to fly partially or fully identical instrumented landers or sub-spacecraft, even higher AIV schedule parallelization becomes possible. Concurrent-AIV concepts could then be extended well into the instrument calibration phase and possibly even help to support similar post-launch and post-mission activities to improve science return. Since landers and sub-spacecraft of MASCOT size are small enough to fit into calibration facilities originally designed for the instruments of 'large' scientific space missions, it may even be possible to altogether avoid de-integration of the Flight Spare (FS), Qualification Model (QM), or Ground Reference Model (GRM) unit to return the respective instrument models to their Principal Investigators (PI) for such purposes. If instead the post-launch available models stay integrated, the calibration campaigns could become concurrent for all instruments, and also include fully flight-like cross-testing for mutual interaction of the instruments on their results, an effect more likely in the tight spaces of small spacecraft at each instrument's optimized facilities. The gains offered by Concurrent Calibration and Interaction Testing and Verification beyond improved science output quality and reliable guidance for operations planning to avoid mutually degrading operation of instruments include saving the de-integration and possible repeated re-integration campaigns, preserving the orignal as-built state, and instant availability of a complete functional spacecraft for high-fidelity post-mission testing, ground reference beyond the commonly software-oriented GRMs' capabilities, or ultimately – after all else is seen and done – flight [31].

CONCLUSION

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 [32]. The DLR MASCOT project, a small 11 kg Asteroid landing package on-board JAXA's HAYABUSA2 space probe launched on December 03, 2014, had such constraints. [33] Selected at a time where its conceptual design and scientific payloads had not been fully defined. With the carrier spacecraft already in its critical design phase with most of its interfaces fixed leaving only 2 years until a proposed final delivery of the flight unit and no heritage to use off-the-shelf equipment leading to a full prototype design of a miniaturized asteroid lander to an unknown target.
But by applying a philosophy of Concurrent-AIV in addition to a Dynamic Model Strategy helped to identify and mitigate design and manufacturing issues and shortened the project timeline from an earlier planned 4-5 years down to 2.5 years. This novel approach has a high potential to act as a showcase model for projects with a similar demand in high performance and short development time, which will be the case, for example, for future secondary or piggy back payloads. [30][34][23][31] Due to the advances in spacecraft miniaturization (e.g. all-electric propulsion and advances in MEMS technology) many launch vehicles need to be equipped with ballast to reach the minimum load not entirely filled by the primary payload. [35] This trend will likely offer affordable launch opportunities also to small interplanetary missions added as 'live' ballast, which then need to fit their development schedule into the timeline of the primary payload for which the launch window has been agreed and optimized.

Figure 9L: MASCOT FM Final integration steps at Hayabusa2.

Figure 9R: Launch of Hayabusa2 and MASCOT on December 3rd, 2014 from Tanegashima Space Centre in Japan

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