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CALLISTO: Towards Reusability of a Rocket Stage: Current Status

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JAXA, CNES and DLR have decided to cooperate to develop and fly a scaled reusable VTVL rocket stage called CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss - back Operations). This vehicle is paving the way for future reusable launch vehicles in Europe and in Japan. During phase B important progress in term of methods and operation philosophy specific to RLV have been made. Amongst other progresses, that will ease the development of future operational VTVL, in the domain of aerodynamic modelling, GNC landing leg deployment but also flight domain definitions are presented. These are concrete results which can at least partly be useful for other RLV projects.

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

Nomenclature

AIV	:	Assembly, Integration and Verification
ALS	:	Approach and Landing System
AoA	:	Angle of Attack
AVF	:	Avionics Validation Facility
CALLISTO	:	Cooperative Action Leading to Launcher Innovation for Stage Toss-back Operations
CDR	:	Critical Design Review
CNES	:	Centre National d'Études Spatiales
CSG	:	Guiana Space Centre
DLR	:	Deutsches Zentrum für Luft- und Raumfahrt e.V.
ELV	:	Expendable Launch Vehicle
F	:	Folded (either FCS/A or ALS) (e.g. FUO)
FCS	:	Flight Control System
FCS/A	:	FCS/Aerodynamic
FCS/R	:	FCS/Reaction control
FCS/V	:	FCS/thrust Vectoring
G&C	:	Guidance and Control
GNSS	:	Global Navigation Satellite System
HNS	:	Hybrid Navigation System
JAXA	:	Japan Aerospace eXploration Agency
LH2	:	Liquid Hydrogen
LOX	:	Liquid OXygen
MECO	:	Main Engine Cut-Off
MEIG	:	Main Engine IGnition
MRO	:	Maintenance and Repair Operations
N	:	engine off (e.g. UFN)
O	:	engine on (e.g. UFO)
OBC	:	On-Board Computer
PDR-P	:	Product Preliminary Design Review
PDR-S	:	System Preliminary Design Review
ReFEx	:	Reusability Flight Experiment
RLV	:	Reusable Launch Vehicle
RSR	:	Reusable Sounding Rocket
RV-X	:	Reusable Vehicle-eXperiment
SRR	:	System Requirement Review
TVC	:	Thrust Vector Control (angle)
U	:	Unfolded (either FCS/A or ALS) (e.g. FUO)
VEB	:	Vehicle Equipment Bay
VPH	:	Vehicle Preparation Hall
VTVL	:	Vertical Take-off and Vertical Landing

1. Introduction

Europe and Japan are renewing their launcher fleet with the introduction of Ariane 6 and H3 in the coming months, replacing their reliable but more expensive workhorses Ariane 5 and H-IIA. These upcoming launch systems address the current need for more versatility, sustainability and in particular decrease cost of access to space.

Many studies and concepts, considering partial or full reusability of launch vehicles, conclude that it has the potential to reduce the cost of access to space. Recent analyses, [1] have shown that depending on the architecture of the vehicle and the type of recovery method a sensible reduction of the recurring costs of launch vehicles should be achievable. The commercial success of Falcon 9 by SpaceX is surely at least partly linked to the fact that the first stages can be reused numerous times. Naturally, the advantage brought by reusability for the launch cost depends on many parameters such as the accessible market but also technical and operational parameters. The knowledge of these parameters is the main limit of system studies. It is possible based on expert judgment to make assessment of the costs of the additional systems needed to make a stage or a vehicle recoverable and then reusable. However, these assumptions can only be validated and confirmed with the help of tests in real environment and conditions. Operations specific to reusability, for instance to prepare again the vehicle for the next flight after the recovery, are even harder to evaluate and their considerations in the cost assessment are based on particularly rough assumptions as long as no real data are available.

With the goal to improve the knowledge of the reuse of launch vehicle and rocket stages, CNES, JAXA and DLR have decided to develop, build and test a reusable demonstrator of a vertical take-off and vertical landing first stage. In the frame of the project CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss - back Operations) a 13,5 m high and less than 4 metric tons rocket stage will be built and tested in flight.

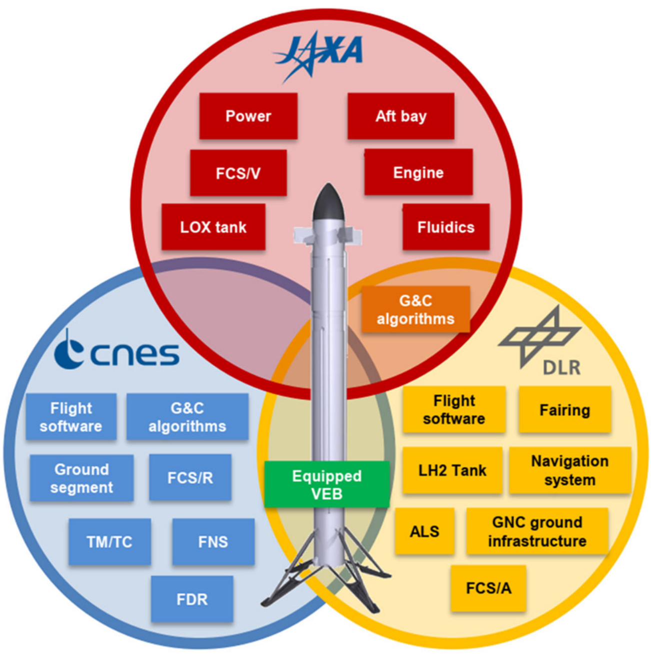
The second major goal of the CALLISTO project is to build the know-how which is needed to develop, optimize, build, test and operate an RLV efficiently. This is primarily linked to technologies, [2,3,4] such as throttleable and re-ignitable engines, flight control systems, health monitoring systems, reusable structures and mechanisms, thermal protection systems, but not only. Procedures, methods, tools and techniques have to be adapted or even developed for RLV and here in the specific case of VTVL.

First a short overview of the project status and of the system which is being developed is provided. Then a selection of operational and technical aspects at system level specific to VTVL for which progress have been recently achieved are presented.

2. Project Status

2.1. Development steps

After a preliminary conceptual phase, the project CALLISTO started with a trilateral agreement signed during Paris Air Show in June 2017. It was followed with the phase A of the project, which was completed during the spring 2018 with a successful SRR (System Requirement Review). A relatively long phase B was then started during which the requirements cascaded from the system to the products were refined step by step with the help of the increasing level of details of the products, the results of the first breadboard or engineering tests and the increasing understanding of the challenges specific to the reutilisation. The system preliminary design review (PDR-S) was declared successful in the spring 2020, which opens the way for the preparation of the preliminary design reviews of the products (PDR-P). Some products, in particular those reused or derived from other programs such as the reaction control system, called FCS/R (Flight Control System / Reaction), which is prepared by Nammo, performed their PDR-P in 2020 or early in 2021. This is also the case for the LOx/LH2 RSR2 engine which is derived from the RV-X experimental vehicle developed by JAXA, [5]. Other products and subsystem have been performing their PDR-P in the second half of 2021. After the completion of all the PDR-Ps and due to the detailed work performed during the iterations in the phase B the manufacturing and testing of qualification models for some main products will be started soon. A relatively tight schedule is planned to achieve a first



ALS: Approach and landing system
FCS/A aerodynamic flight control system
FCS/R: reaction flight control system
FCS/V: thrust vectoring flight control system
FDR: flight data recorder
FNS: flight neutralization system
G&C: guidance & control
TVC: thrust vector control
TM/TC: telecommand and telemeasure
VEB: vehicle equipment bay

Fig. 1. Major subsystems of CALLISTO, arranged by work share between project partners.

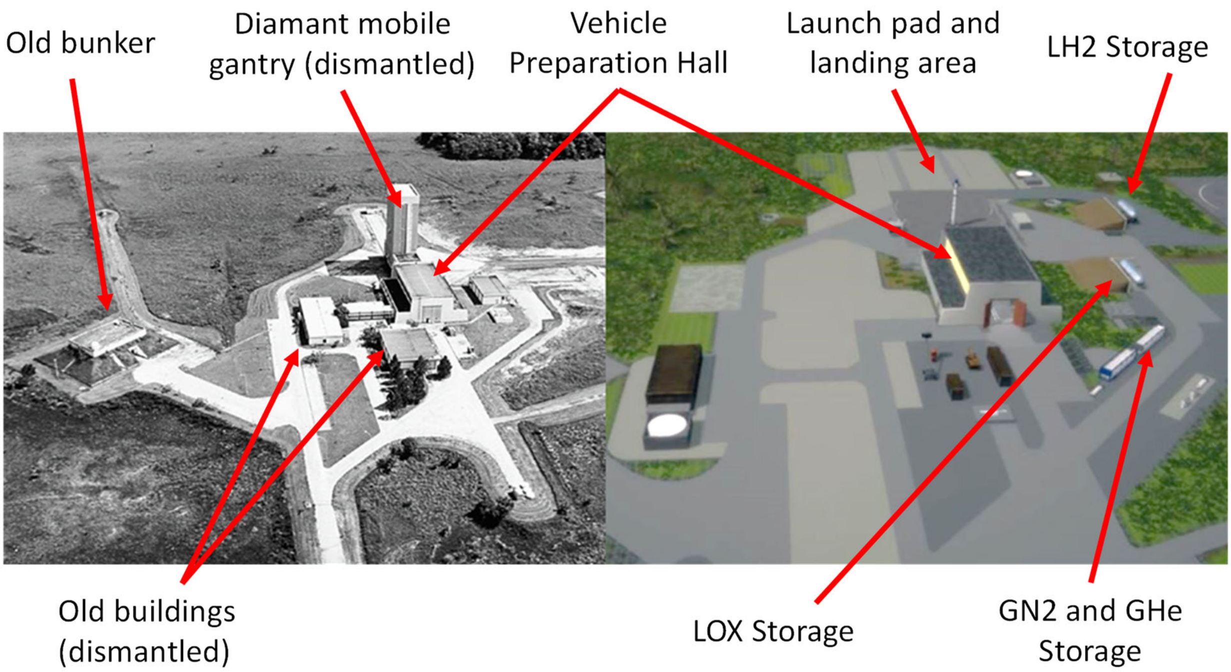


Fig. 2. Photography of the former Diamant Launch Complex from the 1970s (left) and rendering of the new CALLISTO Launch Complex (right), reusing the Vehicle Preparation Hall (VPH) and other infrastructure.

launch from Kourou in French Guiana before the end of 2024. Ref. 6, 7 and 8 are providing a global overview of the project and the CALLISTO system.

2.2. System design status

The CALLISTO system consists of the vehicle segment, which implements a typical VTVL rocket first stage demonstrator, and the ground segment, which provides all necessary infrastructure to perform the test and demo flight campaign.

As visualized in Ref. 9), the vehicle is a 13.5 m long rocket stage, with an external diameter of 1100 mm and a maximum take-off mass of less than 4 tons. It is propelled by a 40 kN class LOX/LH2 engine with a throttling capability from 115% (compared to RSR1 engine version) down to 40%, [6]. The vehicle is designed to operate within a flight envelope (see chapter 3.1, so that different flight conditions and mission objectives can be achieved in a campaign of up to 10 flights.

The vehicle can be further subdivided into several functional subsystems as shown in Fig. 1. From a geometrical point of view, these subsystems can be aggregated into six modules, which consists each of a primary structure with accommodated equipment. From top to bottom, these vehicle modules are,[3]:

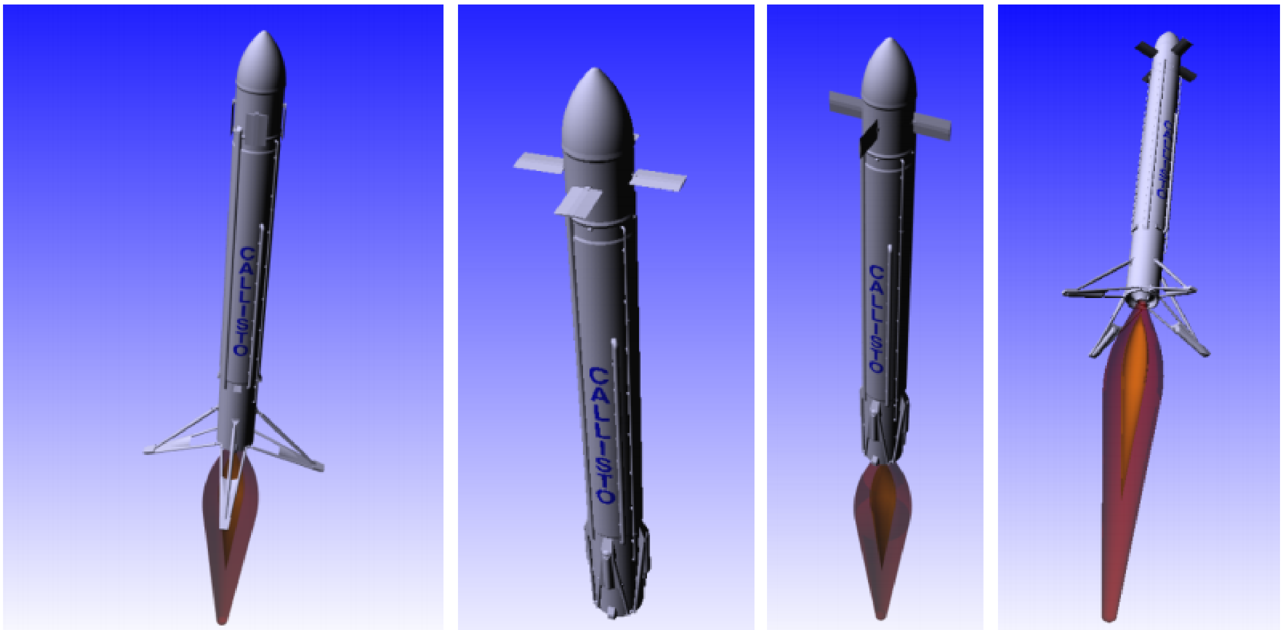
- Nose Fairing Module, providing a smooth aeroshape and housing the GNSS antenna and elements of the Flight Neutralization System (FNS);
- Vehicle Equipment Bay Module (VEB), accommodating the Reaction Control System (FCS/R), four deployable aerodynamic control surfaces (FCS/A) as well as most of the avionics components;
- LOX Tank Module and LH2 Tank Module, whose primary structures are the integral propellant tanks that are also carrying the main part of the cable ducts traveling along the vehicle side as well as fluidics lines;
- Bottom Module, housing the engine, the thrust vector control system (FCS/V) and the tank pressurization system, as well as avionics and fluidics components;
- Approach and Landing System (ALS), which consists of four deployable landing legs attached to the Bottom Module and a dedicated pneumatics system.

The ground segment of the CALLISTO system, which provides all required means for flight preparation, operations, maintenance and repair activities, will be installed in the French Guiana European Spaceport (CSG) in Kourou. It consists of a dedicated CALLISTO launch complex and shared ground support equipment of the launch range, which is also used for other launch system. As shown in Fig. 2, the launch complex itself is currently under construction/adaptation at the former Diamant site with the goal to retrofit and reuse existing infrastructure as far as practical. The construction work of the ground segment has started on the Diamant site with the dismantling of the former mobile gantry and setup of ancillary networks.

3. Operation Philosophy: Towards Reusability

3.1. Design of the flight envelope and flight test plan

In the case of ELV, using the maximum performance is often the only and most efficient way to minimize the cost of access to space. This is the reason why usually fleet (e.g. currently for Arianespace: Vega, Soyuz and Ariane 5) are used to cover as well as possible the spectrum of missions (low to high energy orbit and low to high payload mass). In the case of RLV, other parameters have to be considered as well. The flown trajectory is characterised by a certain level of loads (mechanical,



(a) FUO (b) FFN→UFN (c) UFO (d) FUO→UUO

Fig. 3. Some possible CALLISTO configurations - including test flight and transitional configurations.

thermals, …) and has therefore a direct impact on the wear of the vehicle. It is usual, that to achieve the best performance, one has to reach the limit of what a vehicle is capable to support. In some cases, it can be acceptable for a reusable stage or vehicle, because it is reusable not to use it at the full performance. Flying a lighter payload allow therefore to follow less harsh trajectories and then preserve the life of components of an RLV. It may also allow to prefer a return to the launch site and then save time and cost compared to downrange landing for instance on a barge, as it is the case for Falcon 9.

RLVs are intrinsically more versatile than ELV and can be designed not only for limited number of mission but for a flight domain or a flight envelope. CALLISTO also is designed to fly within a flight envelope that will be explored during the tests in flight. The difference for CALLISTO compared to operational VTVL is that the envelope is answering the need to fulfil requirements linked to the demonstration objectives and not the need to launch a broad spectrum of payload.

The structure of the CALLISTO flight test plan is derived from:

- The objective in achieving a required target flight envelope (typically Mach ≥1 at descent) with associated flight profile features (e.g. imposed maneuvers providing flight data & demonstrating technologies for future RLV)
- the will to adopt an incremental approach with respect to flight envelope exploration, hence a step by step approach. Also, as far as practical, vehicle configurations have to be robust to flight envelope corner limits resulting from “high energy” flights to prevent additional vehicle features which would not be useful for max flight envelope.
- A limited number of flights – which impose to find reasonable risk/opportunity balance in between each flight envelope increase. For instance, the numerous in-flight configurations and the transitions between them (see for instance Fig. 3) will be tested progressively.

The vehicle itself features several in-flight configurations, considering:

- ALS which can be either folded or unfolded
- Aerosurfaces (FCS/A) which can also be either folded or unfolded.
- Engine itself, which is in-flight re-startable

Then, notional flight test plan (see Fig. 4) will typically feature:

- Low energy flights, where the vehicle lifts-off from its own legs, meaning with ALS unfolded. These flights will enable first vehicle characterization and check of touchdown performance. For very first flights, lift-off and landing will occur from the same pad (short duration, low altitude, no maneuver).
- Medium energy flights, which aim at:
  - extending the flight envelope to gain insight into system in-flight behavior and environment
  - testing in-flight unfolding of ALS under low magnitude environment. Hence the vehicle lifts-off from a dedicated lift-off table.
  - perform in-flight maneuvers such as roll maneuver and lateral drift. To be noted that this drift is anyway requested since landing cannot obviously occur right on the lift-off table.
- High energy flight per se (see Table 1 for a typical flight sequence).

For low and medium energy flights, the engine is planned to be not shut down (risk mitigation).

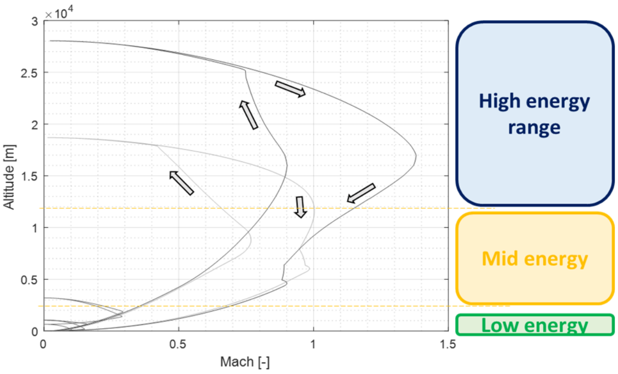


Fig. 4. Notional view of flight envelope incremental exploration.

Table 1. Typical target high energy flight sequence.

Time	Event	FCS/A	ALS	Engine
0	MEIG#1	F	F	ON
120	MECO#1	F	F	ON
140	FCS/A unfolding	F	F	OFF
	Reentry	U	F	OFF
200	MEIG#2	U	F	ON
230	ALS unfolding	U	U	ON
240	Touchdown	U	U	OFF

In relation with the flight test plan itself, a detailed post-flight data analysis plan is under construction which will combine both in-flight measurements and rebuilt flight data. Input collection and analysis, together with the incremental flight envelope approach, will enable to gain valuable insight into vehicle life cycle and compare it with pre-flight predictions. It will be an important input for the so-called flightworthiness assessment (see 3.2). Of course, it will be also possible to adjust prediction methods to better fit observations and predict future RLV life cycle (fatigue, MRO operations, etc.).

3.2. Flightworthiness

CALLISTO is designed to be reusable, while being at the same time a demonstrator with a proto-flight model approach, resulting in many activities related to Verification & Validation ahead to the flight- and test campaigns and Maintenance and Repair Operations (MRO) in between flights.

Established reviews, which are commonly applied in launcher projects or space projects, such as Manufacturing Readiness Review (MRR) or Flight Readiness Review (FRR), will ensure:

- A sufficient confidence level in manufacturing and qualification for products and modules of the vehicle,
- The acceptance of products and modules for next higher assembly stage and testing phase,
- And finally, that the launch system (vehicle and ground segment) is ready for final countdown resulting in a launch of the vehicle.

To support the FRR and to increase confidence of the system being ready, the CALLISTO project will perform a flight worthiness assessment in incremental steps starting from phase C until the End of the flight campaign at CSG in Kourou. This process will be separated in two phases.

Phase 1 concerns the manufacturing quality and verification of products, modules and functional chains and is mainly conducted during Phase C and D at product owners' premises or during the combined testing programs at Noshiro in Japan or at CSG in Kourou. The phase 1 is classic and not particular to a reusable vehicle.

During phase 2, the flightworthiness in terms of operational matters will be assessed; starting during the combined testing phase at CSG for functional end-to-end testing and mating checks for complete and in-flight configuration assembled vehicle. Phase 2 will continue during all the test campaign and in particular between the flights to ensure that at the end of the MRO the vehicle is flightworthy. A complete but efficient assessment of the vehicle and of the subsystems should be achieved. It is recalled that one objective of CALLISTO is to keep the MRO activities as low as possible, even if, of course, it is expected that many lessons learnt on how to improve the design for MRO will be drawn at the end of the project.

Finding a very reliable way to ensure that the vehicle is still flightworthy or in other words that components have not reached yet the end of their life after a flight or series of flights is a challenging task. For ELV or for the first flight of an RLV, the loads applied a component before the flight are very well controlled and predictable. This is quite different for an RLV expected to fly a large flight domain. The flightworthiness process being set up in the frame of CALLISTO is a first step to tackle the aforementioned challenge.

Any issues or results identified during Phase 1 and 2 will be reported by dedicated Flight Worthiness Reports, which are submitted for a Flight Worthiness Review (FWR) performed before each set of flights. The results of those reviews will support the planning of the MRO and the decision of FRRs performed separately ahead of each dedicated flight.

The report for the FWR will be a compilation of sheets, issued by the owner of products and modules or by the involved parties for a functional chain, while experts of the joint project team will validate the reported progress and confirm the flight worthiness contribution to the overall vehicle. The report will compile any deviations in terms of anomalies or configuration identified during Integration, Assembly and Verification (AIV) and during MRO in between flights in relation to the associated requirements and accompanied documentation. In particular events with possible impact to mission degradation or success will be submitted for review. Next to that the reliability activities will be evaluated to enhance the qualitative confidence for the flight worthiness assessment.

4. Development of RLV Specific Technical Capabilities

After the classic ascent, shared also with ELV, CALLISTO will change several times its configuration (see Fig. 3) and performed highly dynamic manoeuvres. These are of course possible sources for deviations and uncertainties. During the phase B, important efforts have been spent on one side to guarantee that:

- the guidance and control methods will be robust while

still preserving the performance
- the navigation system will be reliable and accurate
- the uncertainties linked with aerodynamic aspects are kept as low as possible
- the landing and landing leg deployment sequence are well understood and simulated

Naturally these efforts will be continued during the following project phases. The gained know-how and the developed methods will be very useful for the development of future RLVs.

4.1. Guidance and control

For the guidance and control development a flight is divided into different phases. These phases are of different nature since different actuation means are available. Besides the ascent phase, for which a pre-computed guidance solution is stored onboard and tracked. All the other phases, those particular to the recovery of the vehicle, and chronologically in this order the boostback, the aerodynamic descent, and the powered landing, employ online techniques to compute a valid trajectory corresponding to the off-nominal, inflight conditions. Advanced techniques developed for the guidance phase include predictor-corrector schemes and pseudospectral sequential convex optimization, [10]. During phase B, these methodologies have been prototyped in Matlab and tested within a high-fidelity 6-DoF nonlinear simulator. An example of trajectory obtained with such techniques for phase B, and specifically for the aerodynamic descent, is depicted in Fig. 5, where the body axes of CALLISTO are shown (x-axis in red, y-axis in green, z-axis in blue).

In terms of control strategy robust techniques are adopted. Special emphasis is given to the use of structured H_∞ control techniques, able to match robust control methodologies within well-known control structures, such as PID or LQR, while guaranteeing at the same time stability margins through the specifications of frequency-domain constraints. The overall scheme is depicted in Fig. 6, where the structured controller is represented as a PID control law followed by a transfer function H(s).

During the phase B two different methodologies have been tested: a more classical configuration with separation of outer and inner loop, [11] and an integrated methodology where attitude and trajectory are controlled at the same time. The former has been extensively and successfully tested within the 6-DoF nonlinear simulation environment throughout the phase B. An example of the application of the latter methodology is visible in Fig. 7, where the Nichols plot shows that good margins (specifically, about 21 dB for the gain margin and 54 deg for the phase margin) could be obtained. In this specific case a simple PID-like structure was imposed. Given the improved performance compared with the former methodology, the integrated formulation of control is currently the main candidate for the actual flight, and is getting more extensively tested and refined during the forthcoming Phase C of the project.

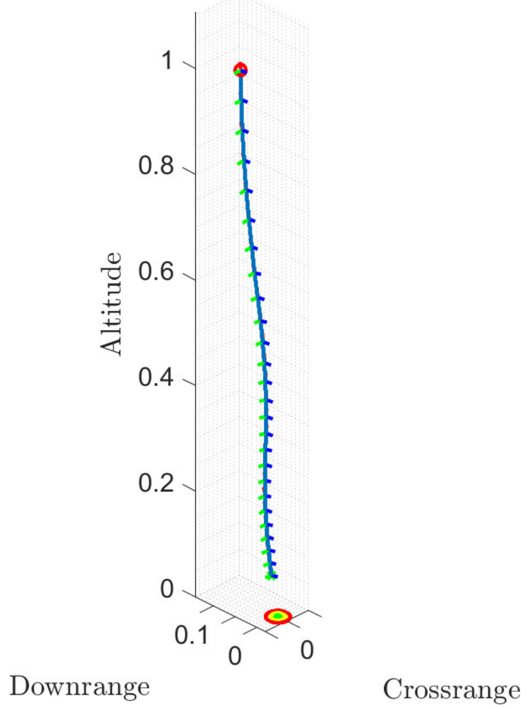


Fig. 5. Example of aerodynamic descent trajectory obtained with pseudospectral sequential convex optimization.

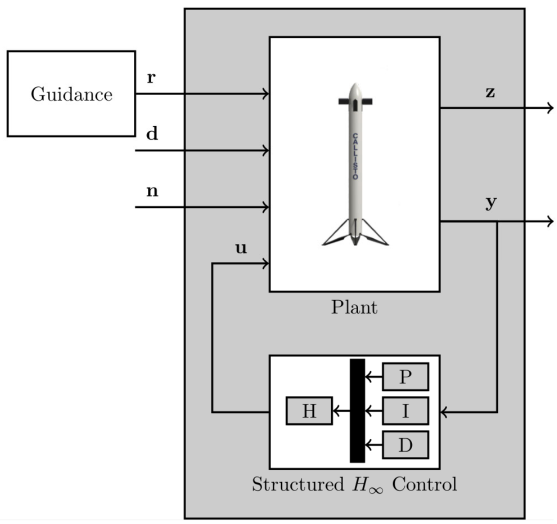


Fig. 6. Guidance and control scheme for CALLISTO with structured controller in the loop.

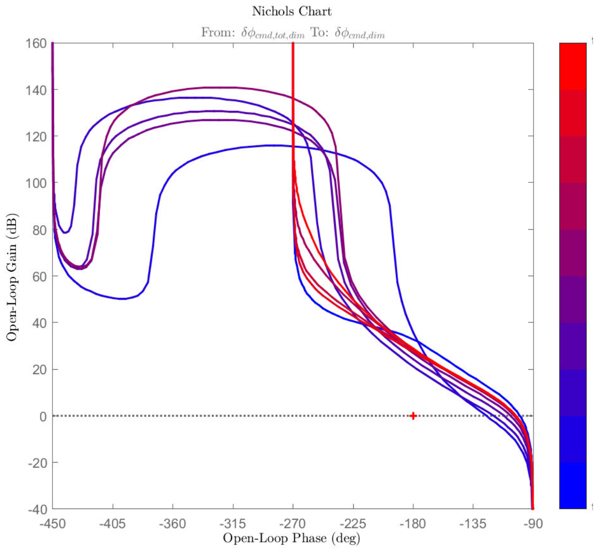


Fig. 7. Nichols plot for the roll control during the aerodynamic descent.

4.2. Navigation

The requirements set for the navigation accuracy to be able to perform the desired mission profile with a pinpoint landing are very high. The navigation function is performed by a Hybrid Navigation System (HNS), which is based on the HNS developed for DLR's Reusability Flight Experiment (ReFEx) with CALLISTO-specific adaptations to fulfil the strict requirements requested from the navigation function for VTVL stages. A more complete overview of the preliminary design of the HNS at the beginning of Phase B can be found in Ref. 12).

The HNS fuses inertial measurements provided by a DLR developed tetraxial Inertial Measurement Unit (IMU) with the information coming from two GNSS receivers and a Flush Air Data Sensing (FADS) system. Originally, using measurements of a customarily developed radar altimeter system with radar reflectors placed on ground was foreseen as well to improve the accuracy of the flight altitude estimation. However, intensified studies on an alternative solution relying on carrier-based Real-Time Kinematic (RTK) operation of the GNSS receivers in consideration of cost and schedule constraints as well as maturity level reached for the subsystem Preliminary Design Review (PDR) led to the conclusion that this alternative solution has better potential for realization in the frame of CALLISTO while reducing complexity at the same time. The decision to remove the radar altimeter system from the baseline in favour of the RTK-approach was made as a consequence of the successful conclusion of the subsystem PDR.

4.2.1. IMU modelling and navigation filter design

During Phase B, a lot of attention has been given to the analysis and mitigation of the effect of the flight environment, such as temperature variations and random vibrations, on the IMU as well as on the overall HNS performance. These effects have been modelled according to environmental and sensor specifications, and test-based values provided by the sensor manufacturers. In particular, it became clear that structural vibrations are a critical error contributor. The navigation filter design has therefore been adjusted accordingly to minimize the loss of performance and robustness that might be caused by these effects.

Additionally, whereas before Phase B most of the navigation performance analyses were based on the navigation filter's estimated covariance, more extensive Monte Carlo campaigns have been carried out during Phase B, which allowed to verify the navigation filter's consistency and analyse the behaviour of the actual estimation error.

4.2.2. GNSS subsystem

CALLISTO is equipped with a multi-constellation, multi-frequency GNSS subsystem using the Galileo and GPS constellations. The two on-board GNSS receivers are complemented by a GNSS ground station, which allows performing differential GNSS (DGNSS), thus increasing the accuracy of the solution, which is needed in particular during the most critical landing phase.

During Phase B, the DGNSS subsystem was mainly used in code-based differential mode to provide sufficient position accuracy in the horizontal direction during the landing phase. On the other hand, the required position accuracy along the vertical direction was achieved mainly by means of a radar altimeter system. In parallel, an additional approach for enhancing the GNSS subsystem accuracy in vertical direction has been studied and focus has been shifted towards using the GNSS subsystem in carrier-based RTK mode during the very last part of the landing phase in order to provide the required position accuracy not only in the horizontal but also in the vertical direction. Thorough modelling and simulation have shown more promising results than first expected. This technology will be developed and analysed further during Phase C.

4.3. Aerodynamics and aerothermodynamics

The aerodynamic and aerothermodynamic assessment of the CALLISTO vehicle includes many different tasks, among them: the aerodynamic studies, aeroshape definition and optimization, performance assessment, estimation of aerodynamic and aerothermal loads, aerodynamic/aerothermal database generation, as well as uncertainty analysis before and after the flights. For this purpose, various studies using computational fluid dynamics (CFD) and complementary wind tunnel experiments at multiple facilities were already conducted during most of the phase B, [2, 3, 7, 8, 13, 14)].

While it may appear that aerodynamic characteristics is not much important for a vehicle which is using its engine for part of the recovery, this impression is incorrect. A VTVL vehicle is characterized by a low lift to drag ratio and many protuberances but performs the main part of the return duration only under the influence of aerodynamic forces, making an accurate knowledge of those a prerequisite for any refinement of the requirements towards products and therefore of the design. Know-how gained during the phase B and methods specific to reusable vehicle developed will be very helpful also after the end of the CALLISTO project for future reusable vehicle. Some examples of these RLV specific aerodynamic aspects treated for CALLISTO are presented in the following paragraphs.

Main challenges for the characterization of CALLISTO aerodynamics are on one hand the extensive number of possible configurations and conditions, which include un-/deployed legs (ALS) and fins (FCS/A), various engine operation levels including thrust vectoring, as well as large ranges for angles of attack, roll angles, and fin deflection angles with a slightly asymmetric aeroshape, and on the other hand the integration of the multiple data sources into consistent system engineering databases. An example of the numerical and experimental work performed on wind tunnel models is shown in Fig. 8. For all numerical studies the DLR TAU, [15] code was used.

Current tasks which will continue after the end of the phase B, include:

- Development of aerodynamic databases for test flight configurations and uncertainty model
- Development of an aerodynamic FCS/A deployment model
- Determination of impact and models for aerodynamic effects of thrust vector nozzle gimbaling

4.3.1. Development of aerodynamic databases for test flight configurations and uncertainty model

In 2021, the CALLISTO AEDB was significantly extended. In addition to the basic configurations required for the demo-flight simulation, calculations were performed for the configuration used specifically in the test flights, e.g., FUO-configuration, with folded fins and unfolded landing legs. In addition, data were prepared to make the simulation of ascent flight with unfolded fins possible. Further aerodynamic data for transient configurations were prepared to simulate the fin deployment process. Some of the possible CALLISTO configurations, [14] - including test flight and transitional configurations are visualized in Fig. 3.

For the CFD based AEDB the influence of different physical modelling aspects like turbulence or surface roughness are now considered in an uncertainty model. Figure 9 shows on the example of the UFN configuration at M=0.7 and AoA=180° the influence of the numerical turbulence model on the integrated drag distribution. The change from a one-equation Spalart-Allmaras model to a Reynolds stress equation model increases the total drag by 14%.

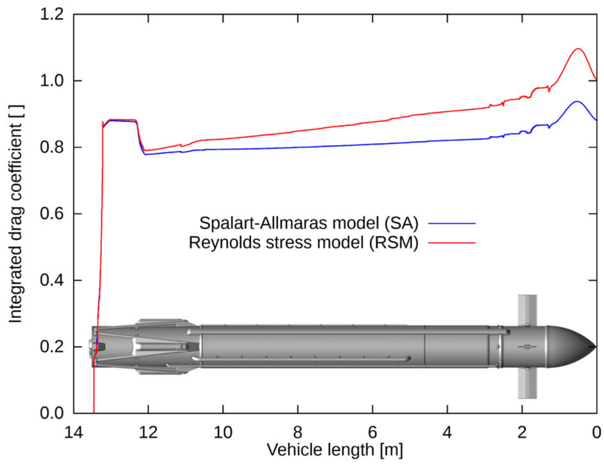


Fig. 9. Integrated drag coefficients for UFN CFD simulations with different turbulence models at M=0.7 and AoA=180°.

4.3.2. Development of an aerodynamic FCS/A deployment model

The aerodynamic FCS/A deployment model is developed for evaluation of the fin deployment dynamics. In the ideal case deployment should take place at minimum dynamic pressure where deployment disturbances are negligible. However, test flights cover a different flight envelope than the demo flight. The flow disturbance and influence on pressure due to the final step of fin deployment (fin angle at 90 deg) is visualized in Fig. 10.

4.3.3. Low velocity aerodynamics

According to (i) flight test plan and (ii) flight features themselves, low velocity conditions (Mach number/ high angle of attack) will be experienced either for long periods or key flight events, e.g.:

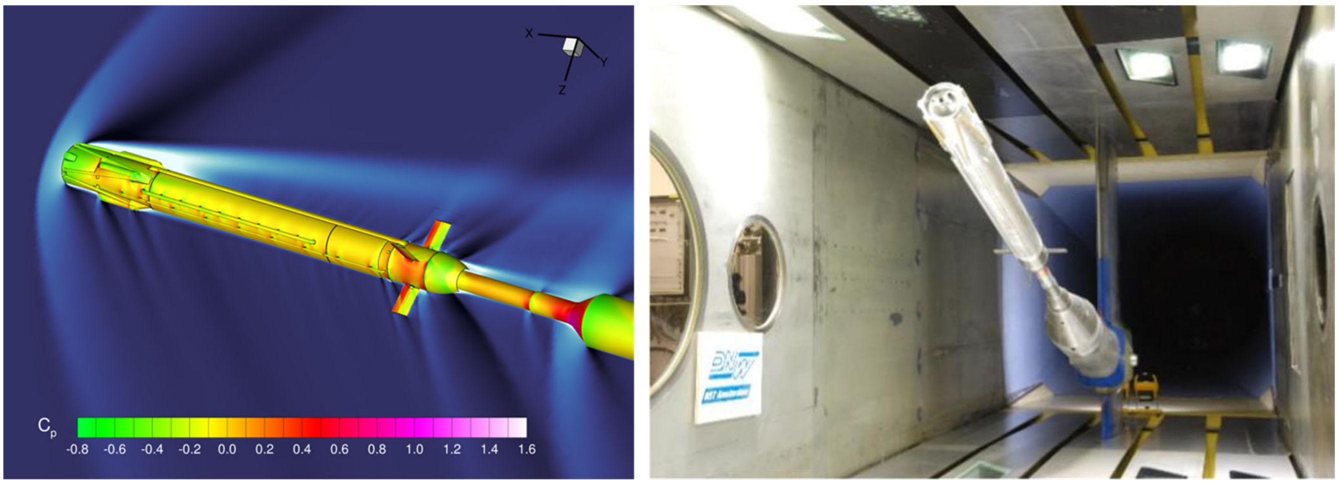


Fig. 8. (left) CFD of WTT re-building at M=1.3 and AoA=190°, (right) CALLISTO 1:10 scale model with unfolded fins mounted for force measurements in the HST test section (DNW High-Speed Tunnel (HST) in Amsterdam.

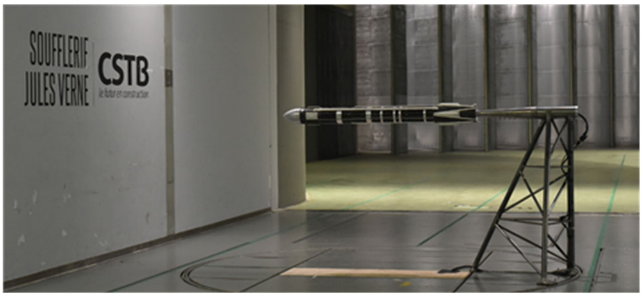
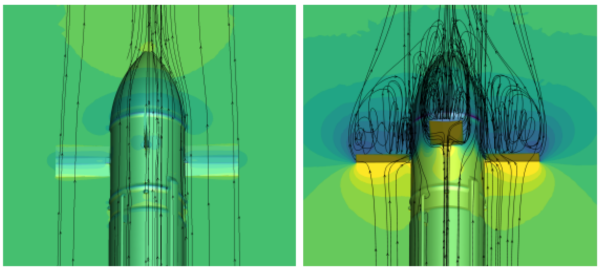


Fig. 11. CSTB Wind Tunnel Test 1/7th Model.



(a) AoF = 0 deg (b) AoF = 90 deg

Fig. 10. Deployed fins at different angles of attack, contours represent pressure.

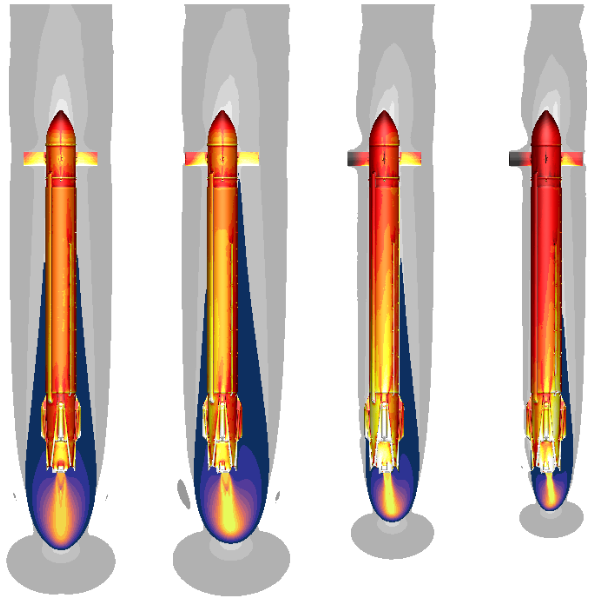
- most of low and medium energy flights
- for high energy flights, altitude culmination and last period of landing braking boost, both of which are critical from system standpoint (e.g. control).

These flight regimes (high AoA, low Mach number) are also quite complex to capture though numerical analysis. Hence in order to secure AEDB (see above) during these flight phases (for various system aspects, including GNC, Environment & Loads, etc.) a dedicated wind tunnel test campaign was conducted at CSTB Nantes, featuring a 1/7th scale vehicle model, compatible with configuration changes (ALS, FCS/A) and nose-forward (ascent flight) and aft-forward (descent flight) configurations, see Fig. 11.

As for other AEDB contributions, systematic comparison with numerical AEDB is completed, to consolidate and secure nominal data and related uncertainties.

4.3.4. Determination of impact and models for aerodynamic effects of thrust vector nozzle gimbaling

The Thrust Vector Control (TVC) or FCS/V via engine gimbaling is used by CALLISTO for attitude control during both ascent and landing phases. Especially in landing phase (retro propulsion phase) the strong impact of engine plume deflection onto the aerodynamic forces and moments is expected. The primary objectives of the performed study were the numerical evaluation of this impact and the development of the aerodynamic model extension for taking it into account for the flight simulation: the AEDB was originally estimated for the undeflected engine plume. Numerous CFD-calculations with engine thrust deflection were performed for the TVC-impact study. A method of accounting for the TVC-impact on aerodynamic characteristics, e.g., drag, based on the calculation of the effective local flow angles in the base area has been developed. This method considers the engine mode and nozzle deflection angles, the flow-field for different TVC and thrust levels for the UFO configuration (compare Fig. 3) is shown in Fig. 12.



(a) (b) (c) (d)

Fig. 12. Mach contours (grey), gas temperatures (color in field) and heat flux (color on surface) for different nozzle deflection angles and thrust levels at 180 deg AoA. (a) no TVC deflection / 110% thrust (b) 5 deg TVC deflection / 110% thrust (c) 5 deg TVC deflection / 40% thrust (d) 5 deg TVC deflection / 110% thrust.

Future studies will focus on delta-aerodynamics, data validation and flightworthiness assessment of the aerodynamic / aerothermal system aspect.

4.4. Landing legs deployment

Another VTVL specific event for which big progress have been done during the phase B is the simulation of the deployment of the landing legs and more generally of the approach phase, [16]. As mentioned in the previous chapters, CALLISTO is equipped with deployable landing legs. During the ascent and most of the descent deployed landing legs would strongly increase the drag and disturbances. To keep the aeroshape as "clean" as possible the landing legs are stowed along the fuselage of CALLISTO until the last seconds of the flight. Then a tight window is available for the deployment of the legs. If the deployment is too early the aerodynamic forces (know from a specific AEDB) are too high and in addition of the high loads on the structures and very high aerodynamic disturbances a powerful but certainly heavy deployment mechanism would be needed. If the deployment is too late or lasts for too long, the risk for having the legs not fully deployed and not ready at touch-down is increasing. A precise simulation of this phase comprising the interaction between the vehicle G&C, the pneumatic deployment system and its performance and finally the impact of the changing aeroshape of the vehicle during the deployment is needed. A systematic approach was developed in order to cover the full flight domain of

CALLISTO during the approach phase see Fig. 13, [16]. This method can of course be applied to future VTVL development.

As seen in the figure, during this phase dispersions should be strongly reduced by the G&C before the very short landing phase. All disturbances created by the deployment of the ALS, itself impacted by the G&C states and commands should be corrected also by the G&C. To complement the simulations landing legs deployment tests have been performed in a test stand developed by DLR, to ensure that on the full flight domain the vehicle will behave correctly and that the deployment of the landing legs will be smooth and successful.

5. Conclusion

The CALLISTO demonstrator developed jointly by JAXA, CNES and DLR is paving the way for potential future reusable launch vehicle in Europe and in Japan. While the phase B is finishing also for the products, new methods and philosophy needed for RLV and specifically VTVL have been developed. This is an important preliminary step, as important know-how has already been gained. Flight data will of course help to improve them prior to the development of operational VTVL. It should be noted that part of the work presented in this paper can be applied as well for exploration missions with vertical landers on celestial bodies with or without atmosphere.

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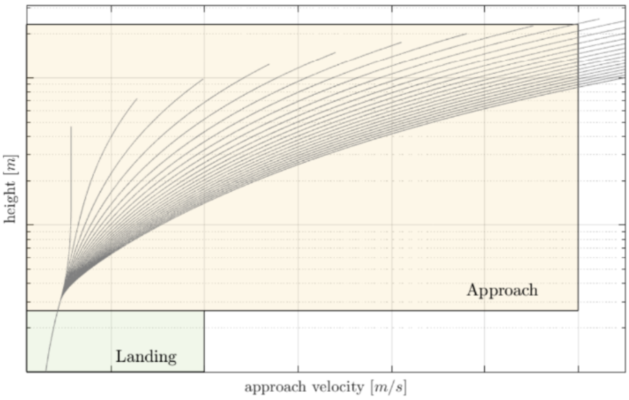

Fig. 13. Schematic view of the approach flight domain.

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