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OVERVIEW OF CALLISTO VEHICLE DEVELOPMENT STATUS

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Abstract

The CALLISTO vehicle is a flight demonstrator for future reusable launcher stages. The program involves three countries and their space organizations: CNES for France, DLR for Germany and JAXA for Japan. The first tests will be conducted in 2024 from the CSG, Europe's Spaceport for commercial launches. The challenge is to develop, all along the project, the skills of the partners. This knowhow includes Products and Vehicle design, Ground Segment set up, and post-flight operations for Vehicle recovery then reuse.

This paper provides an update on CALLISTO Vehicle development status.

At first, program objectives are briefly listed focusing on Vehicle mission design and Vehicle life cycle, and their specificities wrt European and Japanese legacy expendable launch vehicles.

Details on flight test plan architecture and features are provided (e.g; in-flight experimentation), showing how it will both incrementally secure acquisition of key VTVL technology while preparing for high energy missions - which encompass the full scope of in-flight demonstration.

Finally, an overview of Vehicle development status is provided through a review of main architectural features including, and not limited to, load carrying structures, avionic, Rocket Propulsion System, Flight Control System, highlighting major milestones achieved over last year and progress toward first flights.

1. Introduction

CALLISTO is a demonstration program aiming at gaining experience in key techniques needed for reusable VTVL vehicles, through flying a rocket propulsion powered vehicle several times, within environments representative of those that will be encountered by a reusable first stage of operational vehicle.

Key techniques especially involves:

a. Recover: bring the Vehicle safely back to the landing zone, after having flown at several tens kilometers altitude
b. Reuse: perform several flights, and especially experience maintenance, repair and overhaul operations in between flights necessary to get the vehicle ready for next flight

CALLISTO Vehicle will be operated in CSG Spaceport - French Guyana.

CALLISTO Vehicle is a ca. 14m tall, 1.1m diameter single stage Vehicle (as opposed to multi-stage operational launch vehicles) featuring a LOX/LH2 rocket propulsion system delivering ca 40kN (sea level). Its thrust can be throttled in a range [40% - 115%] vs. its 100% reference thrust setting.

General overview of the Vehicle is provided on Figure 1

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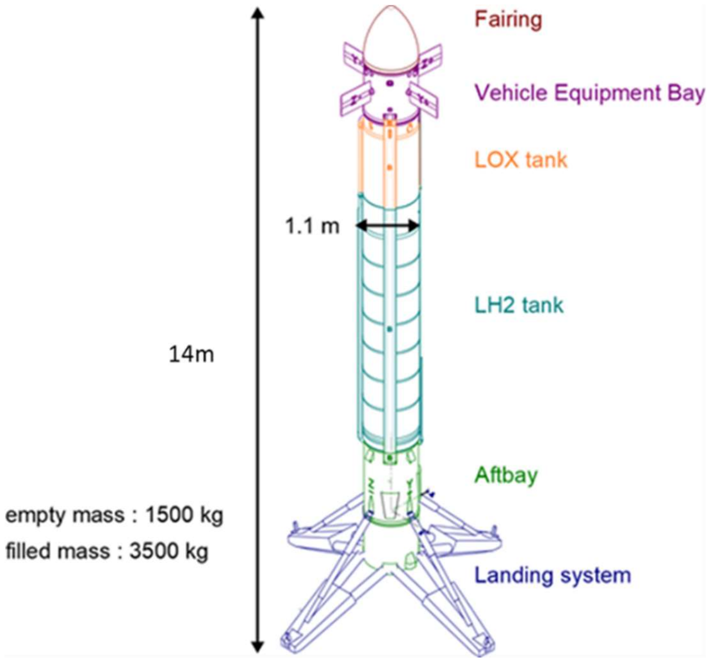

Figure 1: View of CALLISTO Vehicle

Compared to standard expendable launch Vehicles, CALLISTO includes additional features needed for achieving recovery & reuse functions:

- Unfoldable & controllable aerosurfaces, used to perform controlled descent in atmosphere
- Unfoldable landing system (ALS), used to perform touchdown phase

Capability to unfold those systems results from aerodynamic & flight control restrictions during ascent and descent phases.

1. Vehicle Lifecycle & Environment

CALLISTO Vehicle is designed to be operated up to 10 flights. After development period completion, the Vehicle life cycle is split into two different primary phases interacting with each other in CSG over a series of flights:

- Ground phases, during which Vehicle will be inspected and maintained ahead of next flight including as few testing as possible,
- Flights themselves: different flights have been designed so as to allow for an incremental exploration of flight envelope , up to high energy flight for which a typical flight sequence is provided on Figure 2.

The objective of the incremental approach is to manage the risk at each step along with gaining experience of in-flight operations, especially wrt environments and loads. From these perspectives, one shall highlight some key environment the Vehicle will be exposed to, which may significantly differ from standard expendable launch vehicles (ELV) :

- Touchdown, with energy dissipation over a ultra short period of time
- Unpowered descent, during which the vehicle will experience:
    - High dynamic pressure
    - Transonic regime and unsteady aerodynamics flow
    - increasing external pressure, needing repressurization of internal cavities for balancing delta-pressure and avoid over-sizing carrying structures
- Landing Boost during which the Vehicle will be travelling through its own engine plume travelling backwards, with high temperature surrounding gas.

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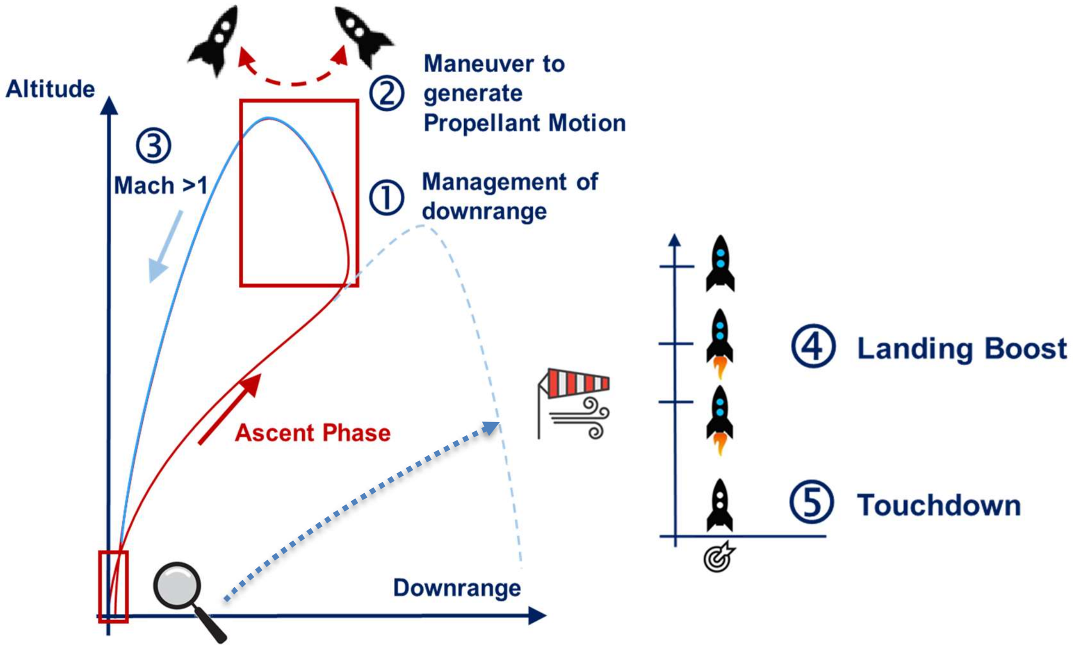

Figure 2: Schematic flight sequence

Then more specifically, flight envelope is better defined considering:

- Vehicle Configuration :
    - Aeroshape (aerosurfaces deployed Y/N, landing legs deployed Y/N)
    - Engine configuration: ON/OFF
- Flight regimes:
    - Mach number
    - Altitude

For first (low energy) flights, CALLISTO will be lifting off from its own legs; while those endorse the primary function of absorbing landing shock, they also ensure the supporting function for low energy flight for which ascent drag (and control) is not a major constraint. The first flights will hence concentrate on the following key objectives:

- Touchdown phase, including stability as well as induced environment
- Vehicle flying qualities: indeed, while aerodynamic conditions (dynamic pressure especially) close to ground are limited, this phase is also the one during which the terminal touchdown conditions will be achieved, with critical accuracy requirement. Hence, it is considered that this phase deserves specific attention at first.

Risk is mitigated through a dedicated flight profile design involving less stringent trajectories compared to high energy flight. During these flights, all Vehicle system control parameters are checked so as to keep margins wrt the minimum/maximum values in order to minimize the risk of saturation/ requirement exceedance. This is especially true for:

- Engine throttling capability
- Propellant budget
- Control capability (e.g. thrust vector control)

Mid energy flight will extend to flight envelop and provide insight into actual vehicle performance drivers, such as high speed aerodynamics, in-flight propellant behaviour, flying qualities, etc.

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Whenever Vehicle configuration changes are to be performed (Aerosurface unfolding, ALS unfolding), those are planned in the flight sequence to occur under limited environmental conditions. Examples are provided on Figure 3, which show superimposed profile of:

- High energy flight (yellow, full flight envelope)
- Low energy flight with Aerosurface unfolding at zero velocity (orange)
- Mid energy flight with ALS unfolding at low velocity (grey)

And then some vehicle configuration change events along those trajectories.

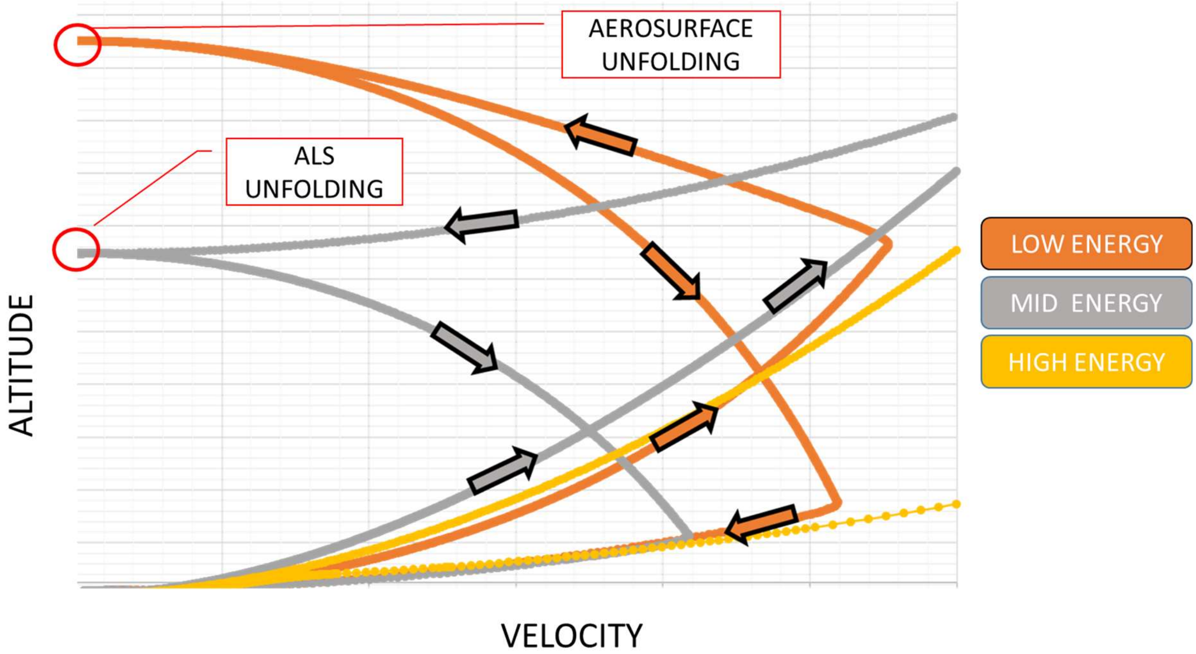

Figure 3: Schematic flight sequences and flight profiles

Considering this flight test plan, and compared to a standard ELV, CALLISTO needs to cope with extended lifetime that results in:

- Several tens engine ignitions,
- Load-carrying structure fatigue,
- Design-to-repair for some low life parts.

Developing capability/know-how to specify requirements associated to this unique lifecycle already involved significant effort in engineering disciplines such as:

- Aeroscience related, and especially:
  - Aerodynamics for mechanical loads computations further down,
  - Aerothermal computations used for thermal design
- Dynamic/Vibration conditions for assessing mechanical response of the Vehicle,
- Thermal engineering for assessing the thermal response of the Vehicle to its external environment. Coupled to this, there is the depressurization / repressurization history at ascent and then descent which differs from legacy ELV.

Extensive characterization of the Vehicle environment inside its flight envelope has being performed, using both numerical analysis and testing. Illustration of such an hybrid design & test approach is provided on Figure 4 (left), which depicts acoustic testing performed by CNES (MARTEL test bench) for configurations corresponding to touchdown (low engine nozzle ground clearance, engine ON conditions); these test campaigns have allowed significant refinement of computation-based environment assessment. Other characterization included Wind tunnel testing, at various flight regimes (Mach number, Angle of Attack, configurations) as well as on-site acoustic measurement during

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engine firing test. Among noticeable findings was the fact that for some flight phases, relative small scaled CALLISTO vehicle would be experiencing environment outside of the one of operational vehicles, as shown on Figure 4 (bottom left)

Management of those environment has also been found to sometime request specific design features compared to standard ELV. For instance, dynamic environment associated to various portions of the flight might necessitate the use of dedicated damping device to secure Vehicle equipment dynamic environment (GO & SEE Figure 4, right)

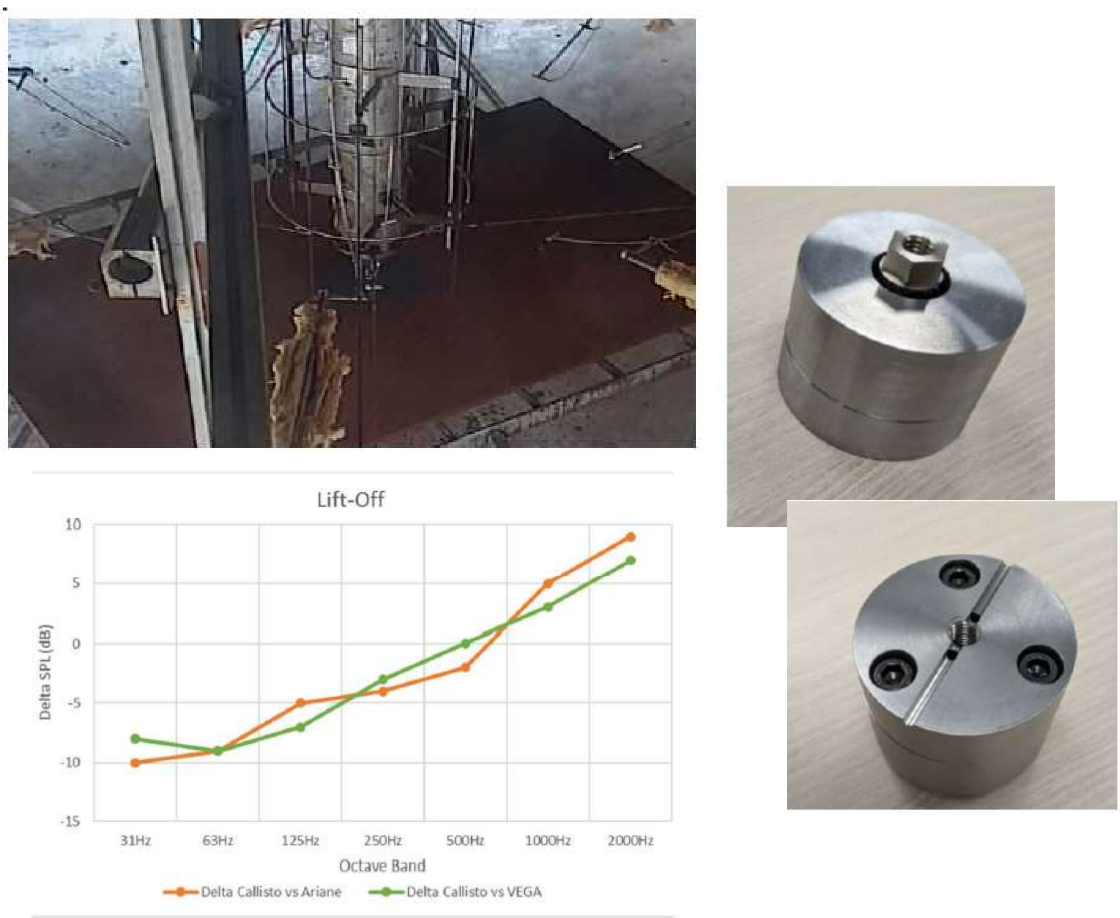

Figure 4: Acoustic testing setup- (top left) / Acoustic environment comparison with ELVs (bottom left)
Vibration management device (right) – from [4]

2. Vehicle Status

The following sections highlight some achievements over the past months regarding Vehicle H/W development.

a. Mechanical Design

Load carrying structure are into their critical design phase , with some being already produced for qualification testing. This is the case of the Vehicle Nose fairing structure which is composed of a CFRP sandwich with an additional (cork) TPS to manage heat fluxes during the flight. Manufacturing of this qualification hardware has allowed to derisk manufacturing processes and component integration, as well as operations; its now close to start qualification campaign. Illustration of Engineering Qualification Model of the nose fairing is given in Figure 5 (left).

Of significance importance is also the progress of the landing system (ALS), which is designed to enable a safe transition from vehicle flight configuration to vehicle ground configuration , thus involving two complex and critical functions:

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- Energy absorption at touchdown
- Deployment during flight

Extensive design tasks have been undertaken to reach close to CDR; meanwhile, HW has been manufactured to secure the main (critical) design features and develop capability to validate (mathematical) models used for performance assessment. Figure 5 (right) show one leg on its test stand. Tests for both primary functions have been performed and enabled to assess design compatibility wrt to requirements, while gaining experience on H/W operations (□[2]). On top of H/W aspects, major inputs toward Vehicle System (interface loads, dynamic environment) were measured during these test campaigns, allowing further consolidation of the Vehicle overall design.

Multiple touchdown and deployment simulations on different levels (system & product) have been developed and based on the test campaign results validated. These simulators provide the capability to predict the ALS deployment and touchdown dynamics for different flight scenarios, which are further used for the consolidation of the vehicle overall design. The ALS deployment dynamics have been analysed in-depth in [□[9]]"

Figure 5 Load carrying Structure – development hardware
Fairing (left, □[1]) / ALS (right, □[2])

Regarding propellant tanks, both LH2 & LOX tanks are approaching their CDR, with LLI being already delivered for LH2 Tank (GO & SEE Figure 6, left). In this case, LH2 tank features a specific design made of cylinders of identical height welded in between them through a circumferential welding, explaining the shape of LLI (raw aluminium cylinders) that will later be machined to get to the needed thicknesses.

Figure 6 : Propellant tanks H/W (left) / Overall Design (right)

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For LOX Tank, the tank design is advancing fast with specific focus being made on thermal protection and its maintenance in between flights. Dedicated elementary tests have been performed in order to down select candidate coatings capable of managing the possibly harsh condition at TPS surface, especially due to retroburn at landing which can lead to high temperature peak.

The aft part of the Vehicle is composed of an integrated structure (Module) called “BOTTOM Module”. This complex structure houses especially:

- The engine itself
- The pressurization system tanks (Gaseous Helium)
- (Some) Avionics
- ALS pneumatic deployment system
- The 4 ALS leg subassemblies each of which being attached to 6 interface points:
    - 3 attachments used for load transmission at touchdown
    - 3 additional attachment for managing the locking and the release of the legs during flight

BOTTOM Module is getting close to its CDR with on-going consolidation of detailed lay-out and mechanical sizing, which is particularly demanding during the touchdown phase. A general overview of the BOTTOM Module (with one leg attached) is depicted on Figure 7 (left). Among noticeable feature of this integrated structure is the built-in capability for maintenance, which request unique access capability Figure 7 (right).

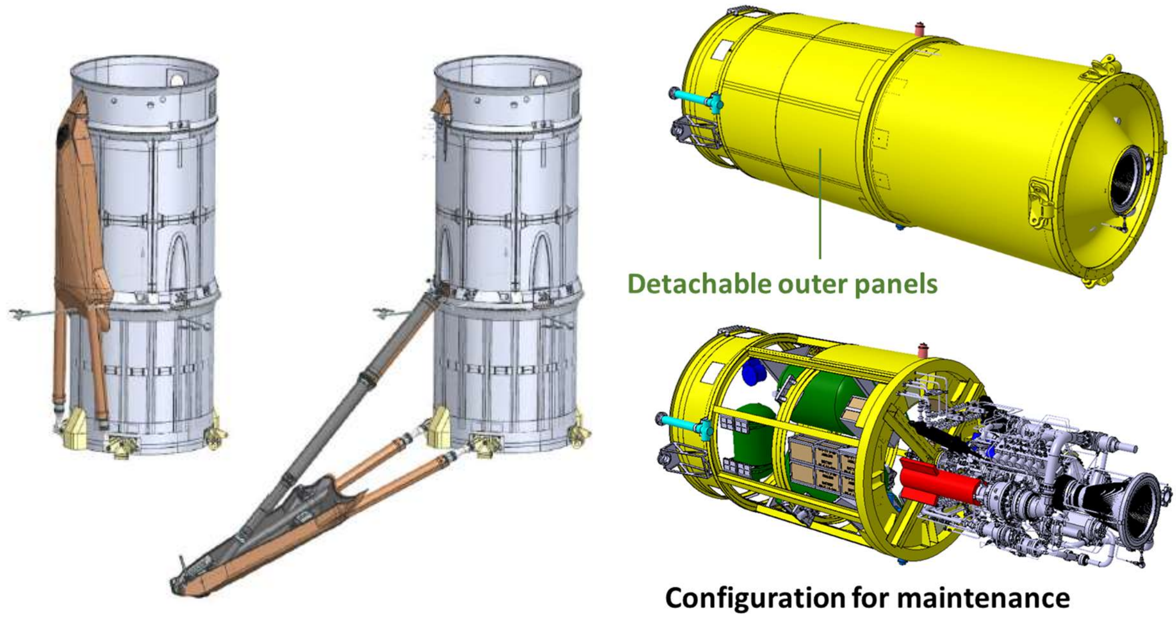

Figure 7 BOTTOM Module external Lay-out (extract from [2] and [5])

b. Rocket Propulsion System

For the three Partners, Rocket propulsion development activities have been centered on the two main life phases which are:

- Flight preparation on-ground
- Flight itself

Ground phase related studies mostly aim at defining operations needed to get the Vehicle ready for flight with the necessary propellant on-board., the work was thus focused on developing a fluid system simulator encompassing both ground segment fluidic installation (Fluid Ground Support Equipment , FGSE) and Vehicle itself, through the modelling of each fluidic component, as well as fluid thermodynamical modelling itself. Details can be found in [3]. Different filling strategies have been studied, leading to preliminary timeline as described in Table 1 and illustrated on

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Figure 8. Optimization of this timeline will be continued up until the combined test that will set the final tuning based on actual coupled FGSE/Vehicle behaviour.

Species	LH2	LOX
Loaded Mass [kg]	330	1800
Filling duration [s]	1800	5500

Table 1: Preliminary filling operation characteristics (from [3])

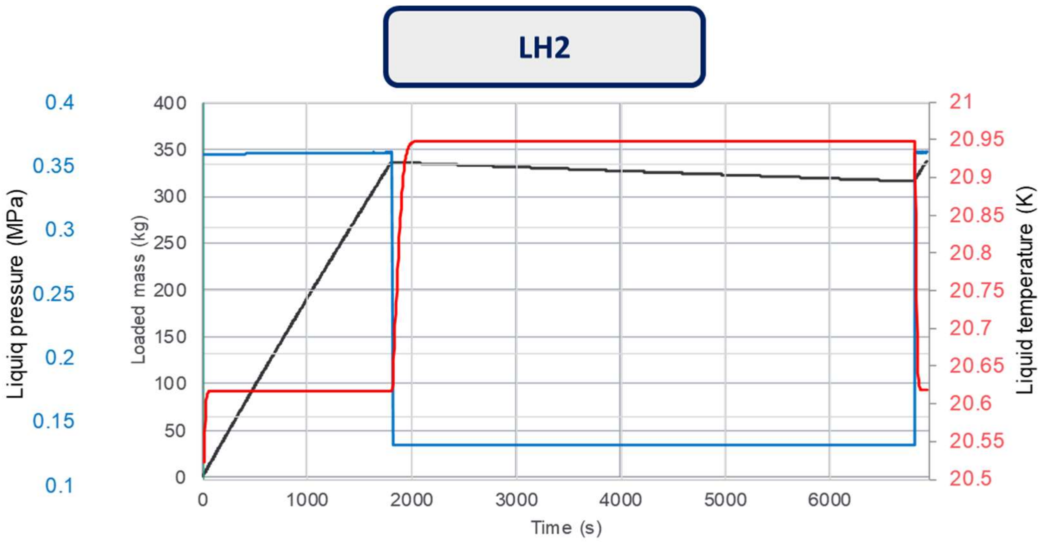

Figure 8 : LH2 propellant filling operations (from [3])

During the flight itself, two main criteria are looked at:

- Usable propellants, meaning how much propellant can actually be used to deliver thrust. This is mainly limited by geometrical characteristics of the propulsion system as well as by thermal response of the propellant to its environment
- Needed pressurant (Helium), which is mostly driven by propellant tank capacity and in-flight sloshing that can generated complex thermodynamical behaviour.

In order to provide assessment of those quantities, simulations of liquid behaviour during flight have been undertaken, considering complex fluid behaviour (e.g. sloshing). Those allowed to consolidate the fluid budget and hence the in-flight performance. Figure 9 ([8]) illustrates the impact of sloshing assumption on usable the propellant thermal gradient, and then usable propellant:

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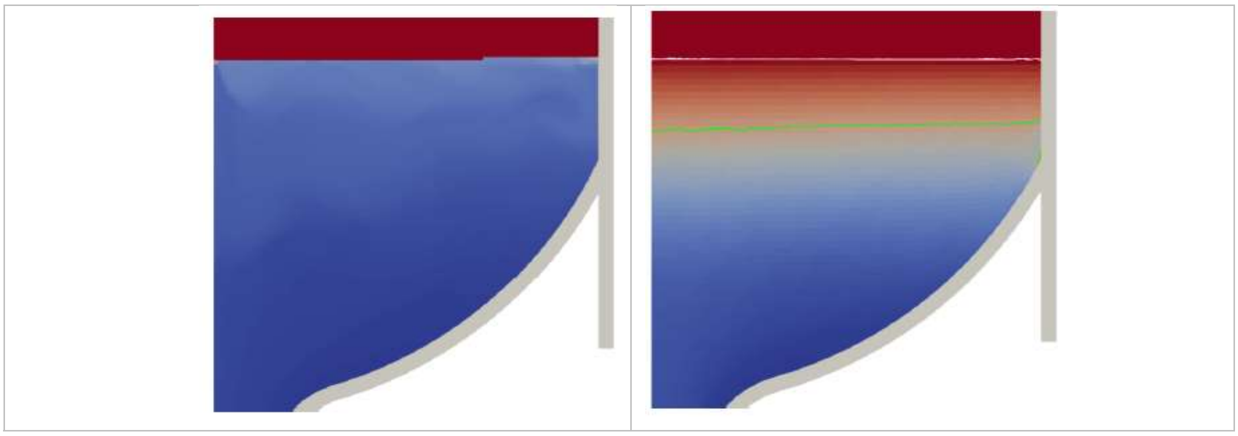

Figure 9 : Comparison between with/without sloshing LH2 propellant temperature

c. Flight control systems

Flight control systems involve three actuator classes:

- Reaction control system, through ON/OFF thrusters;
- Aerodynamic control, through all-moving aero-surfaces;
- (engine) thrust vector control through engine gimballing.

Those three actuators are used in a blended fashion depending on flight control strategy and each flight phase specificity.

Reaction control system development is well underway (detailed in □[6]), with some H/W procurement already engaged. This function relies on 8 thrusters which have to be accommodated inside the Vehicle Equipment Bay Module. This is done through the usage of a dedicated supporting structure that is accommodating:

- The propellant tank,
- The electronics controller
- the propulsion H/W combining thrusters, valves and piping,

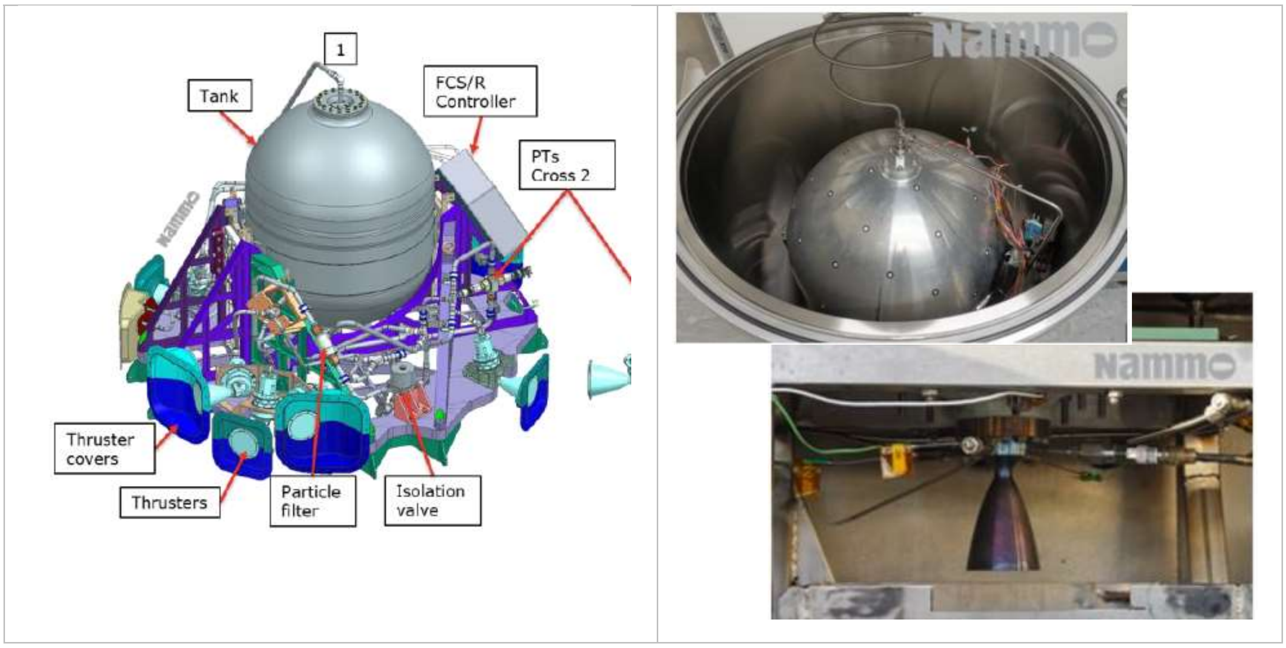

Figure 10 : CAD Model of integrated FCS/R (left) /
Development (Proof of Concept) H/W (Tank top right, thruster Bottom right) – from □[6]

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Aerodynamic control is performed through the deflection of 4 aerosurfaces independently, relying on electromechnical technology - rotational actuator. Those aerosurfaces are located on the VEB, which is rear side of the Vehicle when flying in aft-forward configuration, providing stabilization and control capability. Aerosurfaces also provide capability for in-flight unfolding and post-flight refolding so as to better manage ascent drag and vehicle recovery operations after flight. Significant effort was developed to design the various components of the aerodynamic control system (FCS/A), including controller, actuators and load carrying aerosurface. Configuration of aerosurface on the VEB is shown on Figure 11 (left), while hardware under manufacturing is shown in Figure 11 (right)

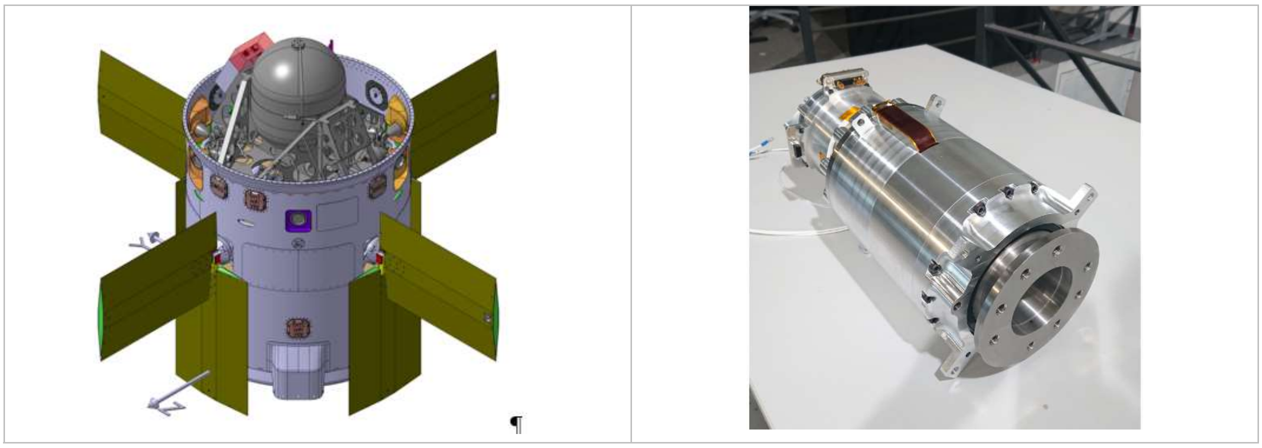

Figure 11 : FCS/A configuration on VEB (left) and development H/W (right)

The (engine) thrust vector control (TVC) is standard design, and performed by orientating the engine along two orthogonal axis, with 2 dedicated and identical electromechanical actuators. The control of each actuator position is managed through a dedicated controller, while electrical power is delivered by a dedicated set of batteries. Development H/W is in progress and/or already procured, as depicted on Figure 12. Actuators will rely on components used previously on JAXA RV-X demonstrator.

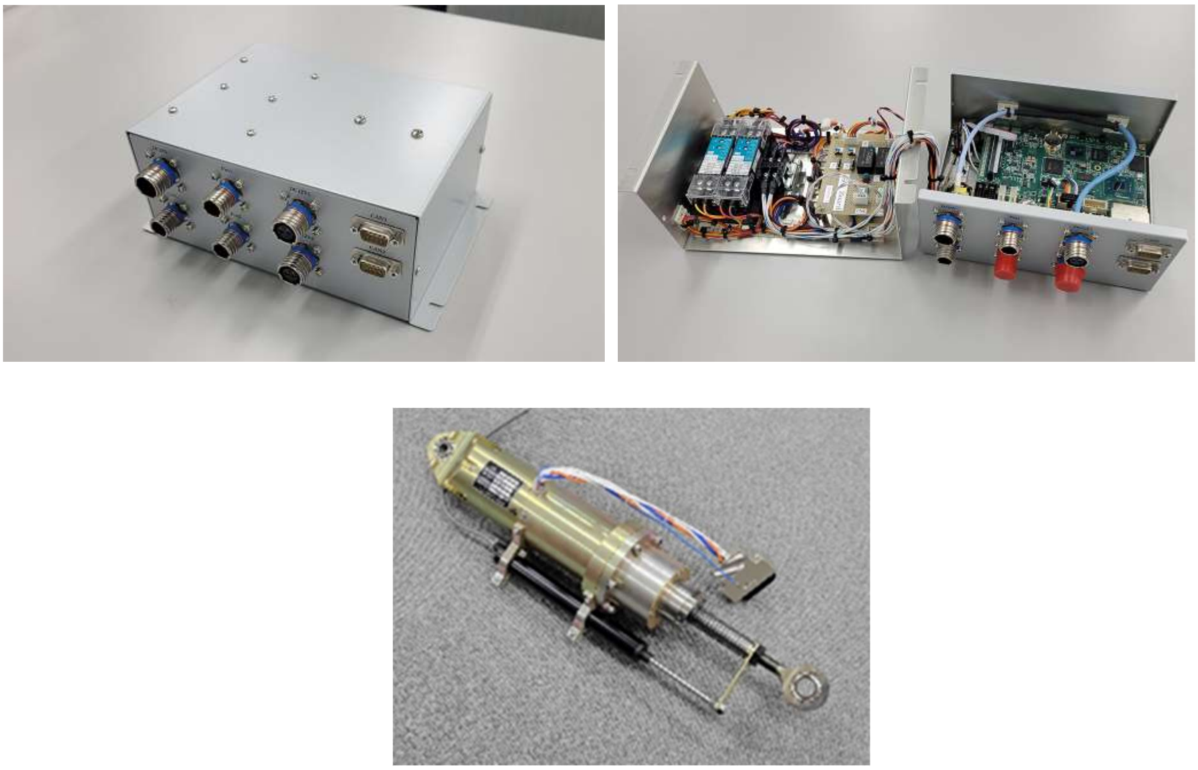

Figure 12 : Thrust Vector Control (TVC) controller (top) and actuator (down)

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d. Avionics

Avionic system at large provides many key functions of the Vehicle, including (but not limited to):

- Electrical Power generation & Distribution
- Communication
- Telemetry
- Data collection

For the sake of planning efficiency, as much avionics items as possible are COTS items while others are designed specifically for CALLISTO purpose. In any case, environmental conditions related to CALLISTO lifecycle often require some dedicated delta-qualification to verify and validate the capability to withstand the entire CALLISTO life cycle. This involves especially vibration environment which features significant differences compared to standard ELV as shown on Figure 13.

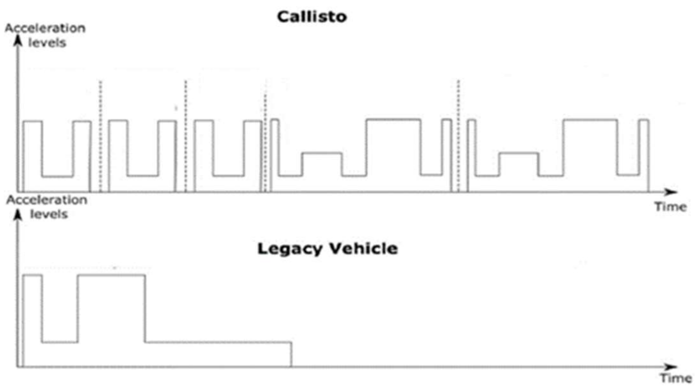

Figure 13 : CALLISTO vs Legacy Vehicle (□[7])

For equipment developed specifically for CALLISTO, significant progress on the design side is witnessed, with development & qualification hardware already under preparation, for instance for power subsystem components (Figure 14):

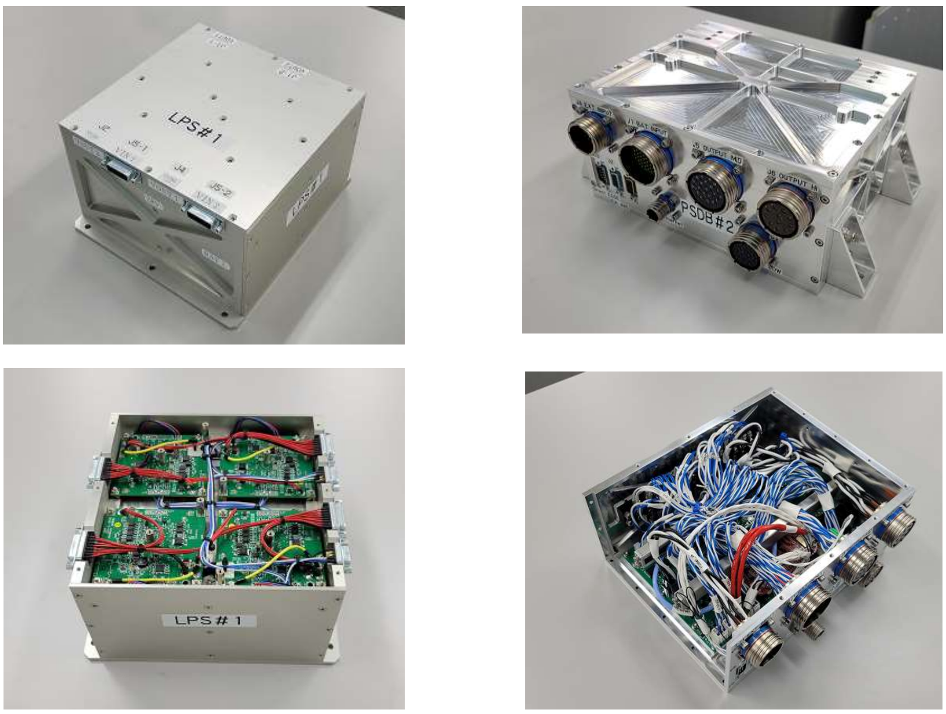

Figure 14 : Power Generation (Left) / Power Distribution (Right)

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3. Conclusion

CALLISTO Vehicle detailed design phase is showing significant progress with regard to both:

- System design, including pre-flight & in-flight operations as well as associated environment
- Hardware development and testing, especially against environments

Next major milestones will be the CDR of Vehicle components (items, integrated structures) and then CDR at system level.

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