

CALLISTO : ITS FLIGHT ENVELOPE AND VEHICLE DESIGN

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With the emergence of space launch systems featuring recoverable & reusable rocket stages, Europe and Japan are investigating their own way and merge their capabilities in developing CALLISTO Flight Demonstrator. As such, this original project relies on assets from JAXA in Japan on one hand, and DLR and CNES in Europe on the other hand.

Intent of both parties is to collect direct knowledge and data in operating a space launch stage-like vehicle being recoverable (in vertical position) and then flown several times over a short period of time with minimized maintenance effort in between two flights from Space Center in French Guiana.

One core contribution to this project is the rocket propulsion system from JAXA. It is a heavily reusable pump fed rocket engine mixing liquid oxygen and hydrogen and having a long heritage already. In addition, this robust engine offers a wide range of thrust setting capability and then gives design engineers flexibility in adapting flight paths in terms of range, altitude, speed and maneuvers to be (in flight) tested.

The mission analysis is also enriched by CALLISTO advanced Flight Control System combining Thrust vectoring, Reaction Control and, last but not the least, a set of 4 aerosurfaces.

In addition to airborne maneuvers, and thanks to systems sourced from DLR (Approach & Landing System, Hybrid Navigation System e.g.), accurate landing with various vertical touch down speeds is a primary objective as well.

This paper provides a status of the CALLISTO project focusing on flight envelope and vehicle design matters and how they interrelate with each other.

Key Words: CALLISTO, Recover, Reusability, Demonstrator, System Design, VTVL

Nomenclature

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

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, Aerosciences 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.

In chapters below, this paper focuses on vehicle design and how it interrelates with its flight envelope.

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 CALLISTO vehicle are two-fold:

- demonstration of accuracy down to metric precision for flights involving supersonic reentry as well as boost-back manoeuvre,
- and demonstration of in-flight propellant management.

CALLISTO vehicle will be operated from Centre Spatial Guyanais (CSG) located in Kourou, French Guiana, France.

CALLISTO flight is sketched hereafter, with primary flight phases highlighted.

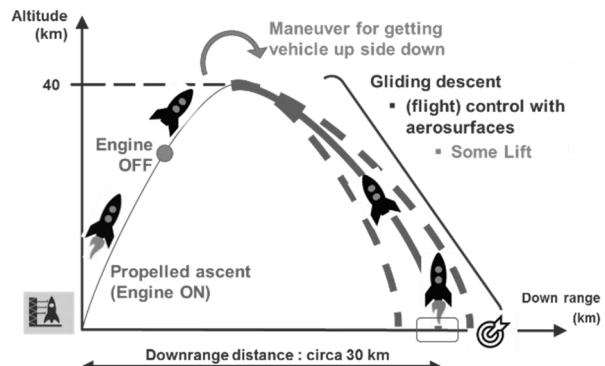


Figure 1 : CALLISTO flight & primary events

Flights have been designed such that objectives described above may be completed over either one or several flights. Figures below illustrates two class of possible flight profiles. Then tables 1 and 2 provide more details and some orders of magnitudes.

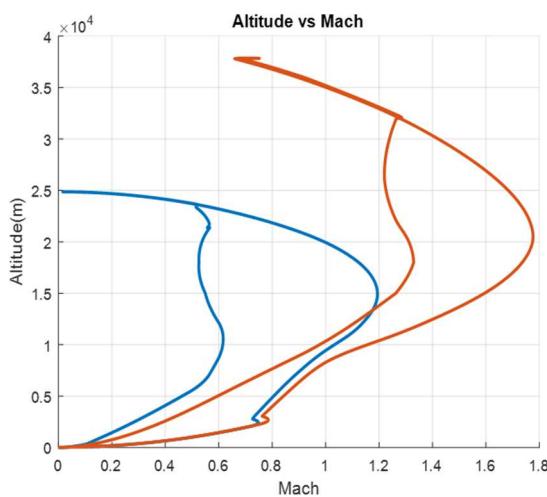


Figure 2 : Altitude vs Mach (Top) for 2 different flight classes #1(red) and #2(blue)

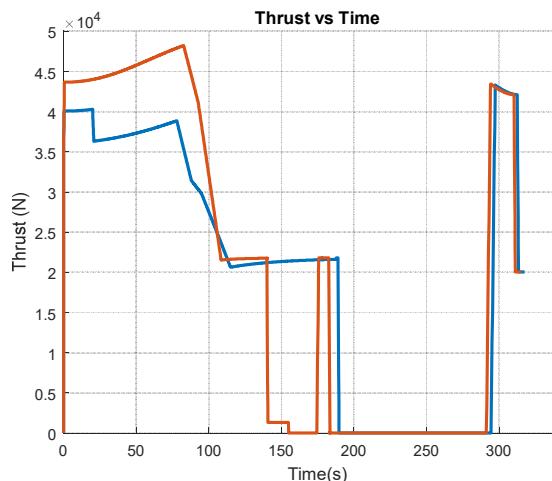


Figure 3 : Rocket engine Thrust vs Time (Bottom) for 2 different flight classes #1(red) and #2(blue)

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 engine 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 retro-boost, during which landing platform is targeted. The retro-boost phase is some ten seconds long, leaving little time for re-ignition dispersions compensation. As a consequence, this sequence requires specific kinematic states location 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 (FCS/A), 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 Q max ~ 20kPa
Ascent		
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 class #1-timeline and events

The high versatility of CALLISTO vehicle missions is a significant system 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 below. 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		
Landing Boost	290	Vehicle Configuration Change : Landing system unfolding
MECO#2 & Touchdown	315	~15- 25s landing boost, hard landing

Table 2 : Flight class #2-timeline and events

On figure below, one can see that the variations of dynamic pressure (Q) vs. Mach number are quite large 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.

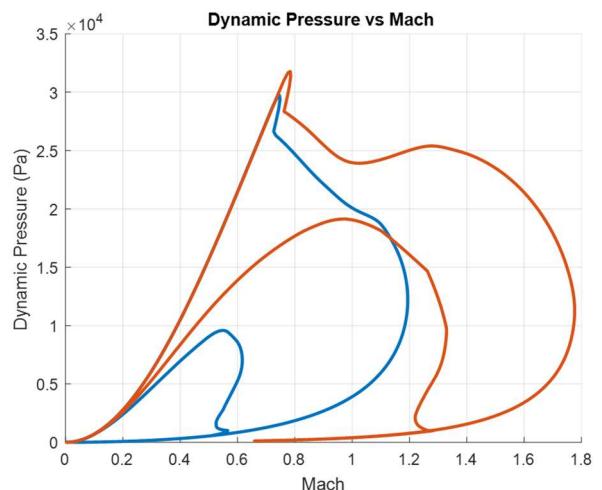


Figure 4 : Dynamic pressure vs Mach for profile #1(red) and profile #2 (blue)

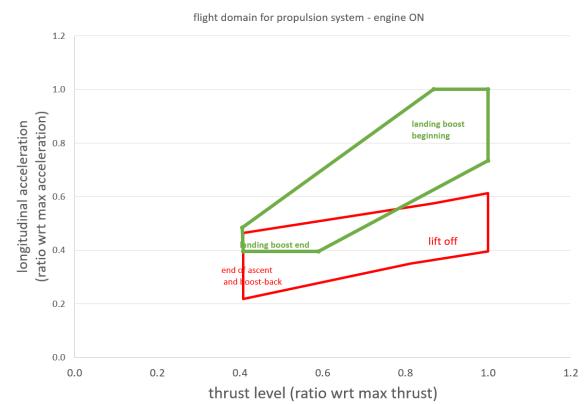


Figure 5 : Longitudinal acceleration vs Thrust flight domain

3. Vehicle Design

CALLISTO Vehicle is a single stage vehicle around 13 meters high 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 pressurization 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:

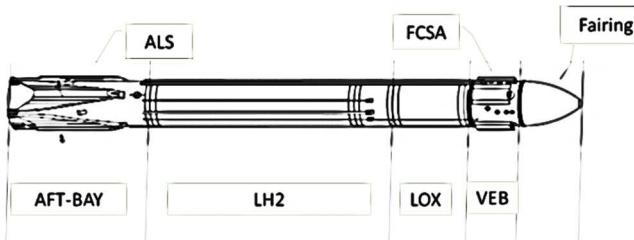


Figure 6 : General architecture of CALLISTO Vehicle

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:

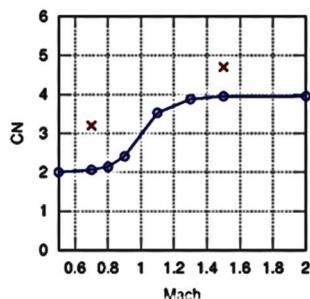


Figure 7 : protusion effect to aerodynamic Lift coefficient

Figure above 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 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 (FCS/A), 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 thruster system, located near the top of the vehicle, with a dedicated architecture so that it enables – when required – three axis control of the vehicle. FCS/A 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.

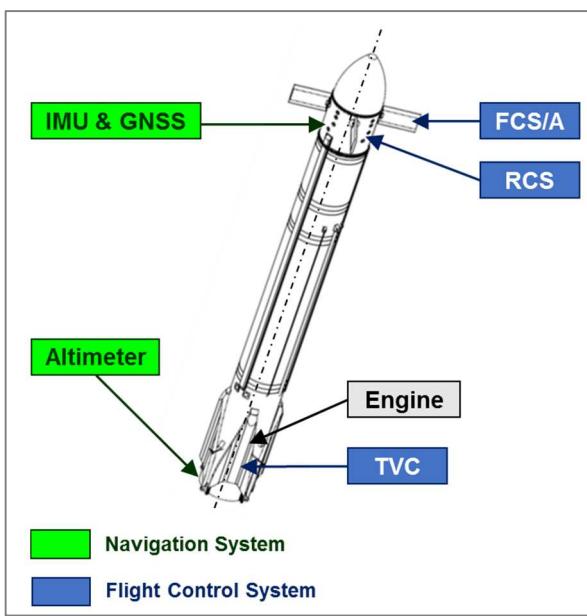


Figure 8 : Flight control - reentry configuration

Usage of these actuators, or a combination defines the flight control strategy in Yaw (Y), Pitch (P) and Roll (R) for the various flight phases, as detailed in table below.

	TVC	RCS	FCS/A
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 phases and 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:

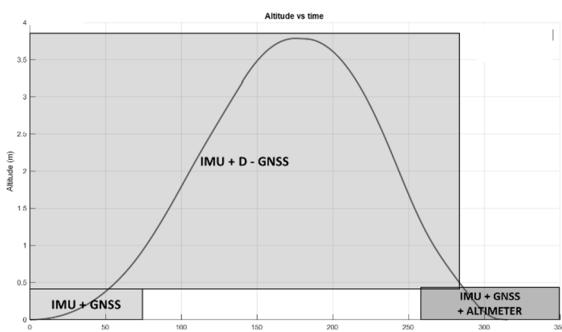


Figure 9 : Set of Navigation sensors - usage

Figure above 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 the flight control architecture can be sketched in figure below where management of flight control system via 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.

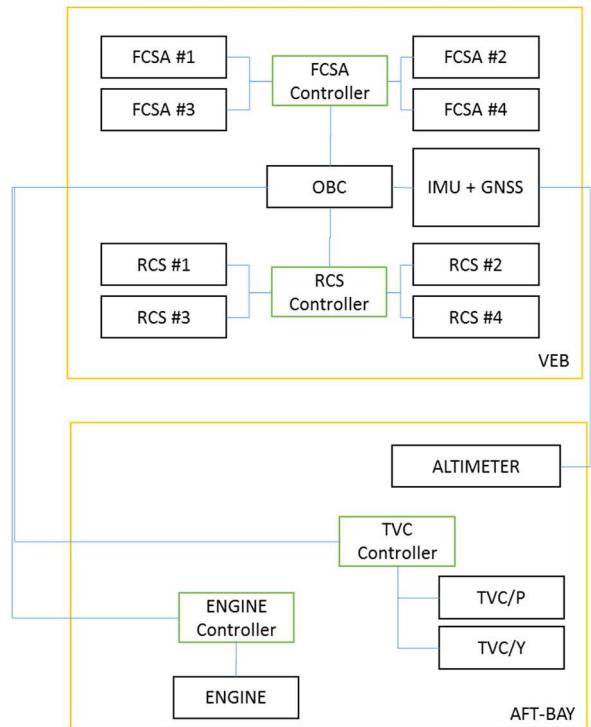


Figure 10 : Flight Control architecture overview

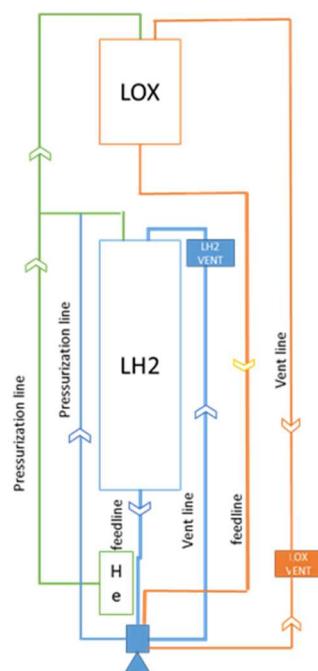
5. Rocket propulsion system architecture

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 is dedicated 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 where 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.

RSR2 engine is a slightly modified version of long heritage RSR engine developed by JAXA. Especially it features a thrust setting capability from 40% to 110% of RSR (40kN at Sea Level) with a dynamic modulation which is a major function interfacing with flight control. Engine thrust modulation provides additional degree of freedom in flight management, all along the flight, and more specifically at landing and its breaking boost.

On top of these capacities, the engine is capable of “idle mode” during which engine turbopumps are by-passed.



Among specific requirements acting as constraints 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 aeroshape changes can be compensated by Flight 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 perform deployment, as figured below.

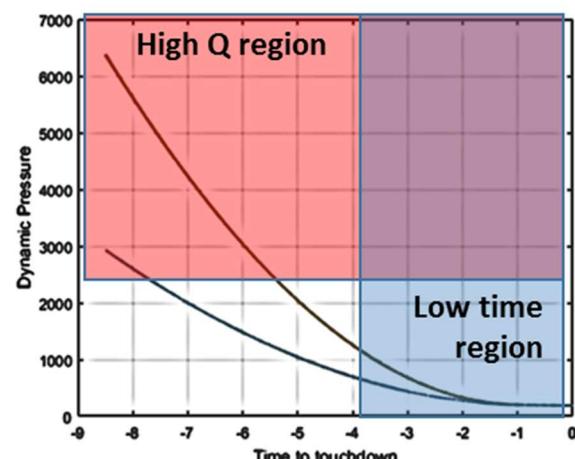


Figure 11 : Time-to-touchdown vs. dynamic pressure – set of some constraints to ALS legs unfolding

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.

Last but not the least, it is also intended to use landing legs of initial set of Test Flights for Lift-Off operations instead of a devoted (Lift-Off) table. Such configuration would be helpful for mitigating the risk of improper unfolding maneuver of ALS. Meantime, it would be the occasion to get final validation of ALS design.

7. Insight into Test & Demo Flight 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:

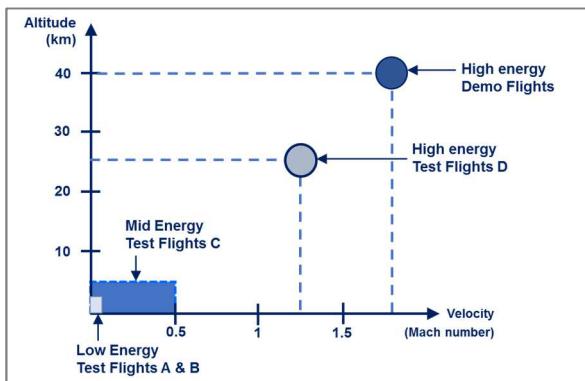


Figure 12 : Test & Demo Flights – some features

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 profiles are very low altitude (“hop”) flights for which vehicle would lift-off directly standing on its landing system (see section above), 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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