CALLISTO reusable vehicle system design

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JAXA, CNES, and DLR have jointly conducted concept design and project definition activities for a vertical-take off, vertical landing, experimental vehicle called CALLISTO (Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations), which objectives are to master key technologies to recover and reuse future operational reusable first stages. The vehicle has a diameter of 1.1m, it is roughly 13m high, with a mass at lift-off of roughly 3.5tons. Main propulsion is based on LOx/LH2 RSR2 engine (enhanced version of RSR engine of JAXA RV-X experiment [3]) and roll control system uses H2O2. This paper presents a further overview of the CALLISTO vehicle system & mission design.

First, mission design is addressed, with emphasis on flight profiles and flight sequence definition. Specific technical challenges associated to each flight phase are detailed, in particular with respect to their impact on vehicle design requirements. Then vehicle design is presented, going through the main system level functional architectures. Main features are connected to mission design such as to highlight the vehicle design drivers. Finally insight into test plan is provided, which will contribute to demonstration flights de-risking logic.

Key Words: CALLISTO, reusability, Demonstrator, System Design,

Nomenclature

TVC : Thrust Vector Control
RCS : Reaction Control System
FCSA : Aerodynamic control surfaces
Q : Dynamic pressure
CSG : Guiana Space Center
MECO : Main Engine Cut-off
MEIG : Main Engine Ignition
VEB : Vehicle Equipment Bay
AoA : Angle of Attack

1. Introduction

JAXA, CNES, and DLR are jointly conducting concept design and project definition activities for a vertical take-off, vertical landing, experimental vehicle called CALLISTO (Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations), which objectives are to master key technologies to recover and reuse future operational reusable first stages. The technology performances will be linked with operational capability in order to validate the concepts, verify the cost model hypotheses and identify further enhancement.

Callisto project [1] has been proposed firstly in 2015 taking into account the need to update launcher and launch base concepts for the recovery and reusability at least of the launcher first stage. Feasibility studies have started in 2016, continued in 2017 [2] with the start of the international cooperation between JAXA, DLR and CNES in June 2017.

The 3 partners have shared the work to be performed which can be globally summarized by the following: System Vehicle, safety, and ground Segment for CNES, Aeroscience and active control mechanisms for DLR, Rocket Propulsion System and project lead for JAXA. The feasibility phase has been concluded by the System Requirement Review in 2018. The general concept choice for operating the demonstration safely in French Guiana Space Center (CSG) has been confirmed.

Preliminary Design is ongoing with the update of the vehicle and ground systems specification along with the related product and means requirement for development, qualification and operation.

This paper is proposing an overview on vehicle system & mission design.

2. Mission Design

CALLISTO vehicle is a roughly 3.5t GLOM class of vehicle, 2.1t of which being LOX/LH2 propellants, the rest being composed of dry mass as well as other fluids, in particular related to rocket propulsion command/control (using Helium) as well as attitude control systems (using H2O2). It is powered by an enhanced version of JAXA RSR engine, derived from the one used by JAXA on RV-X experimental vehicle ([3]). delivering a vacuum thrust of around 50kN. Main engine is gimballed using a Thrust vector control system, and CALLISTO vehicle control is complemented by RCS control and aerosurfaces during reentry.

Objectives assigned to the flight profiles of CALLISTO experimental vehicle are two-fold: demonstration of accuracy down to metric precision for flight profiles involving supersonic reentry as well as boost-back manoeuver, and demonstration of in-flight propellant management. CALLISTO vehicle will be operated from Centre Spatial Guyanais (CSG) located in Kourou, French Guiana, France.

General mission profile is shown on Fig 1, with main flight phases highlighted:

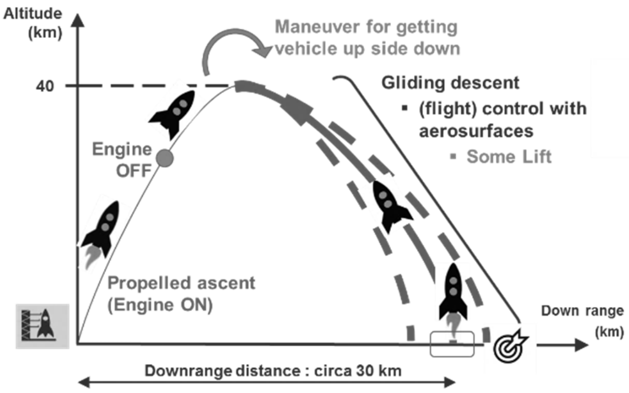
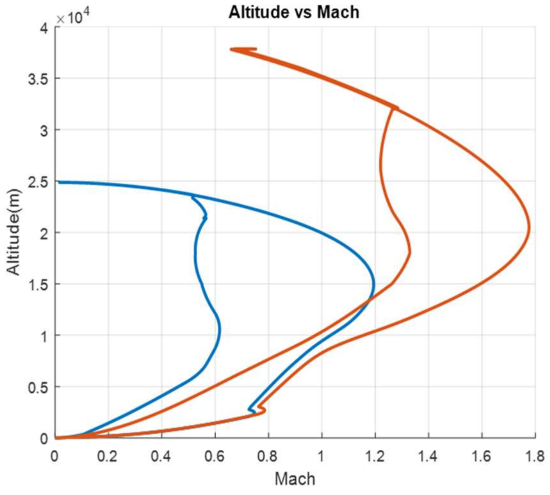


Fig 1. Schematics of Mission architecture

Mission profiles have been conceived in a way to demonstrate the objectives described above in one or several flights. Fig 4 illustrates two class of possible demonstration flight profiles, in terms of altitude versus Mach and longitudinal acceleration vs time. Table 1 & Table 2 provide more details on the envisaged profiles, with main orders of magnitudes.



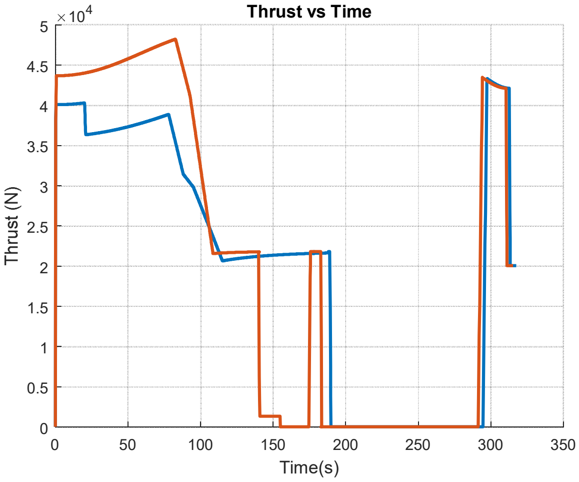


Fig 2. Altitude vs Mach (Top) & Effective Thrust vs Time (Bottom) for flight profile #1(red) and #2(blue)

CALLISTO flight profiles are characterized by a large number of state changes, leading to strong interactions at system design level.

From lift-off to MECO#1, the vehicle performs a relatively standard ascent, using gravity turn-like profile, however with a high ascent flight path angle so as to gain altitude and reach low atmosphere density regions. End of Ascent is triggered when vehicle has reached such a state that it is able to either get back to the landing site in case of flight profile #2 (see table 2), or reach nominally the landing platform located some 30km downrange from the landing site for flight profile #1 (see table 1). Definition of the cut-off criteria plays a major role in the success of the rest of the mission.

In case of flight profile#1, right after ascent and MECO#1, vehicle enters a coasting phase during which the main objective is to exchange (decreasing) velocity with (increasing) altitude, so as to reach low enough local atmosphere density and to be able to perform the so called “tilt maneuver” during which the vehicle will perform a 180° angle of attack (AoA) inversion so as to prepare for subsequent reentry with a rear-forward position. Next sequence is a so-called retroboost, during which landing platform is targeted. The retroboost phase is some ten seconds long, leaving little time for re-ignition dispersions compensation. As a consequence, this sequence requires specific kinematic stateslocation accuracy management, which is one of CALLISTO demonstration objectives.

In case of flight profile#2, only two boosts are performed. Right after end of ascent, main propulsion system is not shut-down, but vehicle enters a maneuver at relatively high dynamic pressure and angle of attack so as to significantly modify velocity slope and to enter into a return trajectory with a target landing site close to Lift-Off site. This “in atmosphere” maneuver brings additional flight control issues that need to be managed via the flight profile definition so as not to exceed TVC capability to counter aerodynamic torque.

For both flight options, after a vehicle configuration change through aerodynamic surfaces unfolding, vehicle performs reentry with the two objectives of dissipating kinetic energy and reaching end conditions enabling a 15 -25s landing boost during which terminal guidance will be performed to reach metric accuracy. Landing legs are deployed during the landing boost itself.

Event	Timeline	Description
H0	0	Main Engine ignition / Lift-Off
Ascent		Q max ~ 20kPa
MECO#1	150s	
Coast#1		Residual atmosphere / low AoA
MEIG#2	175s	
Retroboost		Retroboost, AoA maneuver (0° to 180°) landing site targeting Vehicle configuration change : aerodynamic surfaces unfolding
MECO#2	185s	
Coast #2		AoA ~180°
Reentry		Mach ~1.6 / 1.8, Qmax ~35kPa
MEIG#3	290	
Landing Boost		Vehicle Configuration Change : Landing system unfolding
MECO & Touchdown	315	~10- 25s landing boost, hard landing

Table 1. Flight profile #1

The high versatility of CALLISTO vehicle missions is a significant systems engineering challenge. Management of such a high variability is performed through the definition of flight envelopes for various disciplines (mechanical loads, rocket propulsion, flight control, etc.), which required investigation of most significant physical parameters driving each function or set of loads. These flight envelopes are somehow correlated to preliminary trajectory studies, but serve then as a baseline for designing the vehicle system, and then upcoming trajectories options will have to fit within the design envelope of the vehicle. Typical flight envelopes for rocket propulsion system and trajectory data are illustrated on Fig 4. Definition of these flight envelopes enabled entering vehicle design with more insight into the driving parameters for Vehicle Design.

Event	Timeline	Description
H0	0	Main Engine ignition / Lift-Off
Ascent		Q max ~ 10kPa
Powered tilt over maneuver	110	Q ~ several kPa, High AoA, landing site targeting
MECO#1	180s	Residual atmosphere / low AoA
Coast #1		AoA manoeuvre (0° to 180°) Vehicle Configuration change : fins unfolding
Reentry		Mach ~1.2
MEIG#2	290	
Landing Boost		Vehicle Configuration Change : Landing system unfolding
MECO#2 & Touchdown	315	~15- 25s landing boost, hard landing

Table 2. Flight Profile #2

On Fig 4, one can see that the variations of dynamic pressure (Q) vs Mach is quite significant whatever the flight class is. On top, vehicle configurations changes along flight modify aerodynamic properties, thus load distribution. Finally, phases with engine on and engine off are alternating, also generating constraints of different nature that then need to be closely monitored in the frame of system design.

Contrarily, flight profile is constrained in a severe manner by two main design drivers which are flight control authority (capability of flight control to counter resistive torques) and flight safety. They have been monitored and taken into account in mission profile designs since initial design iterations such as to alleviate possible shortcomings.

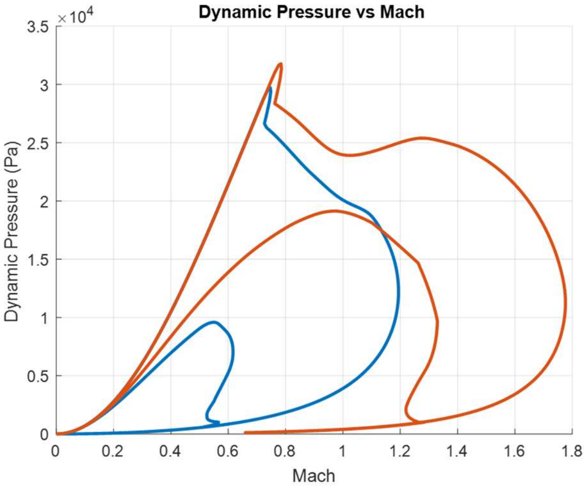


Fig 3. Q vs Mach for profile #1(red) and profile #2 (blue)

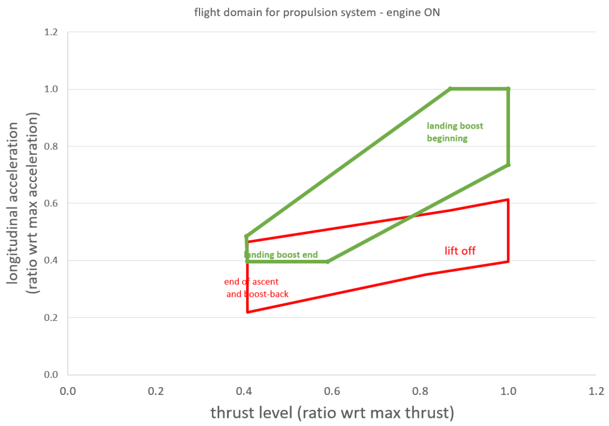


Fig 4. Longitudinal acceleration vs Thrust flight domain for propulsion system covering both flight profiles

3. Mechanical Design

CALLISTO Vehicle is a single stage vehicle around 13 metershigh and with a 1100mm diameter. It includes, from vehicle bottom to top, an aft-bay accommodating a main engine (RSR2 from JAXA), Thrust vector control (TVC) as well as rocket propulsion system control/commands and pressurisation items. Aft-bay section is also the interfacing structure to the Approach and Landing System (ALS) which has been designed so as to fit entirely this structure. ALS system is a “two state” System which can be unfolded during flight following command by vehicle flight management system. On top of the aft bay section, two propellant tanks accommodate the main engine propellants. Considerations on vehicle flight control during al phases have to the compromise of the LOX tank being located above the LH2 tank Around 2.1 tons of propellants can be loaded in those tanks for maximum performance missions. On top of propellant tanks stands the Vehicle Equipment Bay (VEB) that accommodates numerous items, among which avionics for control/command of the Vehicle as well as a reaction control system (RCS) using H2O2 propellant. H2O2 propellant tank is attached to the VEB structures, but also enters into the volume of Vehicle core body upper structure, the Nose Fairing. Also attached on the VEB are four aerodynamic surfaces (Flight control systems/ Aerodynamics, or FCS/A) that are unfolded during flight upon request by vehicle flight management.

General architecture of CALLISTO vehicle is outlined on 5:

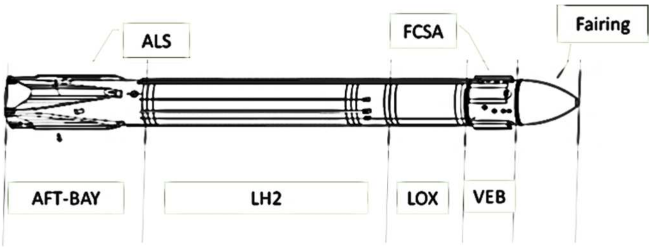


Fig 5. General architecture of CALLISTO Vehicle

Among the peculiarities of CALLISTO Vehicle design, one shall mention the external geometry which features a high number of protrusions: rocket propulsion feed lines, electrical ducts, ALS and FCS/A especially. While not necessarily relevant for standard legacy launch systems during ascent, aerodynamics becomes a key performance index in the case of CALLISTO vehicle, in particular for the reentry and landing phases. Thus, investigations of effect of protrusion local design are on-going already at this stage of design so as to secure vehicle aerodynamics properties. Orders of magnitude of the influence of such protrusions are illustrated on the figure here below:

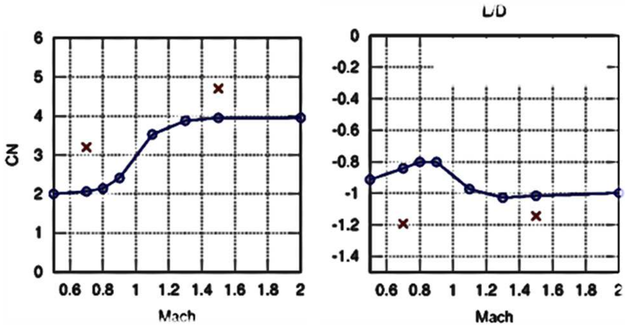


Fig 6. Protrusion effect on Lift & L/D coefficients

Fig 6 shows the effect of external protrusion on Vehicle aerodynamics: plain lines are the one obtained in the case of a body without protrusions while crosses indicates more detailed computation taking into account those protrusions. As showed, protrusion could bring an additional +50% of lift at low Mach numbers, while increasing simultaneously the L/D by a significant amount. This non-conventional effect of external protrusions such as fluidic lines & cable ducts led to anticipated design of those items.

The numerous flight phases of CALLISTO vehicle also generate a large set of mechanical load cases that are not usual for Expendable Launch Vehicles. Among them, one can notice reentry and landing.

Despite not being high energy driven, CALLISTO reentry requires some maneuverability in order to be able to guide and control the reentry path with enough accuracy. This maneuverability then turns into AoA which generates load cases for given structures on the vehicle, in particular where aerodynamic loads coming from FCS/A are introduced toward the vehicle. Main body is also stressed during this phase.

Logically, the landing phase is one of the most critical from the mechanical loads standpoint. Even if requirements for landing accuracy at touchdown are drastic, the remaining energy at touchdown poses a major challenge in terms of loads absorption. ALS system, further detailed in this paper, provides energy dissipation but loads introduced at aft-bay level together with transient kinematics have to be carefully managed not to become sizing cases for the whole vehicle.

4. Flight control systems architecture

The various flight phases experienced by CALLISTO vehicle require a specific flight control strategy with respect to conventional operational launchers, leading to a blend of sensors and actuators whose usage varies along flight in order to cope with the performances requirements of each phase. Three kind of actuators compose the architecture of the flight control systems on CALLISTO: aerodynamics surfaces (FCSA), RCS and TVC. TVC is a classical two axis main engine gimbal angle actuation system, with which the whole liquid propulsion engine is gimballed so as to provide an angulation between vehicle main body and thrust direction. RCS system is a 4 ON/OFF thrusters system, located near the top of the vehicle, with a dedicated architecture so that it enables – when required – three axis control of the vehicle. FCSA is a 4 aerodynamics surfaces actuation system, unfoldable that also allows for a 3-axis control of the vehicle when aerodynamic efficiency is high enough through independent actuation of each of the aerodynamic surface.

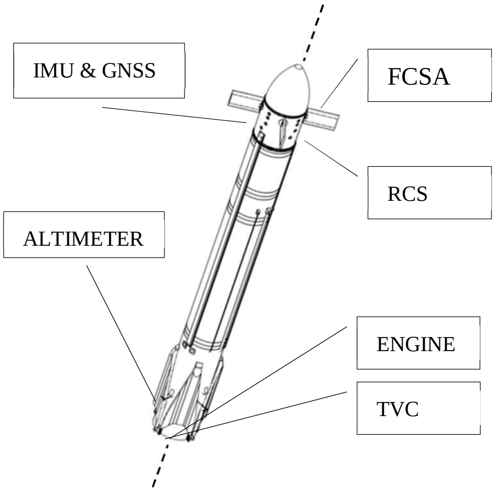


Fig 7. Flight control reentry configuration

Usage of these actuators, or a blend of them defines the flight control strategy in Yaw (Y), Pitch (P) and Roll (R) for the various flight phases, as detailed on the following table:

	TVC	RCS	FCSA
Ascent	Y/P	R	
Coast #1		Y/P/R	
Retroboost	Y/P	R	
Coast #2 – Low Q		Y/P/R	
Coast#2 – High Q			Y/P/R
Reentry			Y/P/R
Landing boost	Y/P	R	

Table 3. Flight control strategy

Navigation System is composed of a mix of sensors allowing to reach the metric accuracy required at the end of the flight. Three main sensors are used: classical IMU, GNSS and an altimeter for terminal accuracy. The following graphs details the overall navigation strategy used on CALLISTO:

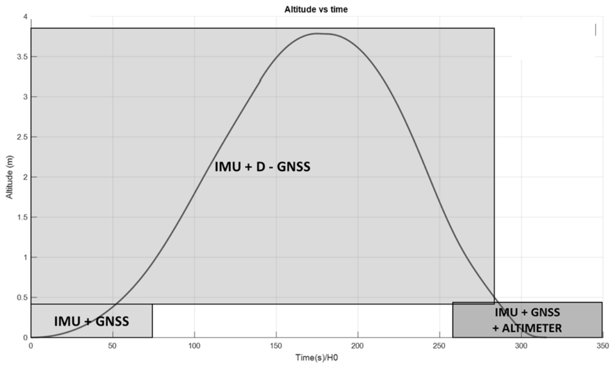


Fig 8. Navigation strategy

Fig 8 provides a schematics of navigation modes through the flight. After an initial ascent where hybridization of classical IMU & GNSS signals is performed, a transition toward a IMU + differential GNSS is done so as to improve on-board GNSS model with respect to atmospheric properties. Gain in accuracy is beneficial to ascent and reentry preparation so as to reach landing boost gate in the best possible conditions. Terminal navigation uses an additional altimeter to gain an order of magnitude in the final accuracy near touchdown, so as to stay within allowable domain for landing system (some meters per second).

GNC algorithms are embedded inside the on-board computer which commands the various actuators, as well as engine ignitions and shutdowns. RSR 2 being throttle able, it is taking a major role in the overall flight control system architecture, in particular with respect to position and velocity management, so that an extended flight control architecture can be illustrated on Fig 9, where management of flight control systems by a decentralized avionics architecture can be highlighted. Each actuator is equipped with a dedicated controller that executes sequential order such as folding/unfolding or ignition/shut-off sequence in the case of engine, based on sequential orders sent by OBC, as well as control commands coming from GNC.

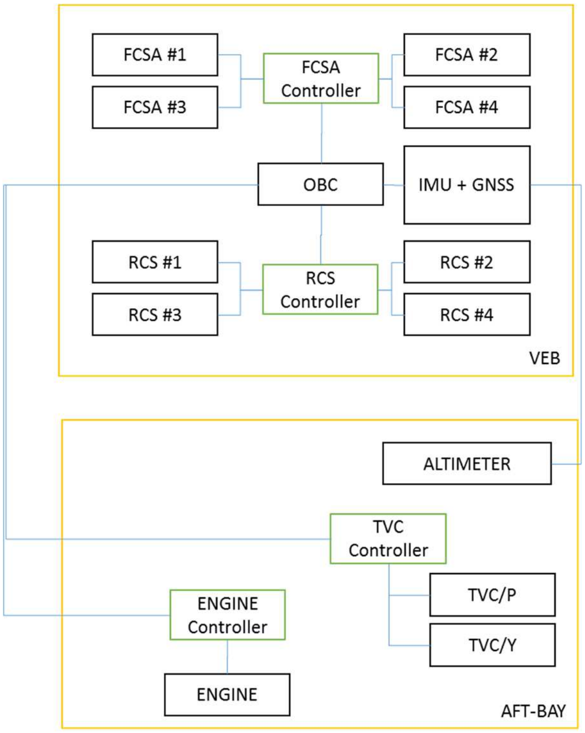


Fig 9. Flight control system overview

5. Rocket propulsion system architecture

CALLISTO vehicle is powered by a LOX/LH2 engine called RSR2, which is an upgrade of JAXA's RSR engine from RV-x experimental vehicle [3] with lighter mass and slightly higher thrust. Propulsion system main architecture is composed of two propellant tanks, and 3 Helium tanks: two tanks are dedicated to pressurization, and one higher pressure tank isdedicated to command. RSR2 engine provide pressurization to LH2 tank through the main thrust chamber regenerative circuit, while LOX tank is pressurized by dedicated He spheres located at the bottom part of the vehicle. In the case of CALLISTO LOX/LH2 vehicle, the rocket propulsion functional architecture is, of course, driven by propellant delivery to engine in appropriate thermodynamic conditions, but also by additional requirements coming from the flight operational life cycle of the vehicle, which includes in particular a phase under low non gravitational acceleration were significant attitude change maneuvers are performed, leading to propellant motion inside the tanks that needs to be mastered (from the propulsion and system standpoint). The in-flight management of propellant motion for attitude maneuver of this class is one of the demonstration objectives of the CALLISTO project, and this specific phase leads to an additional need in LH2 tank pressurization by Helium, to compensate the lack of GH2 coming from the engine, which is Off during this phase. Another driver for the architecture is the post-landing phase during which vehicle shall be drained from its propellant so as to safely grant access to human operators and enable its retrieval from the landing site. Considerations on atmospheric concentrations limit related to explosive atmosphere led to a geographical segregation of LOX and LH2 vent ports.

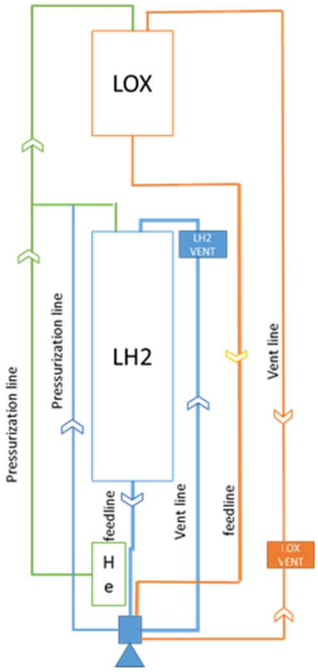


Fig 10. RPS architecture

RSR2 engine features a thrust variation capability from 40% to 110% of RSR previous version reference thrust (40kN in ground conditions) with a dynamic modulation which is a major function interfacing with flight control aspect, in particular with respect to the final landing boost. Engine thrust modulation provides additional degree of freedom in flight management, all along the flight, and more specifically at landing.
On top of these capacities, the engine is capable of "idle mode" where engine turbopumps are by-passed.

Among specific requirements acting as contraints on CALLISTO rocket propulsion design is the operational environment through which the vehicle is passing through descent, and especially the landing boost re-ignition where the engine needs to be reignited in an aerodynamic flow acting against engine plume.

6. Approach & Landing System

The last phase of vehicle mission is a vertical landing; the function of "landing the vehicle safely" is performed by a four legs deployable landing system (ALS), designed by DLR. During ascent, ALS is in so-called "folded" configuration, in order to limit its impact on aerodynamic properties during ascent, especially drag but also to master possible aerodynamic sourced perturbations during reentry. ALS deployment is triggered during the final landing boost so that aerodynamical shape changes can be compensated by control system (here, TVC), which is not the case during reentry.

Landing boost is a challenging phase since it aims at vehicle terminal accuracy management under conditions where subsequent vehicle state changes occurs, among which engine ignition, ALS unfolding and finally, touchdown. ALS unfolding is of peculiar sensitivity since it shall be triggered in a way such that vehicle configuration changes will not cause detrimental impact on accuracy – through residual aerodynamics effects e.g. – but should simultaneously be commanded early enough so as not to oversize the deployment system and then unnecessary deployment speed. This trade-off can be illustrated through a visualization of typical landing profile dynamic pressure evolution with respect to time, where region of high residual aerodynamic – acting against deployment – can be identified, together with region where not enough time is available to perfom deployment, as depicted on Fig 11

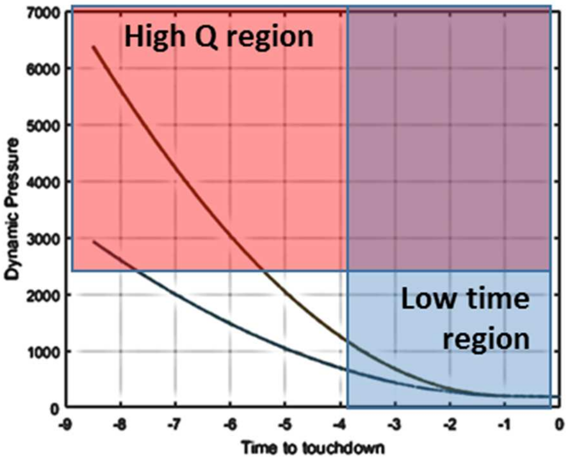


Fig 11. Illustration of constraint acting on deployment

Right after deployment, touchdown phase occurs during which the ALS shall ensure landing loads absorption while not jeopardizing stability and geometrical clearances with respect to vehicle body. Load path and load absorption level are among the main drivers during these phase, facing counteracting requirements such as stability and load dissipation. In particular, potential geometrical deformation induced by landing loads absorption are of importance in the overall performance. Landing touchdown dynamics have been assessed through numerical simulations to gain more insight into this non-conventional phase with respect to a classical operational vehicle. Monte Carlo analysis have been performed to get more exhaustive coverage of the landing performance.

7. Insight into flight test plan

CALLISTO vehicle design has been oriented toward the achievement of mission requirement objectives; however, the project features a dedicated flight test plan so as to limit the risks associated to Demo Flights themselves. Then an incremental approach is adopted, where flight envelope is progressively explored so as to secure mastering of vehicle in-flight behavior, and to progress in the understanding of physical phenomena driving flight performances. A schematic view of the performance envelope exploration is provided in Fig.12 and low, medium and higher energy flights are identified:

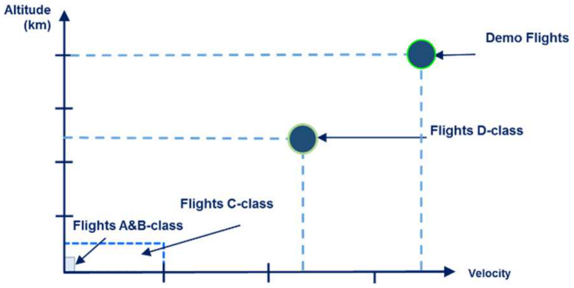


Fig 12. Test flight envelope exploration logic

Flight Test plan is currently Work in Progress, involving mission design as well as vehicle configurations definition. Specific care is given to the compatibility between “performance oriented” design targeting Demo flights, and “Risk reduction oriented” design that shall not be detrimental to vehicle performance. Among envisaged profile are very low altitude (“hop”) flights for which vehicle would lift-off directly standing on its landing system, as well as more energetic flight profiles involving vehicle configuration changes.

8. Conclusion

CALLISTO Vehicle system design is under good progress, in a joint effort of CNES, JAXA and DLR, with the objective of demonstrating the capability to recover and reuse a vehicle featuring a VTVL architecture in order to validate the concepts, verify the cost model hypotheses and identify further enhancement for an operational launcher.

Through a review of some of CALLISTO mission & vehicle peculiarities, technical challenges which have to be tackled in the course of CALLISTO development have been addressed in this paper.

In particular, addition of flight profiles with respect to operational vehicle modifies the usual design logic, adding complexity of systems engineering task, with direct impact on vehicle design. A first outline of test plan logic has been presented in the perspective of further definition work on this aspect.

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