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# CALLISTO, a demonstrator for reusable launchers

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## Abstract
Japan and Europe are now getting ready for the maiden flight of their new workhorse launch vehicles: H-3, Vega-C and Ariane 6. But continued improvements, especially in term of costs, are necessary to continue to offer an affordable access to space. To prepare this next step, three countries and their space organizations: CNES for France, DLR for Germany and JAXA for Japan have developed the CALLISTO system as a joint project. This include the CALLISTO vehicle which is a flight demonstrator for future reusable launcher stages. The challenge is to develop, all along the project, the skills of the partners. This know-how includes products and vehicle design, ground segment set up, and post-flight operations for vehicle recovery then reuse. The first tests will be conducted in 2024 from the CSG, Europe's Spaceport for commercial launches, and this paper presents an overview of the status of the CALLISTO project. General development status is described. Next step of the development will be the Critical Design Review.

## 1. Introduction

Japan and Europe are now getting ready for the maiden flight of their new workhorse launch vehicles: Ariane 6, Vega-C and H3. Nevertheless, continued improvements, especially in term of costs, are necessary to continue to offer an affordable and competitive access to space. To prepare this next step, JAXA, CNES, and DLR have developed the CALLISTO (Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations) system as a joint project [1] in order to understand the specificities of reusable launch vehicles in terms of design, optimization and operations, and mature the required key technologies.

Key technologies address many domains, like guidance and control - for which two versions are in development, one by CNES, the other jointly by JAXA and DLR -, landing system, aerodynamic control system and navigation system, reusable engine with reignition and throttle capability, propellant management in flight, optimisation of Maintenance & Repair Operations in between flights, use of services of an operational spaceport with associated constraints, landing zone definition, first operations after landing to ensure continuous safety …

Reflecting this, the Launch system includes a scaled Vertical Take-off Vertical Landing (VTVL), reusable vehicle and its Ground Segment supporting the flight and ground operations of the vehicle. The flight campaign will be initiated by end of 2024 at Guyana Space Center (European spaceport).

## 2. Project organization

A joint CNES-DLR-JAXA team was put in place to manage this project. An apparent challenge could be to work with very different cultures in the same project. This is usual for orbital or exploration missions, but relatively new for the launcher field. Thanks to agile tools, organisation [2] and face-to-face collocated working meetings (as far as the Covid pandemic authorised), the benefit of exchanging with different technical background balances largely the apparent complexity in decision making. The motivation of staff involved is also a key factor, and this is a reality, supported also by the strong involvement of each organisation, for which CALLISTO project is part of their global launcher roadmap towards reusability.

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The work sharing has been defined considering each partner background and technical motivation. Structural pillar of the development is to take benefit from the availability of some key products, including a throttleable reusable engine developed by JAXA, avionic developed by DLR and the CNES launch base in Guyana.

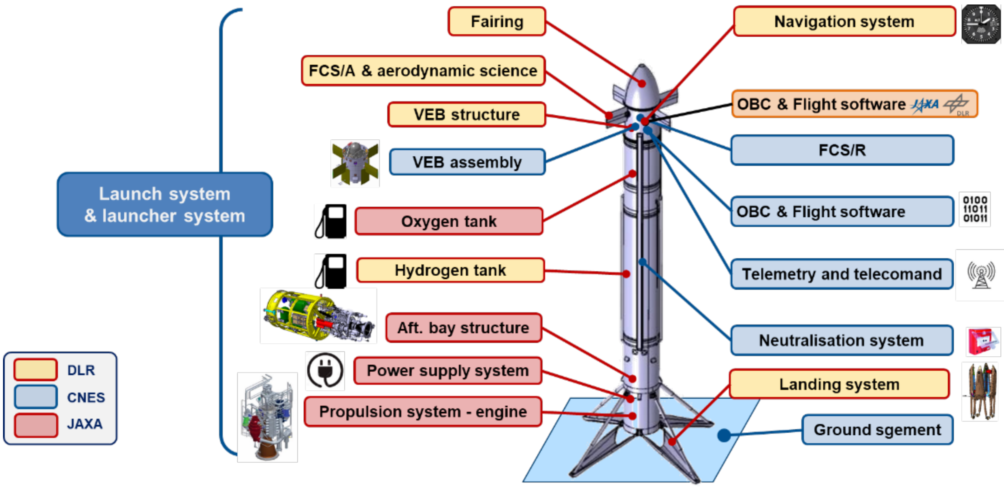


Figure 1: Work sharing among the organisations

## 3. Project and mission objectives, launch system development status

The project and mission objectives, as agreed by the tree organisations, shall cover the following:

- Vertically land on a designed landing zone, following an ascent phase and a return phase including a boostback manoeuver and an unpowered aerodynamic manoeuver such to reach the transonic region,
- Demonstrate a large and quick manoeuvre at low dynamic pressure while managing cryogenic propellant behaviours inside tank,
- Perform at minimum one landing with a minimum non-gravitational acceleration of 1,3g
- Optimise the inter launch operations to reach an objective of at least 8 launches within 6 months.

Considering the aforementioned objectives, a trade-off between a landing point on a sea barge localized in open sea downrange, and a return back close to the lift-off pad was performed and concludes in favour of the second option.

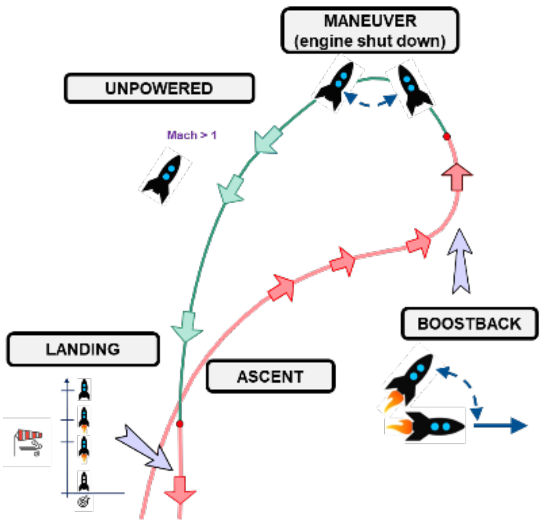


Figure 2: Main phases of the demonstration mission

According to the development logic, the “Verification Key Point” held in December 2020 confirmed that the vehicle and the launch system at large, with the design derived from the one presented previously at the Preliminary Design Review, is able to reach those objectives.

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This paved the way to the ongoing period of products and modules PDR and then, following a standard V development, associated Critical Design Reviews. A system design iteration will be performed in this period and a System Critical Design Review is planned end of 2022.
Because CALLISTO is a demonstrator, without consideration of any need for industrialisation, start of manufacturing of flight hardware, and long lead item procurement, if needed prior to CDR, can be authorized case by case via devoted Manufacturing Readiness Reviews. This will be the case especially for the propulsion block which should perform static fire by the first semester of 2024 at Noshiro test center in Japan.
Finally, flight worthiness reviews will be organized to authorize the combined tests and the test flight campaign at CSG.

As CALLISTO will be flown from a space center where commercial launches are regularly carried out, it was decided to get it compliant with the requirements of French regulations on space operations. The safety review process is therefore initiated in parallel and the first phases occurred nominally.

# 4. Vehicle development status

## 4.1 Configuration

Presented at the system Preliminary Design Review (PDR), the vehicle configuration is now frozen. The vehicle is compliant to the objective to perform the requested maneuvers in flight, to reach the transonic regime and to return to its home base. Main characteristics are summarized in table 1.

Table 1: CALLISTO vehicle size and mass

| | Value | Unit |
|---|---|---|
| Diameter | 1.1 | m |
| Total height | 13.5 | m |
| Dry mass | 1 520 | kg |
| Take-off mass | 3 600 | kg |

## 4.2 Vehicle equipment bay (VEB) module

The development of the VEB module is shared between DLR and CNES. DLR is responsible for the VEB structure and CNES is responsible for the VEB module which includes in addition all equipment mounted inside or onto the VEB. This comprises all avionics equipments delivered by CNES, JAXA and DLR, electrical harnesses, the aerodynamic Flight Control System (FCS/A) and Reaction Flight Control System (FCS/R).

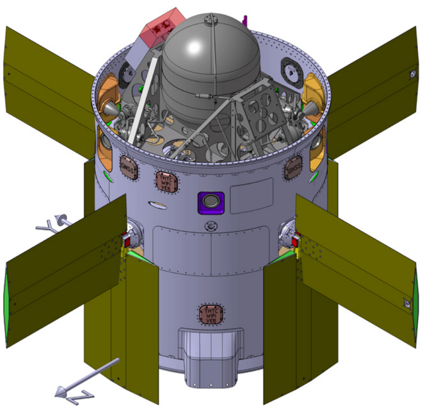

Figure 3: View of the Vehicle Equipment Bay module

DOI: 10.13009/EUCASS2022-7239



The challenge is to put in a small sized vehicle equipment bay many standard launcher hardware with its sizes and mass not designed for such application. Additionally, environmental loads are not decreased proportionally, and put additional constraints which require, for instance, specific damping devices. Finally, provision shall be added for performing maintenance and repair operations between flights, if needed.

The VEB module PDR is planned soon. Regarding Assembly, Integration and Test (AIT) of the VEB Module, a PDR review of the processes was performed successfully in March 2022.

The development plan include a structural model of the VEB which will be thoroughly tested. The plan includes environmental and acoustic tests planned early 2023. The hardware manufacturing is ongoing. The manufacturing of the VEB flight model will follow.

## 4.3 Flight Control System (FCS)

The CALLISTO vehicle will be equipped with three types of Flight Control System (FCS): reaction, aerodynamic and trust vector control, developed respectively under CNES, DLR and JAXA responsibility. Depending on the flight phase, the control of the vehicle will rely on one or simultaneously two actuator classes.

The FCS/A features four deployable fins controlled and actuated by equipment directly exploiting synergies with DLR ReFEx project. Fins will be deployed in flight, when dynamic pressure is low, before the re-entry phase.

FCS/V is two electro-mechanical actuators gimbaling the engine, an electronic controller and miscellaneous items. It will allow the orientation of the engine thrust.

The FCS/R is directly derived from the one currently in development by Nammo for Vega-E and Space-Ride programs. It includes eight hydrogen peroxide ($H_2O_2$) thrusters, installed on the vehicle equipment bay. Components development tests are ongoing, including vacuum testing. PDR for CALLISTO application was completed in 2020 and components PDR are planned in the frame of the Vega contract..

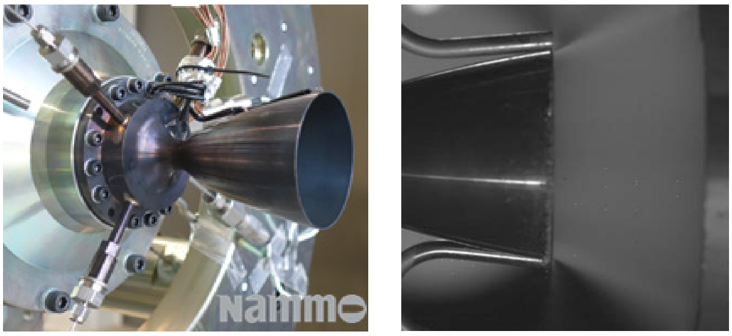

Figure 4: FCS/R thruster (courtesy Nammo)

## 4.4 Propulsion block

The Propulsion Block combines the two propellant tanks, the Bottom module below and ALS (Approach and Landing System) as well.

The engine selected for CALLISTO is derived from the LOx / LH2 40 kN re-ignitable engine developed by JAXA for the Reusable Sounding Rocket (RSR), with 15% thrust increase, and layout change to fit inside the aft-bay diameter. This engine, called RSR2, will have a throttling range from 16 to 46 kN allowing adequate control of the vehicle.

JAXA is responsible of the Bottom module including the aft-bay structure where the engine is accommodated, together with ALS and additional equipment. This module will face directly the demanding landing loads transmitted by the ALS, and shall embed avionics and fluidics items as similar constraints in term of size, mass and accessibility as the VEB modules does.

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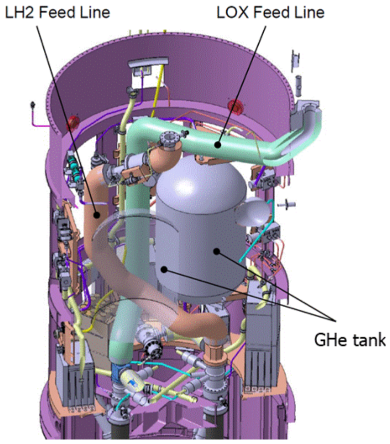


Figure 5 : Aft-bay lay-out

JAXA is also responsible for the fluidics system. Many components, like valves, pressure regulators, high pressure vessels are off-the-shelf or coming from other launch vehicles. The oxygen tank is developed by JAXA and the hydrogen tank by DLR. Both feature propellant management devices to keep propellants around outlet at the tank bottom in a low-gravity environment.

For engine and propellant tanks, the PDR were performed, and the first long lead items have been ordered.

### 4.5 Avionics

CALLISTO avionics combines off-the-shelf (COTS) products and devoted developed items coming from the three partners. To manage easily the system aspects of the avionic architecture, a decentralized architecture was selected, which allows each partner to perform relatively independently the development of its hardware. Nevertheless, CNES is particularly in charge of the avionics system architecture ensuring global consistency of avionics functions shared between equipment units, modules and Electrical Ground Support Equipment at CSG. For this reason, for instance a set of design rules compatible with the development approach of each partner was issued and is applied.

COTS products are the Digital Acquisition Units (DAU), Ethernet switches, OBC (for CNES flight software), S-band coupler, some antennas, batteries … Especially Equipment Qualification Status Reviews were conducted, and if a given requirement was not fulfilled, additional tests (especially environmental ones) were ordered.

Other equipment are specifically developed, like the S-band transceiver, S-band / GNSS antennas and FCS/R controller under CNES responsibility, the Hybrid Navigation System (HNS), OBC (for DLR/JAXA flight software), FCS/A controller and ALS controller under DLR responsibility and FSC/V, Engine control box and Propulsion system controller under JAXA responsibility. One primary development driver is vehicle reuse (multiple flights) and then special attention is given to health monitoring and need for optimized control in between flights. Product PDR are performed or are on-going, without any major issue.

As the three organizations are interested in the G&C algorithms, two versions of flight software are currently elaborated, one by CNES and another one by JAXA and DLR. Both performed their PDR. The one for CNES and ArianeGroup G&C algorithms took place in May 2022.
A real time validation of the whole avionics system is foreseen, including flight software's, thanks to the Avionics Validation Facility implemented at ArianeGroup in Les Mureaux, France. The validation is foreseen step by step, first with simulators then with hardware in the loop. The implementation has started in March 2022 with DAU, switch and OBC. This platform will be maintained during the combined tests and the flight campaign itself to analyse possible anomalies and to validate possible modifications.

### 4.6 Fight Neutralisation System

CALLISTO will fly from Guyana Space Center and consequently must comply with French safety regulation. From Flight safety perspective, a neutralisation system is mandatory for flight, with a logic tailored according to expected flight envelope. Considering reusability objectives, this flight termination system includes new features and technologies compared to legacy expendable launcher: a digital bus is used instead of pyrotechnic transmission [3], an

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on-board localisation system is implemented and a new flight safety kit is developed to manage on board safety equipment and its communication with the launch range safety.

### 4.7 Approach & Landing System (ALS)

For vertical landing the CALLISTO vehicle is equipped with a deployable landing gear, which is called the ALS. It is folded during ascent and unfolds shortly before touchdown by pneumatically actuation of the telescopic primary struts (4 legs). Deployment tests and touchdown tests were started in 2021 and are on-going at DLR. The goal is to validate the kinematics, the pneumatic and mechatronic design. It is allowing to generate the detailed definition followed by the manufacturing of  the flight models.

### 4.8 Nose Fairing module

The Nose Fairing module primary function is to protect the top of the vehicle from external aerodynamic flow, in particular during the ascent flight. It is made out of CFRP sandwich, following numerous material characterization tests to state the final product design and manufacturing processes. A thermal protection is added to protect the CFRP, and assure the reusability of the Nose fairing. To assure a proper neutralisation of the vehicle, pyrotechnics devices are implemented in the fairing. Tests are ongoing to qualify pyrotechnic device attachment under vibration loads, and to verify the ability of the pyro cord to cut properly the Nose fairing wall. The Preliminary Design Review was performed, and gives green light to phase C of development and start of flight hardware procurement.

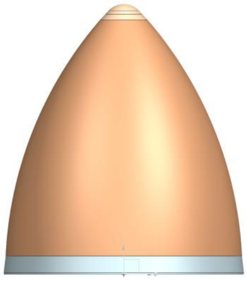

Figure 6: Side view of the Fairing

## 5. Ground segment development status

The development logic foresees the integration of the propulsion block (engine, aft-bay, LOx tank, LH2 tank,  ..) in Japan. Then hot faring static tests will be completed at Noshiro test Center to check performances of the propulsion block. Then the stage will be shipped to French Guyana and CSG where final assembly with VEB module, Legs, Nozzle will be made. A series of combined tests, which includes small hops, will be performed prior to the demonstration flights [4].

### 5.1 Noshiro stage static test

The preparation of test site is ongoing, it includes a refurbished preparation hall and devoted test stand. Dedicated Electrical Ground Support Equipment are currently developed under JAXA responsibility.

Figure 7: Preparation hall at Noshiro Test Center

DOI: 10.13009/EUCASS2022-7239



A structural model of the Vehicle Equipment Bay module will be installed on top of the Propulsion block, to assure a proper handling and erection (and back to horizontale position) of the vehicle assembly. This structure will be instrumented to check vibration loads at avionics equipment level, as secondary objective of the tests. Those tests are also the opportunity to validate operations to be conducted in CSG and to train staff as well.

### 5.2 Guyana space center ground segment status

The Ground Segment in CSG includes the Launch complex and Launch range (adaptations to) as well. As for Vehicle products, objective is to rely to the maximum extent possible on heritage and available material.

The Vehicle Preparation Hall (VPH), Lift-Off Pad and landing zone will be close to each other and located in the former Diamant zone used in the 70' to launch the first French launcher Diamant. This site is located inside the Guyana Space Center between the Ariane 5 launch pad and the sounding rocket pad.

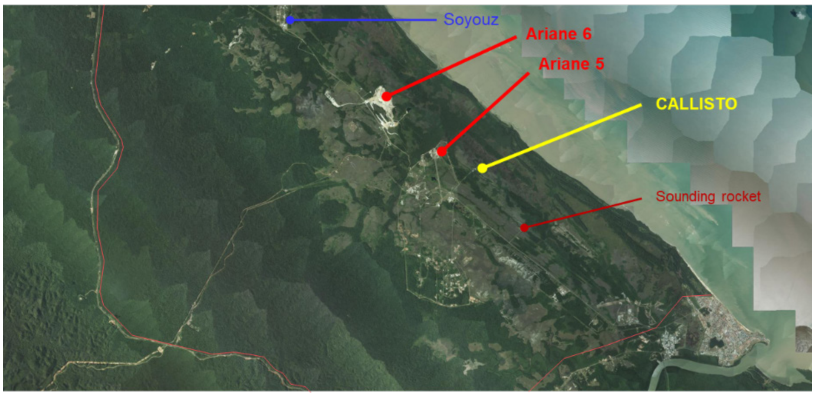


Figure 8 : CALLISTO Launch pad location at CSG

#### 5.2.1 Civil work

The reuse of the Diamant zone implies an extensive refurbishment. Civil work was engaged beginning of 2020 by dismantling the former Diamant mobile gantry and cleaning the zone (with special care to the natural environment and to the fauna present on the site). In 2021, the main networks for energy, telecommunications (optic fiber) and fluid (including nitrogen) were upgraded. Presently, roads, pad and Vehicle Preparation Hall (VPH) refurbishment are ongoing.

Figure 9 : Civil work around the CALLISTO VPH

#### 5.2.2 Mechanical Ground Support Equipment (MGSE)

MGSE includes all moving cryogenic arms, vehicle interfaces with lift-off pad (table, …), means for vehicle mechanical assembly, moving and erection. This also includes the robot dedicated to service fluid (He, N2), data link and electrical power supply that are disconnected before lift-off and reconnected after landing (see [5]). Proof of concept of this robot will take place in July 2022 in the manufacturer premises.

DOI: 10.13009/EUCASS2022-7239



### 5.2.3 Fluid Ground Support Equipment (FGSE)

As CALLISTO is a demonstrator, without production phase afterwards, use of existing means is top priority, for example for hydrogen, oxygen and helium storage. The PDR was performed and contract with suppliers for specific means manufacturing has been sealed.

### 5.2.3 Electrical ground support equipment (EGSE)

Many electrical systems will be put in place for CALLITO, to have a common data management system, a control & command bench to manage the different processes, network link between ground systems and vehicle (wired or wireless). To save time and cost, the control & command bench will use the technology developed for Ariane 6, and will be delivered by the same supplier. The PDR was performed and a first version of the bench control command is available. This ground bench will be connected to a functional model of the vehicle avionics, with hardware in the loop, if possible.
An adaptation of the telemetry and telecommand network in CSG is also foreseen to reinforce the coverage of the Diamant zone, and to consider the geometry of the vehicle during the landing phase (for example the landing gears).

### 5.2.3 Launch range

The launch range covers all means shared between the different launchers at CSG. This includes radars, weather forecast, telemetry station, communication network, coordination of means, security of the site, ground and flight safety…
Some minor technical adaptations are needed and will be made in 2023. Main challenge is compliance with ground and flight safety rules in place at the French Guyana Spaceport, where commercial launchers are operated. A review of all the impacts and mitigation actions was performed, especially for the return and landing phase, and concluded positively the possibility to perform such flight. The precise process follows now the nominal iterations of safety reviews, like for any other launcher. Finally, this is also an opportunity to prepare the Guyana Space center to reusable launchers activities.

## 6. Operation plan

One major objective of the project is to identify and record the duration and cost of the revalidation work needed between flights. The target is to have a mean duration of 15 days between flights. This is very challenging compare to the learning curve observed for VTVL launcher actually in operation or in development.
The top level CALLISTO requirement for the duration of flight campaign in French Guiana is 9 months in total, including flights and combined tests devoted to validation of interfaces in between the Launch Complex, the Launch Range and the Vehicle.
Maximizing the number of flights over this fixed period remains obviously the target taking into-account several constraints including Launch Range availability which manages several launch campaigns for other customers in parallel. This top requirement coupled with a cost reduction approach led also to avoid landing downrange on a barge.
To achieve this objective, analyses are performed during the definition of hardware, in order to minimize the need for refurbishment/inspection, up to operational process after landing to come back ready for the next flight. Main Concept of Operations is available and now subject to refinement (see [4]).

## 7. Conclusion

A significant progress has been reached during the past year, with the achievement of Preliminary Design Review at system level and for most products, modules and ground means. Next step will be the Critical Design Review, which will also include a preliminary status of the flightworthiness. The manufacturing of the qualification models, and for certain product of the flight one's will also take place in 2022. This will secure the planning up to tests at the Noshiro Test Center, and then the combined tests phase at the French Guyana Space Center.
The vehicle definition passed successfully the different milestones, but as usual for this kind of demonstrator, the probability of success in flight will be for sure less than 100 % ! But this is a mandatory passage toward reusable launcher development in Europe and in Japan.

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