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DLR MASCOT on HAYABUSA-II, A Mission That May Change Your Idea of Life! – AIV Challenges in a Fast Paced and High Performance Deep Space Project –

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MASCOT, a small 10kg Asteroid landing package on-board Hayabusa-2 is currently finalizing Phase-C of its development and after official go-ahead during the Critical Design Review it will undergo a final verification program at DLR before send to JAXA to be integrated into the mother spacecraft. Its last stages during the Assembly, Integration and Verification (AIV) process show that by applying a unique mix of conventional and tailored Model Philosophies it is possible to dynamical adapt the test program, limited by a fixed launch date, to accomplish for the shortest planning and a suitable weighing of costs and risks. In addition, this paper introduces the term *Concurrent AIV* to express the many simultaneous running test and verification activities.

Key Words: MASCOT, Hayabusa-2, Asteroid Lander, Concurrent AIV, Dynamic Model Philosophy

1. Introduction

About the size of a shoe box and weighing roughly 10 kilograms, the Mobile Asteroid Surface Scout (MASCOT) is a small landing package aboard the Japanese space probe Hayabusa-2, scheduled for launch in late 2014. MASCOT is currently being developed at the German Aerospace Center (DLR) in close collaboration with the French space agency (CNES) and the Japanese Aerospace Exploration Agency (JAXA). The 5-year sample return mission HY-2 targets the carbonaceous Near-Earth Asteroid 1999 JU3, an object belonging to the most abundant type of space rock in our solar system which is thought to contain water and therefore may have provided the building blocks for seeding life on Earth [1]. The fully autonomous robot MASCOT will carry a full set of scientific payloads to study the temperature, chemical composition, surface texture and magnetic properties of this asteroid.

Originally investigated in the framework of the European Marco Polo study, MASCOT has undergone several concept iterations converging into a system which is very compact in design but still achieving a high ratio of payload mass to total system mass. 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 are challenges during 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. In essence, 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 compared to the master schedule. In other words, the MASCOT development is required to constantly catch up with the master timeline and finally overtake it [2].

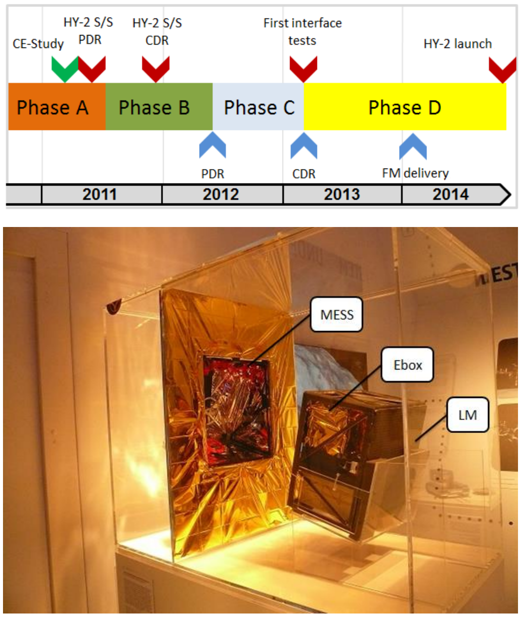

Fig. 1. MASCOT Project Timeline with major milestones [2] and MASCOT STM on display at the ILA Berlin Air Show 2012.

MASCOT entered the realm of hardware with the first unit breadboarding start on June, 6th, 2011, over half a year before formal go-ahead. It passed Hayabusa-2 subsystem CDR in December 2011, and an internal system PDR in July 2012.

The project is currently in Phase C, with testing activities on-going. After a series of subsystem midterm reviews, the internal system CDR takes place on April 22nd, 2013. According to current planning, the MASCOT flight model has to be delivered in February 2014 for launch in December 2014. The tight schedule, due to a launch date fixed by celestial mechanics, is one of the major challenges during the MASCOT development and specifically in its Verification and Validation Program.

2. The MASCOT Mission

2.1 Asteroids – Cradle of Life or Source of Hazard?

The search for the origins of life and increasing the Earths safety against possible meteor impacts are two corner stones in the international space exploration endeavor. Asteroids, which are the residual population of planetesimals, have formed during the accretion process of the solar system some 4.5 billion years ago. Since this time, they have changed only little preserving the original content of material from which the planets, including the Earth, have been formed. It is assumed that especially the carbonaceous asteroids (C-type), which are with almost 75% of all known asteroids the most common type, contain organics and perhaps water as well. Analyses of meteorite fragments, like the one of the Tagish lake, Canada, contained comparatively much organic matter including traces of amino acids [3], the building blocks of proteins, essential for forming life. These could have been carried by asteroids to Earth when raining down on it during its early development stages. The question is whether it was a lucky coincidence, that the analyzed meteorite samples contained organic matter, or whether it can be expected in general, that many asteroids carry the essence of life with them. The assumption, that asteroids could contain water, is derived from spectral analyses of infrared pictures of for example 24 Themis. These observations revealed that the surface of this object is covered to a big part by water ice as well as include potential traces of organic matter [4].

In order to verify this theory, it is required to gather in-situ information of such objects. The Hayabusa-2 mission targets therefore the carbonaceous asteroid 1999 JU3 to collect primitive unaltered material samples. This Near-Earth Object is also an Earth-crossing body, which in general pose a potential threat when on an impacting course. Even small objects can have severe consequences. Like the *Tunguska Event* in 1908, a similar recent incident in Russia of the Chelyabinsk meteor made this very clear. This asteroid had an estimated size of only 17 to 20 meters, weighting between 10,000 to 18,000 tons, and it burst in a height of approximately 23 km causing a shock wave which shattered windows and did further damage to buildings. More than 1000 people were hurt, mainly by broken glass [5]. Depending on the size and composition of such an object, events like this can be confined to the closer vicinity of its impact location only or, in worst case, have a devastating global effect which could even extinct all life on earth. Missions to investigate asteroids will help to know better about this type of space objects and hence to identify and establish the most effective prevention measures. Once it comes to the need for deflection, the response of the surface and the immediate environment of the asteroid to any method of impulse transfer need to be understood. For kinetic deflection, the mechanical properties resulting from surface mineral composition, porosity and possible volatiles influence the factor by which impact energy is converted to impulse. Deflection methods employing radiative ablation, whether by continuous illumination or pulse irradiation, require understanding of the surface composition, porosity, thermo-optical properties and heat capacity. Many of the parameters related to orbit determination would require decades of observation from the ground to be constrained to sufficient precision. MASCOT with its dedicated set of instruments has the capability to quickly constrain many surface and environment parameters relevant to precise orbit determination and deflection [6].

2.2 MASCOT – Targeting for the Context!

Hayabusa-2 (HY-2) will launch from Tanegashima Space Center and arrive at 1999 JU3 in June 2018. After arrival, HY-2 will first perform a global mapping in order to characterize the asteroid. With the landing site selected based on local geology and thermal constraints, MASCOT will be released to the surface, either during a dedicated descent or during one of the sampling dress rehearsal maneuvers. The mothership will descend to the separation altitude of 100 meter, at which point MASCOT will be ejected via a spring mechanism with a controlled low velocity in the order of cm/s. MASCOT will fall to the asteroid surface under the effects of the weak gravitational field, before landing in an unknown orientation. In order to start the investigation, MASCOT must be orientated to its primary surface side. This is performed by an up-righting manoeuver using an internal mobility mechanism. A full complement of scientific activities will be performed, involving approximately one asteroid day, before MASCOT can be relocated to another site by initiating an uncontrolled hop of up to 200 meters across the surface. Further scientific activities will take place, and then, power depending, a second hop is considered. The expected lifetime of MASCOT is in the order of 12-16 hours. MASCOT takes up a key role in the HY-2 mission aiming to conduct the first ever in-situ measurements on an asteroid providing ground truth information, since rocks nature (i.e. volatiles within rocks) can change during return flight. MASCOT's suite of science instruments is designed for the study of the target asteroid with a focus on surface properties and the close-in space environment that it experiences during descent and landing. The design goal is to provide supporting information to the process of sampling site selection. MASCOT acts therefore as scouting vehicle in favor of the mother spacecraft, but in addition its measurements are on different length scales. The returned samples by Hayabusa-2 will be in the micro- to millimeter scale, whereas the orbiter will map the asteroid from several meters to a few centimeters scale. MASCOT's measurements will complete this picture with measurements in ranges from micrometers to several centimeters scale and hence, providing the context of any collected samples.

3. The AIV Program

The Assembly, Integration and Verification (AIV), a.k.a. Assembly, Integration and Test (AIT) is the final stage in producing a spacecraft and readying it for launch. It includes the simulation and test of the expected space environment and flight operation to verify and demonstrate the overall performance and reliability of the flight system. Choosing the right philosophy or approach of the Verification and Validation (V&V) 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 [7].

3.1. Model Philosophy – Dynamic and Flexible

In European and American space industry there are currently two main model philosophies in use to conduct the verification of a space system. These two philosophies are known as the *Prototype Approach*, sometimes also called the Traditional or Classical Approach, and the *Protoflight Approach* [8, 9]. The basic difference is reflected in the number and types of models being built and tested. In the Classical Approach the design verification evolves in a mostly sequential and also successive fashion from a Dummy Model, a Structural or Structural-Thermal Model (STM), an Engineering/Electrical Model (EM), a Qualification Model (QM), to the final Flight Model (FM), which may also have a sister model used as Flight Spare (FS) in case of launch failure or otherwise as Ground Reference Model (GRM). The Protoflight Approach qualifies the design of a single flight model by replacing critical subsystems during the integration process. The Protoflight Model (PFM) is subject to a full qualification process and is refurbished before launch. It is generally faster and cheaper and applied to projects with no technology critical design accepting a medium risk.

The classical approach would be of course the most reliable method to choose as it gives the highest confidence that the final product performs well in all aspects of the mission. However, due to the tight schedule in the MASCOT project, the extensive and time consuming method of this approach could not be applied. On the other hand, the Protoflight Approach is also not applicable, since the chosen payloads and the system itself have very heterogeneous maturity levels, which prevent the system from being tested as a consistent entity at each stage. Hence, the test philosophy of MASCOT applies a *Hybrid Approach* with a mixture of conventional and tailored model strategies. This approach is common practice in scientific robotic missions [7] but the specific MASCOT model philosophy goes 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 the 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. According to this dynamical process, the decision which model to test and what to test with it was often made simply on the subsystems availability. 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 components allowing the qualification on MASCOT system level. The verification approach is focused around the systems main structure which comprises the MASCOT Landing Module (LM) the Mechanical and Electronic Support System (MESS), which is the main interface to HY-2 remaining 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 defines the overall maturity of each MASCOT model.

3.3. Concurrent AIV – Dealing with Projects Risks

As mentioned before, MASCOT was granted only a limited time which could not hold a classical sequential approach regarding development, test and verification phases or even allowing margins for risks such as coping with delays due to non-conformances on systems, units, parts and facilities. The heterogeneous maturity levels have let us to tailor a mixed model philosophy of the subunits into an adaptable overall MASCOT strategy to maintain reduced programmatic risks. Due to the highly compact and lightweight nature of this system almost all elements are custom made for the specific mission scenario. The risk assessment showed that a high chance for schedule delays can occur due to test repetition of unit failures and late delivery. Keeping this course, the complete path would have taken us approximately 48 month. However, when your ride has minimal options to wait for you defining a time limit less than 24 month and none of the subunits are replaceable by off-the-shelf equipment, how do you proceed?

To catch up with the HY-2 development schedule and maintain enough margins to incorporate risk, the MASCOT project incorporated parallelization of testing activities using identical copies and flexibility in its model philosophy. This in turn created independent unique test threads only joining their dependencies at key points where optional other roads could be chosen. E.g. If a structure was damaged by one test, or in use longer by another, a copy was shortly available to redo the test if applicable, knowing that a new structure manufacturing process would have taken otherwise 4 months or more. 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 introduce here the term ***Concurrent AIV*** to express the many simultaneous running test and verification activities. In effect, the development, test and verification track of Software Development, Functional Testing, Mechanical AIV and Thermal AIV got their own independent routes sharing their verification processes. Meaning that basically almost all environmental tests on STM and functional test with subsystems will have been performed before MASCOT QM and FM are fully assembled reducing the potential delays. In addition, both these final threads (QM/FM – performed in near parallel activities) are sharing as well their verification processes were the QM will endure all environmental qualification tests at DLR herewith validating parts of the FM which in turn does its final acceptance on HY-2 system level, hereby reducing again required project timeline. Knowing the advantages of this novel approach, the challenges in creating parallel development, test and verification tracks are found in team and facility resources if these are not readily and on-demand available. In addition, this philosophy is 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.

4. Dual-Track Test Campaigns

The applied approach is dynamic and evolves while the project progresses. Figure 8 shows the current (as of the time of writing) top level model and test philosophy of the MASCOT system, not including separate model strategies of payloads or other subsystems. What complicated the development process even further, for the verification of the main spacecraft MASCOT had to take part in certain verification activities on HY-2 system level. As these tasks run also in parallel to the own MASCOT development this introduced a Dual-Track test scenario. To cope this situation, again depending purely on subsystem availability, the already tested models of MASCOT, when not needed for any other purpose in its own development process, where used to take part in HY-2 system verification test. Otherwise, additional duplicate or reduced models where built as “built to purpose and schedule”. Nevertheless, this was used as an advantage to shorten the verification process on MASCOT system level by skipping some tests which will be performed on HY-2 system level and focusing mainly on the requirements implied to be verified for launch. The self-given set of requirements, which focusses more on the scientific outcome of the integrated payloads, where handled similar but with a slightly lower priority.

4.1 MASCOT Track - Engineering Thoughts face Reality!

The first model built was a breadboard (BB) model consisting 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. This model was used to initially demonstrate structural integrity on reduced vibration levels (VIB-1). After this test, the MESS and Ebox where refurbished and advanced to an STM, whereas the LM was re-used as demonstration model for the mobility subsystem including pendulum test and parabolic flight. The MASCOT STM1 then featured the previous BB MESS and Ebox as well as a new LM structure. The model, including also the previous S/S mass dummies, was intended to qualify the structural design (VIB-2), but after failing the test structural damage was severe and it was decided to build yet another structure (STM2). The STM1, however, was refurbished and re-used as demonstration platform for the systems separation mechanism needed later in-orbit operation to push out the landing module out of the MESS and HY-2. These tests have been performed in parabolic flight (PFC) as well as in drop tower (DTC) experiments.

Fig. 2. Separation sequence of MASCOT in microgravity during parabolic flight experiments.

In addition, the STM1, though structurally altered, was advanced to represent the initial thermal design of the flight model. The model then underwent a reduced thermal campaign for Cruise Phase – Earth to Asteroid (TVAC-1-B, LM+MESS) and the Return Phase – Asteroid to Earth (TVAC-1-A, MESS only), whereas the return phase was conducted first due to model and setup simplicity. This campaign, though not applicable for qualification, was a valuable dress rehearsal to validate the subsequent qualification and acceptance program. This included test technique, procedures, training of test personnel, logistics, equipment, instrumentation and software.

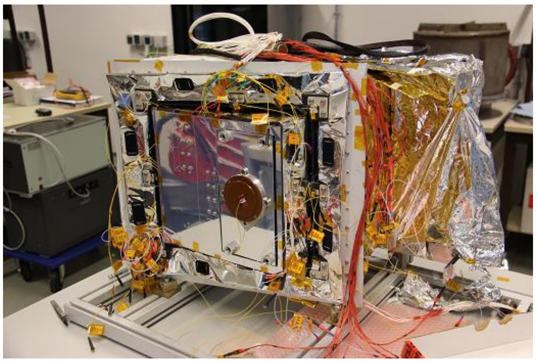

Fig.3. MASCOT STM1 during Cruise-Phase Thermal Vacuum Test.

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 were produced (STM2.1 and STM2.2) which could run completely independent paths of structural and thermal qualification activities. 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 (VIB-3-QL) with qualification levels, which verified also the frequency response and load levels of all subunits, the STM2.1 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 system level.

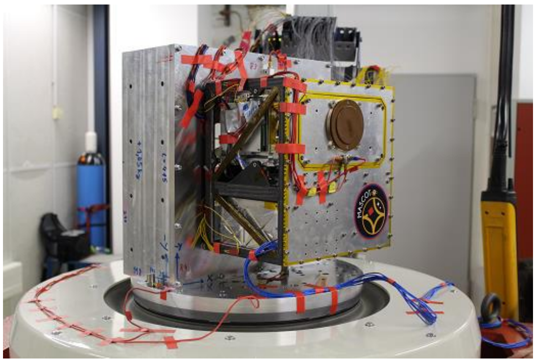

Fig.4. MASCOT STM2.1 during Random Vibration Test to full Qualification Level.

While the STM2.1 underwent the structural verification path, the STM2.2 is awaiting currently thermal verification of the Return and Cruise Phase (TVAC-2-A/B). After vibration, P/L's and other subunits are re-used for the thermal test but are improved again to be thermally representative, including dummy heat pipes, main and sub radiator, optical face sheets, multi-layer insulation as well as controlled heaters. In order to prevent over-testing and to confirm that no structural alteration during thermal cycling has been induced by thermal stresses we incorporate vibrational resonance checks with low level sine-sweeps (VIB-Res) before and after each thermal environment test. After successful test of the return and cruise phase configuration the setup is changed to the third and final On-Asteroid Phase (TVAC-3), whereas this test is again a reduced dress rehearsal for the later QM test (TVAC-4) which will include full functional subsystems and payloads. Both STM2 after completion of the structural and thermal patch will be used afterwards as qualification test bed of other critical system elements (e.g. separation, preload release, umbilical connector, Mobility microvibration as well as P/L FOV alignment tests).

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 functional system tests. 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 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. These functional tests run continuously until functional performance of all real hardware electronic boards is approved and the cards can be implemented into the MASCOT QM.

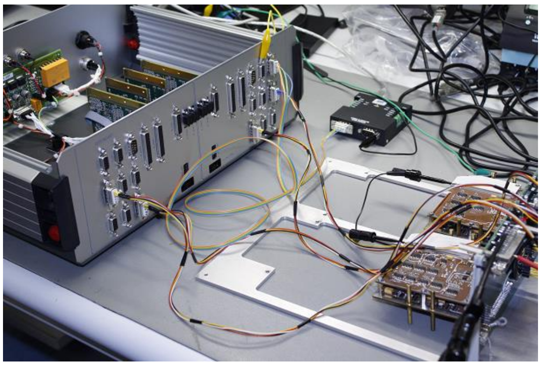

Fig.5. MASCOT SDVF during conducted EMC tests including OBC, PCDU and all Payload Electronic boards.

4.2 Hayabusa-2 Track – Bringing it on the Road!

As mentioned above the MASCOT system tries to catch up with the development progress of the mother spacecraft Hayabusa-2, whose final test sequence is split into sequential test campaigns starting with an environmental campaign with qualification test and the Initial Integration Test (IIT), where subunits are integrated for the first time and end-to-end communication to the main spacecraft is tested. This is then followed by an Acceptance Environmental Test (AET) and the Final Integration Test (FIT) leading all the way up to the launch campaign. Each test campaign is required to see a MASCOT model in order to verify the HY-2 system performance. However, as the MASCOT system only reaches proper maturity at the end of this year, which will be just in time to take part in the FIT, reduced models and mock-ups of MASCOT build to schedule and purpose had to be produced.

In order to receive appropriate vibration qualification levels at the final integration place of MASCOT, a dedicated mass dummy (MD) was created resembling the overall MASCOT system in mass, CoG and mechanical interfaces to HY-2. This MD was send to the JAXA/ISAS test center to take part in the first environmental test of the mother spacecraft.

Fig.6. MASCOT MD during integration and test for the first HY-2 Environmental Test Campaign.

For the IIT a separate EM was built with a mock-up structure resembling MASCOT in form and fit as well as having EM functional communications equipment includeding OBC, PCDU, Antenna and CCOM. 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. After conclusion of the IIT the MASCOT EM will be send back and re-used as trainings model for fit checks and integration procedures.

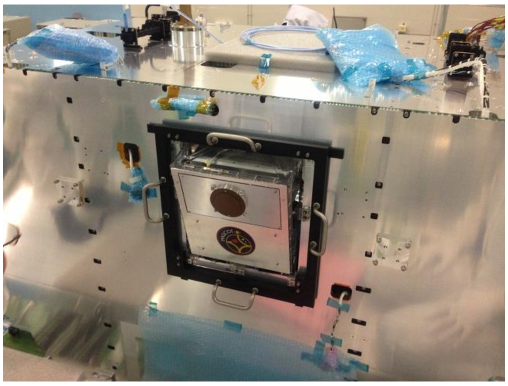

Fig.7. MASCOT EM mounted to HY-2 during Initial Integration Test.

At the time of writing of this paper, the MASCOT FM structure awaits the final go-ahead after which again two identical models of the LM, MESS and Ebox will be build, whereas the first will be used as QM running through a complete qualification process with a mix of integrated STM, EM, EQM, and QM payloads and subsystems. This includes static load tests, random vibration (VIB-4-QT) and shock tests (SHOCK-1-QT), thermal on-asteroid phase (TVAC-4-QT), conducted and radiated electromagnetic compatibility tests (EMC) as well as full functional tests (FFT). After successful completion of the qualification program, the MASCOT QM will be send to ISAS to be included in the AET/FIT campaigns of the mother spacecraft attending additional functional and environmental acceptance test on spacecraft system level (e.g. outbaking, but excluding sensitive MASCOT equipment). The QM, serving as FS/GRM, is exchanged with the FM sometime during the FIT. Currently, delivery is scheduled for February 2014. Again due to schedule limitations, the FM, then including all FM subunits and payloads will be subject to an abbreviated acceptance test program, some of the tests at HY-2 system level, but including calibration campaigns of payloads and full functional tests after each major environmental test.

At this point, MASCOT overtakes the mother spacecraft development progress and the duel-test track of MASCOT and HY-2 merge. After last functional checkouts and the final integration of MASCOT and inserting late access equipment (e.g. battery), with further communication only possible through the main spacecraft, MASCOT will be awaiting completion of HY-2 and shipping to Tanegashima Spaceport for Hayabusa-2 launch campaign.

5. Conclusion

A fast paced and high performance deep space project, like MASCOT, faces many challenges specifically during the last development stages. A standard classical model and test approach would have taken too long, but by applying a unique mix of conventional and tailored model philosophies it is possible to dynamical adapt the test program, limited by a fixed launch date, to accomplish for the shortest planning and a suitable weighing of costs and risks. In addition, using *Concurrent AIV* to identify design and manufacturing issues shortens the project timeline further and keeping an acceptable amount of risk improving MASCOT every step of the way. In effect, a general 4 year AIV phase was reduced to less than 2 years. The challenge is to identify the test dependency, test sequences and which test can be performed in parallel.

Due to its demanding goal and pioneering approach, MASCOT has a high potential to act as a showcase model for projects with a similar demand in high performance and short development time, for example as is the case within this fresh and dynamically expanding field of science. As Near-Earth Asteroids are discovered at an increasing rate, the application of this design approach may one day turn from a rare and welcome launch opportunity to an urgent necessity.

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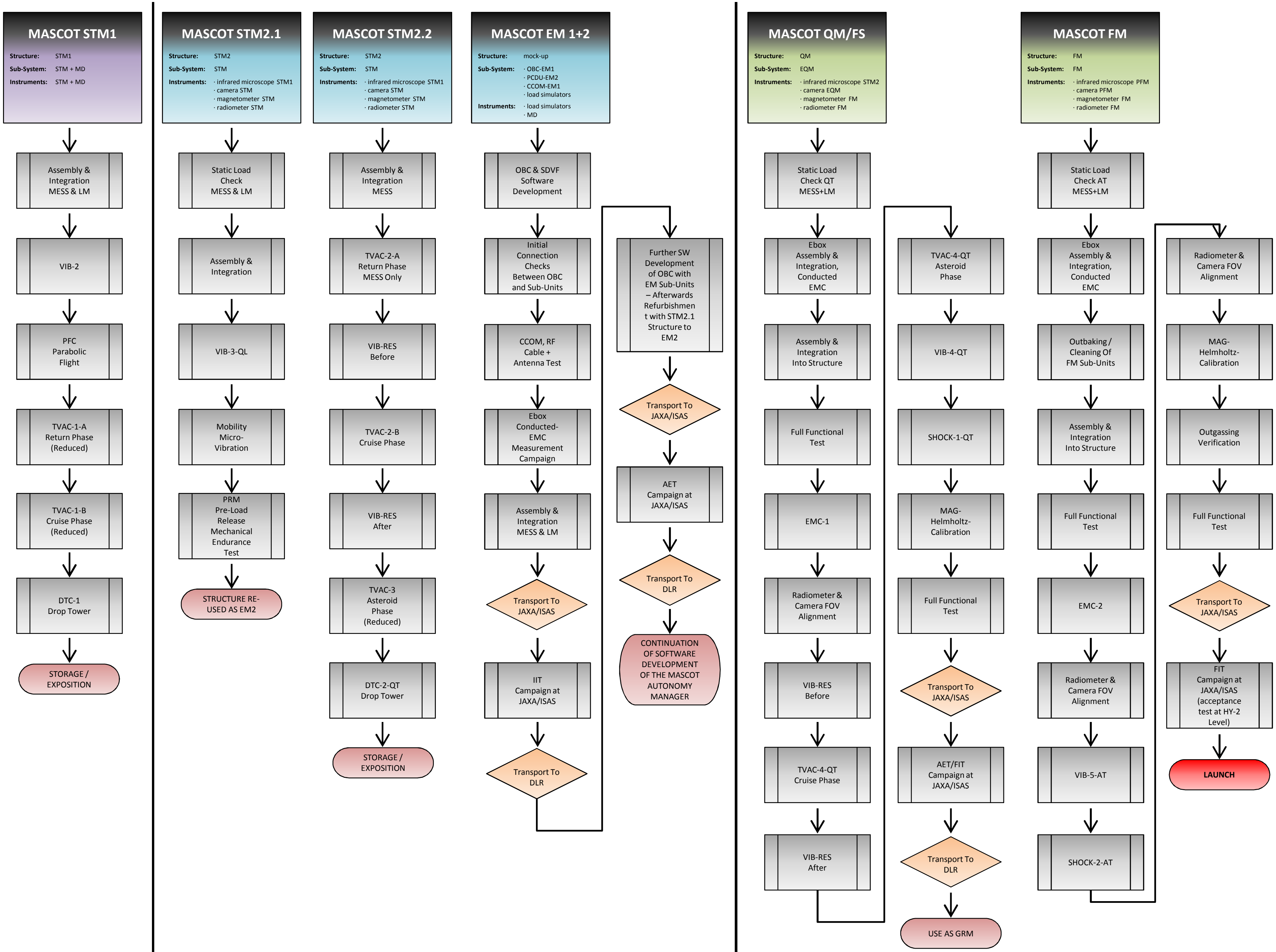

Fig.8. Flow diagram of MASCOT top level model and test philosophy.