

# CALLISTO: Reusable rocket stage demonstrator: getting ready for implementation

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Japan and Europe are finishing the work to introduce their new workhorse launch vehicles: H-3 and Ariane 6. While both vehicles are following an expendable design, reusable launch vehicle are successfully tested and operated in USA. This evolution has shown that reusability could be a solution for further improvement of competitiveness, versatility and sustainability of future launch system.

In order to understand the specificities of reusable launch vehicles in terms of design, optimization and operations, and mature the required key technologies, CNES, DLR and JAXA have decided to join their competences in the project CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss - back Operations). The project aims at developing, building and testing a prototype vehicle which shall, without a technological precursor, demonstrate the mastering of flights and operations representative to a reusable launch stage. Along all project phases, data and knowhow are being gained about design, manufacturing, operations and maintenance solutions, which are essential for the development of future operational vehicles.

The project team is now finalising the design and series of tests in order to be ready to start in the implementation in few months. The paper is giving an overview of the progress achieved at DLR in collaboration with CNES and JAXA.

**Key Words:** CALLISTO, RLV, VTVL, Demonstrator, Reusability

## Nomenclature

AIV	: Assembly, Integration and Verification	FNS	: Flight Neutralisation System
ALS	: Approach and Landing System	G&C	: Guidance and Control
AVF	: Avionics Validation Facility	GNC	: Guidance Navigation & Control
CALLISTO	: Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations	GNSS	: Global Navigation Satellite System
CDR	: Critical Design Review	HNS	: Hybrid Navigation System
CNES	: Centre National d'Études Spatiales	JAXA	: Japan Aerospace eXploration Agency
CSG	: Guiana Space Centre	LH2	: Liquid Hydrogen
DLR	: Deutsches Zentrum für Luft- und Raumfahrt e.V.	LLI	: Long Lead Items
DRR	: Disposal Readiness Review	LLRM	: Launch Lock and Release Mechanism
ELV	: Expendable Launch Vehicle	LOX	: Liquid Oxygen
EM	: Engineering Model	MAIV	: Manufacturing, Assembly, Integration and Verification
EQM	: Engineering Qualification Model	MECO	: Main Engine Cut-Off
FCS	: Flight Control System	MEIG	: Main Engine IGnition
FCS/A	: FCS/Aerodynamic	MRO	: Maintenance and Repair Operations
FCS/R	: FCS/Reaction control	NTC	: Noshiro Test Center
FCS/V	: FCS/thrust Vectoring	OBC	: On-Board Computer
FDR	: Flight Data Recorder	PDR	: Preliminary Design Review
		PFM	: Protoflight Model
		QM	: Qualification Model
		ReFEx	: Reusability Flight Experiment
		RLV	: Reusable Launch Vehicle

RSR	: Reusable Sounding Rocket
SM	: Structure Model
SPCP	: Sequential Pseudospectral Convex Programming
SRR	: System Requirement Review
TM/TC	: Telemeasure and telecommand
TVC	: Thrust Vector Control (angle)
VEB	: Vehicle Equipment Bay
VTVL	: Vertical Take-off and Vertical Landing

## 1. Introduction

Europe and Japan are renewing their launcher fleet with the introduction of Ariane 6 and H3 in the coming months, replacing their reliable but more expensive workhorses Ariane 5 and H-IIA. These upcoming launch systems address the current need for more versatility, sustainability and in particular decrease cost of access to space. Already analyses are being conducted to assess how the evolution or the successor of these new launch vehicles could look like. One possibility is to introduce reusability at least of the first stage <sup>1,2)</sup>.

Indeed, a disruption of the launch service market has been achieved by the implementation of vertical launch and vertical landing (VTVL) on launch vehicle allowing for recovering and reusing launch vehicle first stages. As of late May, 32 Block 5 first stage of the Falcon 9 and Falcon Heavy rocket flew and were able to perform a total of 182 missions, leading to an average of almost 6 flights per stages, with even some stages which performed already 15 missions each and waiting for an increase of their certification to 20 flights. The feasibility of VTVL rocket stages and the reuse of stages within short period of time (less than 1 months) is not any longer to be proven. This capability certainly played an important role in rapid increase of the space transportation market shared by SpaceX. A positive impact on the launch service cost is also to be expected.

The environment and especially the launch service market accessible in Europe and in Japan is different from the one in the USA, still it appears that reusability and VTVL is one of the capabilities having the most promising chances to decrease dramatically the cost of access to space and to reach the economical sustainability of a launch system in Europe and in Japan.

The aforementioned studies <sup>1,2)</sup> have shown that depending on the architecture of the vehicle and the type of recovery method a sensible reduction of the recurring costs of launch vehicles should be achievable. Naturally, the advantage brought by reusability for the launch cost depends on many parameters such as the accessible market and the launch rate but also technical and operational parameters. The knowledge of these parameters is the main limit of system studies, such as the ones mentioned above. Expert judgment and parametric analysis supported by reverse engineering of what is known from Falcon 9 allow assessing the costs of the additional systems needed to make a stage or a vehicle recoverable and then reusable. However, these assumptions can only be validated and confirmed with the help of tests in real environment and conditions. In particular the costs linked with

the Maintenance and Repair Operations (MRO) between flights are difficult to evaluate while they play a decisive role in the evaluation of the economical sustainability of reusable rocket stages. As long as test in real conditions have not been performed only rough estimation are available.

The CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss - back Operations) project lead jointly by CNES, DLR and JAXA has the goal to gather economic and technical know-how and data on re-usable launcher stages and mature and demonstrate the technologies needed for reusable launch vehicle stages. The project was started officially in 2017, with a system readiness review in early 2018, a PDR-S late 2019 and a long and detailed iteration phase between system, & product until the PDR of the product could take place in the course of 2022. Now the design is getting consolidated and numerous tests and simulations have been performed in order to optimize the design and increase the confidence in the implementation.

## 2. CALLISTO Project: An Overview

In the frame of the CALLISTO project a scaled rocket stage is going to be built, tested in flight, recovered and tested again in flight. The flight test campaign is consisting of up to 10 flights, shared in 5 flight classes with incrementally increasing velocity and altitude. The final flight class is intended to mimic each of the main phases and manoeuvres an operational reusable VTVL rocket stage would encounter during a flight. A schematic of the main phases of this last flight class (dubbed demo flight) is displayed in Fig. 1.

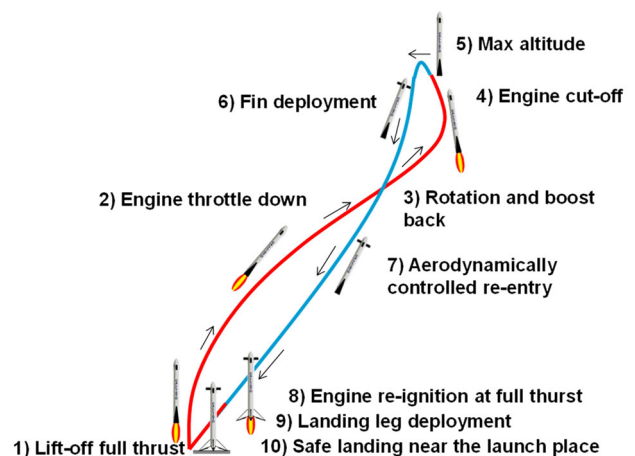


Fig. 1. Overview of the main phases and maneuver of CALLISTO demo flight.

The CALLISTO vehicle is about 14 m high when standing on its landing legs and has a diameter 1.1 m, so that the length to diameter ratio is similar to the one of an Ariane 5 launcher. At launch the gross lift-off mass is lower than 4 metric tons, with a thrust to weight ratio comparable to the one of classic launch vehicle running on liquid rocket engines.

The first particularity of CALLISTO (see Fig. 3) when it comes to compare it with an expendable launch vehicle or stage is its rocket engine. The vehicle is propelled by JAXA's RSR2

engine, which runs on LOX/LH2 in an expander-bleed cycle and provides deep-throttling and reignition capabilities. These two capabilities are compulsory for a VTVL stage with only one engine, to allow for the different propulsion phases and the propelled landing phase. The second particularity of CALLISTO is the approach and landing system (ALS). It is developed by DLR on the base of the long experience gathered with planetary lander and lightweight structure and mechanisms. The ALS main and most visible components are the four deployable landing legs. They are made out of CFRP and titanium and are pneumatically deployed shortly before landing during the demo flight. An important system aspect at this point is the accurate modelling of the deployment process under the strongly varying aerodynamic conditions see Ref. 3).

CALLISTO is also equipped with four deployable fins, electromechanically controlled and part of the so-called aerodynamic flight control system (FCS/A). They are also developed and provided by DLR. The shape of the fin with a symmetric flattened diamond like profile is well adapted to the subsonic and transonic flight regime which will be reached during the descent part of the flight. During this phase the FCS/A is the only active flight control system available. Therefore, the knowledge its aerodynamic characteristics (nominal properties and uncertainties) is decisive, see Ref. 4).



Fig. 3. 3D Rendering of CALLISTO vehicle.

The other components and subsystems are at a first glance similar to the one of an expendable stage but need to be specifically designed for the need of a reusable rocket stage. An overview of the component and the sharing of the

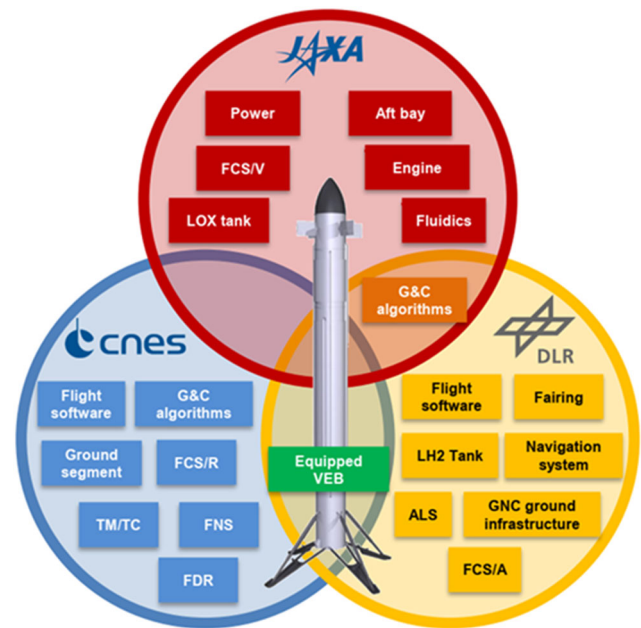


Fig. 2. Major subsystems of CALLISTO, arranged by work share between project partners.

responsibilities between CNES, JAXA and DLR can be found in the Fig. 2. The current status of the development for product with DLR responsibility will be given in the subsequent chapters. In order to place these activities within the global timeline see Fig. 4. In this timeline, the activities linked to the propulsion block flight model involving the LH2 tank and ALS from DLR will start first in Germany. Then these two DLR products will be shipped to Japan for the integration with the other products under JAXA responsibilities, that is to say in particular the aft-bay with the vectoring flight control system and the rocket engine, but also most of the fluid propulsion components and the LOx tank. In order to ease the integration in Tsukuba and the following hot firing tests at Noshiro test centre, parts of the structure/qualification model of the top block under DLR responsibility will be also shipped to Tsukuba after completion of the tests performed in Germany and in France under DLR and the CNES lead. After the hot firing test campaign, the propulsion block will be shipped to Kourou for the combined tests and the subsequent flight tests.

The second part of the flight model integration is concerning the top block, with the main structures, the fairing and vehicle equipment bay (VEB) structure being built by DLR. All DLR contributions for the top block, including the FCS/A but also an OBC (On-Board Computer) and the HNS (Hybrid Navigation System) will meet first in Germany for a fit check, before they will be shipped to Switzerland and then to Toulouse for the integration and test. There further avionic contributions mainly from CNES, but also from JAXA will also be integrated. Upon completion of the MAIV activities, the flight model of the top block will be shipped to Kourou, where it will be integrated with the propulsion block to complete the vehicle.

Starting already now an avionic validation facility (AVF) is incrementally being built to allow for an early check of the proper communication of the avionic components provided by

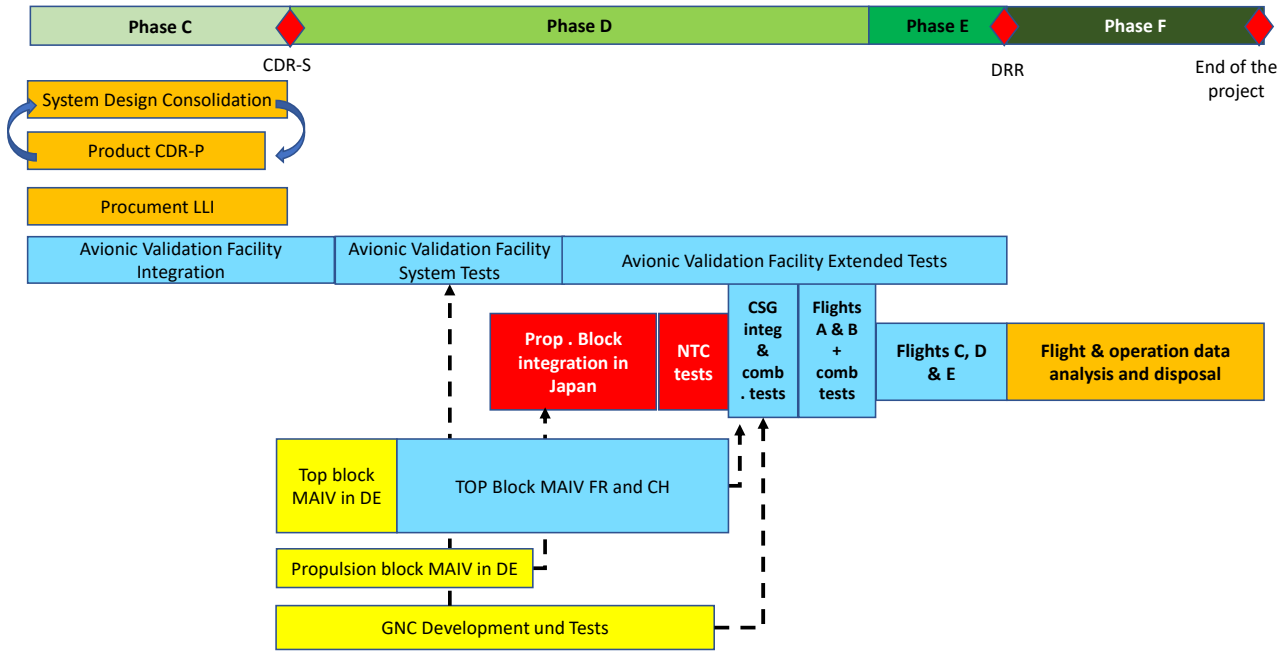


Fig. 4. Main planned tasks from now until CALLISTO program completion for DLR provided components and subsystems, with DE standing for Germany, FR for France, CH for Switzerland, LLI for long lead items, MAIV for Manufacturing, Assembly, Integration and Verification, NTC for Noshiro Test Center, CSG: Centre Spatial Guyanais: Kourou Space Center and DRR for Disposal Readiness Review. Colour code: blue under CNES lead, red under JAXA lead, yellow under DLR lead and orange bi- or tri-lateral led activities.

### 3. Getting Ready for Implementation

With the CDR-S planned for late 2023, the design of all DLR contributions to the CALLISTO program is being consolidated with the help of tests and simulations. Some selected example will be presented in the following subchapters.

#### 3.1. Landing Guidance

In CALLISTO DLR and JAXA are developing together G&C algorithms that will be running on the OBC that will be provided by DLR. In parallel CNES is developing another G&C with different techniques, that will fly alternatively with the DLR/JAXA ones. While progresses in the domain of control can be found in Ref. 5, decisive progress has been achieved in the key aspect represented by the landing guidance system, that must be able to provide a solution even in presence of off-nominal conditions at the landing boost. What is typically done in literature is to formulate the problem as a pure minimum-time or minimum-fuel optimal control problem. However, for a challenging scenario like the CALLISTO one, further considerations on the safety of the trajectory were necessary, especially by considering the non-negligible aerodynamic effects, and the need to trim the vehicle to avoid the presence of large parasitic aerodynamic torques that would make the tracking of such solution harder if not impossible at all. To overcome these difficulties, we developed the landing guidance algorithm by using a Sequential Pseudospectral Convex Programming (SPCP) technique<sup>6,7</sup>, that transforms the continuous Optimal Control Problem into a sequence of convex

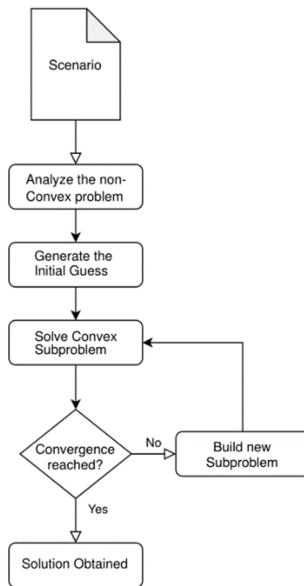


Fig. 5. Landing guidance scheme – Sequential Pseudospectral Convex Programming method.

the different partners and that much before the vehicle will finally stay in on piece in Kourou. These activities are taking place in Les Mureaux, France also with contribution of DLR in the form of engineering or qualification models.

subproblems that quickly converge to a satisfactory and physically consistent guidance solution. The idea is highlighted in the scheme of Fig. 5. Once the scenario is defined, an analysis of the problem is carried out to figure out what elements of the problem require online computation (e.g., the aerodynamic forces) and what can be considered constant (e.g., the gravity is treated as a constant value, given the short time of flight of this phase). After that, an initial guess satisfying the boundary conditions of the problem is generated and employed to define the first convex subproblem and start the iterative procedure, which ends up when the difference between two consecutive sub-solutions is within a predefined threshold, meaning that an acceptable convergence has been reached.

An example of the trajectory obtained is provided in Fig. 6, where the scaled altitude, speed and mass states, together with the engine throttle command, are depicted. It is worth noticing that the bang-bang nature of the thrust profile is a good indicator of the quality of the solution. Moreover, all the states are smooth and the conditions for a pinpoint landing of the rocket are satisfied.

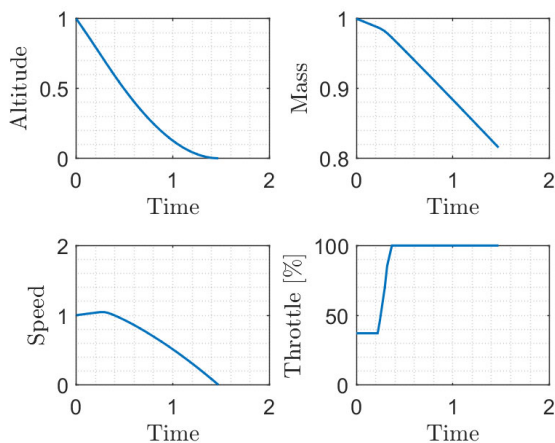


Fig. 6. Landing Guidance solution example.

### 3.2. Real-Time Kinematics for altimetry

After guidance and control, the third aspect of GNC is navigation. CALLISTO will be equipped with a hybrid navigation system (HNS) developed and built by DLR. While the work for the central part of the HNS, the HNS box, doing the fusion of the data provided by the sensor suite is progressing simultaneously in CALLISTO and the other demonstration project looking at reusability at DLR ReFEx, very good progress has been achieved in the last months to confirm the method selected to measure the height above ground with high accuracy during the landing phase. After a preliminary study it was decided to reject a solution based on a radar altimeter, because of the complexity and duration of the implementation and to prefer a solution relying on the hardware anyway already planned for the rest of the flight of CALLISTO, that is to say the DGNSS (Differential Global Navigation Satellite System). The selected solution is based on RTK (Real Time Kinematics) technique, which is offering in terrestrial ground activities a precision in range of centimetres by using the measure of the

phase of the signal carrier waves. Until today no application of this technique in the frame of reusable launcher stages could be found. The difficulty is linked to the velocity of CALLISTO during descent, the altitude difference between the vehicle and the ground station and possible signal interruptions. With this in mind, tests have been performed first with a skydiver. The goal was to approach some the conditions that we would be faced with CALLISTO with a limited effort. Ten jumps from an altitude of about 4500 m have been performed and falling velocities of almost 400 km/h have been achieved, see Fig. 6. During the flights the antenna has also seen different orientations. Sky-diver test data have been analysed and the results have been extrapolated for the equatorial conditions to be expected in Kourou. No showstopper for implementation at software level in the flight model has been found. Recall no modification of the hardware baseline is needed to implement the RTK technique.



Fig. 7. RTK sky diver tests in south Germany.

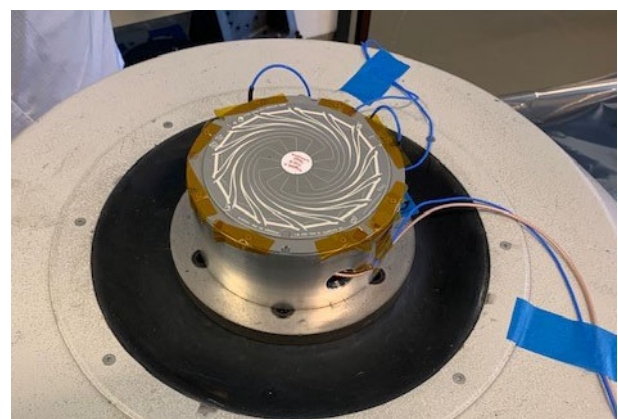


Fig. 8. CALLISTO GNSS antenna during vibration tests at qualification levels.

Hardware tests have also been conducted with the GNSS antenna which passed the 35 gRMS qualification level <sup>8,9)</sup> see Fig. 8.

### 3.3. Top block structure: the fairing and the VEB structure

The refinement of the design of the top block under DLR responsibility made significant progress, so that the fairing qualification model could be manufactured completely with the CFRP ogive, the cork thermal protection, the aluminium flange and aerocover at the lower part and the nose cone equipped with the DGNSS antenna, see Fig. 9. More details about the work performed in the last months can be found in Reference 9). The work performed includes as well tests of the attachment for the flight neutralisation system provided by CNES. These tests (see Fig. 10.) also were successful, therefore the fairing EQM is the first part of the top block ready for the top block QM test campaign shared between DLR and CNES.



Fig. 9. CALLISTO fairing engineering qualification model.

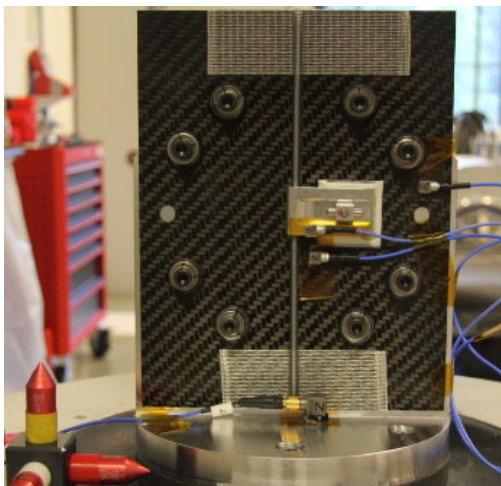


Fig. 10. FNS Attachment on the Shaker.

The second large structure provided by DLR for the top block is the vehicle equipment bay structure. The final design is being frozen together with CNES which is responsible for the VEB module aspects, in order to perform during the summer 2023, the manufacturing of the structure model of the

VEB structure. A cut-out of this complex lightweight structure which is accommodating a large part of the avionic components on dedicated adapter plates but also the FCS/A and FCS/R can be seen in Fig. 11.

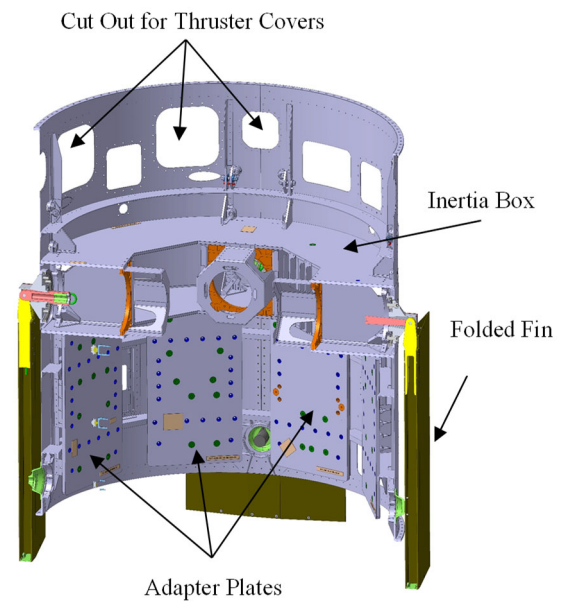


Fig. 11. Cut-out of the VEB Structure (not to scale).

### 3.4. Aerodynamic flight control system

For the aerodynamic flight control system (FCS/A) as well, good progress has been achieved in the design and testing over the last months. One example is the testing of the harness between movable parts of the actuators, see Fig. 12. These tests allowed to optimize the design, which demonstrated now a reliability of over 99,87% with a level of confidence of 90%<sup>8)</sup>.

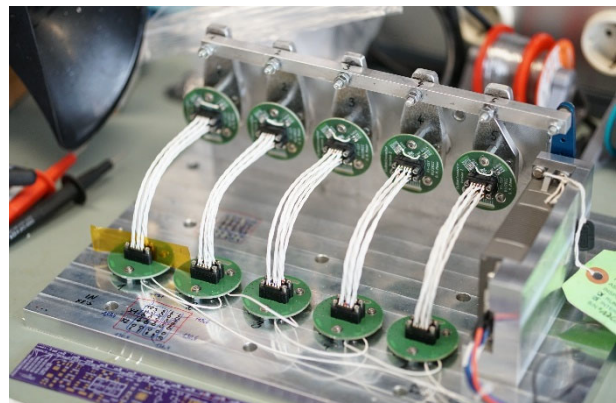


Fig. 12. DLR's flexible harness reliability test rig.

After delivery the main actuator motor has recently also passed successfully the functional test see Fig 13. Next steps will allow for the integration of the rest of the actuator EQM, which will be tested later with the rest of the top block SM/QM. Tests on sub-component level have also been necessary for the structural part of the FCS/A before testing the assembled configuration.<sup>8)</sup> In addition to functional tests of the hinge

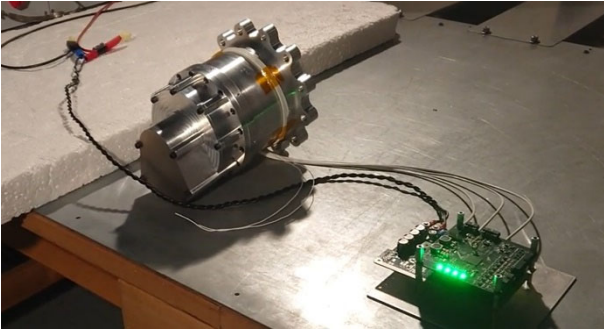


Fig. 13. Functional test of actuator main motor successful.

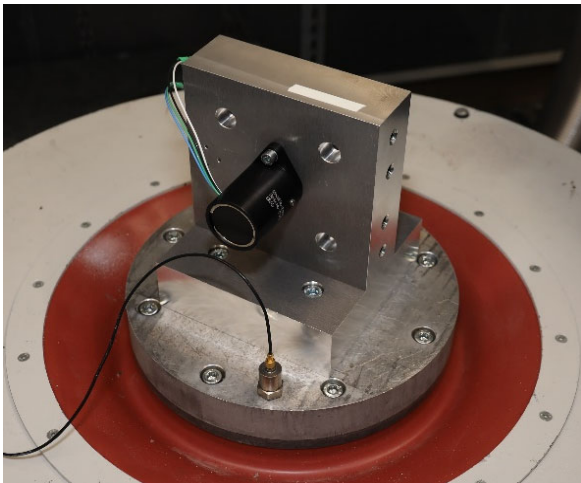


Fig. 14. FCS/A LLRM on the shaker.

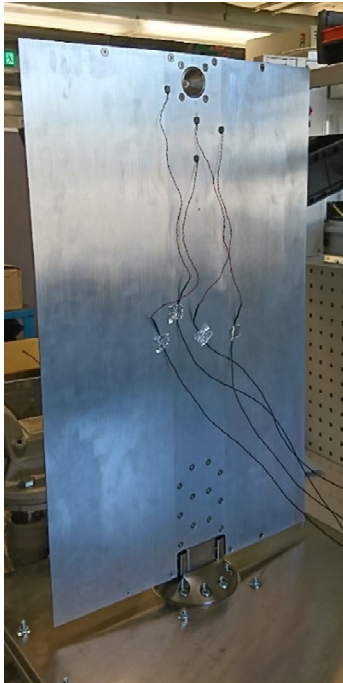


Fig. 15. Instrumented fin EM for LLRM shock test.

device released as expected and showed its operational capability after the test. Fig. 14. shows the LLRM device on the Shaker at DLR Stuttgart. Additionally, Fig 15. displays the instrumented fin structure during the LLRM shock test.

### 3.5. Approach and landing system

The second deployable subsystem under DLR responsibility is the landing gear part of the Approach and Landing System (ALS) see Fig. 16. A second set of touch-down (Fig. 17) and deployment tests (Fig. 18) have been performed with an updated design of the engineering model in order to cover a large range of condition such as those computed and expected for the landing phase<sup>10</sup>. The test results were as expected, so that the procurement of the part for the manufacturing of the PFM of the ALS started during the summer 2023. It concerns also the clip-on TPS which will be used to provide an additional protection to the lightweight landing leg structure during the flights of class A and B. A scale version of the clip TPS has been successfully manufactured in DLR, see Fig. 19, confirming that the full-size clip TPS should be manufacturable with limited difficulties. Further details on the development of the structure of the landing legs can be found in Reference 11.

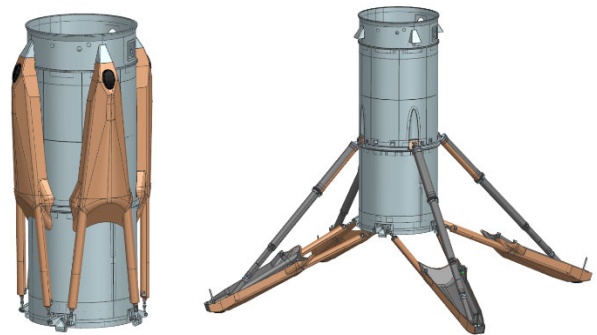


Fig. 16. ALS in folded (left) and deployed (right) configuration including thermal protection seen in brown-orange color.



Fig. 17. ALS touch down test.

mechanism, LLRM shock and vibration tests have been performed on an engineering model. A LLRM vibration test was performed for sine and random loads of all three axes. The



Fig. 18. Deployment of a single landing leg for CALLISTO. Before LLRM release (left) and after deployment and latching (right).



Fig. 19. ALS Clip TPS scaled (1/5).

### 3.6. Equipped and Insulated LH2 Tank

Due to the low density of LH<sub>2</sub>, the LH<sub>2</sub> tank is the largest component of CALLISTO. Two main aspects are guiding the design of this product which is following a PFM philosophy: the structural design and the functional design. For what concerns the structural design, the tank is together with the upper and lower skirt about 6 m long with a diameter of 1,1 m

and has to weight less than 200 kg. The design is now getting consolidated in prevision of the manufacturing set to start in the second quarter of 2024. The second aspect is the functional design and all topics linked with the propellant management. Complex analyses are being performed in order to better predict the behaviour of the propellant for instance during the phases of low gravity and optimize the design of internal components such as the diffusor<sup>12)</sup>. Other analyses are aiming at assessing the pressurisation process in order to evaluate the need of pressuring gas and especially helium which will be limited during the CALLISTO flights<sup>13)</sup>.

### 4. Conclusion

The CALLISTO demonstrator developed jointly by JAXA, CNES and DLR is paving the way for potential future reusable launch vehicle in Europe and in Japan. Numerous test and simulations have been performed in the few past months allowing to confirm the design and authorising the implementation in the coming few months. This step already allowed to gather significant know-how useful for future reusable launch vehicle. Flight data will of course provide further decisive data.

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