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CALLISTO PROJECT - REUSABLE FIRST STAGE ROCKET DEMONSTRATOR

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Abstract
In order to assess more deeply the benefits and to acquire knowledge of the recovery and reusability, experiences are necessary. CNES and DLR are sharing their efforts and risks with an in-flight system demonstration based on a reusable reduced scale first stage rocket demonstrator. It will validate critical technologies integrated into the system in representative environment. The technology performances will be linked with operational capability in order to validate the concepts, verify the cost model hypotheses and identify further enhancement. This paper presents the preliminary objectives, general concepts and reference design of the demonstrator vehicle. The ground segment, the way to learn on maintenance and potential future evolution of the demonstrator are also considered.

1. Introduction

The launch vehicles competition is more and more focused on dedicated launch service and launch cost reduction. Depending on the targeted business case and the refurbishment cost, the reuse of the launcher first stage could lead to a significant cost reduction. Assessment of the business case and technology availability and performance cannot be confirmed without a minimum of concrete experience. Cost and engineering computations need to be tuned taking into account relevant experience obtained in similar cases. One of CNES (French Space Agency) goal is to prepare future technologies and concepts for satellites, launchers and launch base for French and Europeans services. 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. Linked to a step by step approach necessary for reaching the Callisto demonstration objectives, a demonstrator is proposed and other agencies and industry partners are involved. Considering DLR experience on aerodynamic, landing and aerodynamic devices, and the active role of CNES on the evolution of future European launcher, launch base and launch system, CNES and DLR are leading this project, with many internal engineering.
CNES is prime contractor for the ground segment and the vehicle system architecture. For CNES, this rule is similar to the one during the development of Ariane launcher dated many years ago but today with a complete new team, organization and working methods, taking into account lessons learnt and cost analysis of future launch system.

Based on an existing reusable engine, an experimental vehicle has been proposed and preliminary missions with corresponding test plan have been identified. The project was named CALLISTO for Cooperative Action leading to Launcher Innovation in Stage Toss back Operations.
Feasibility activities are ongoing.

2. Objectives

Callisto demonstration has several objectives.

- The first objective is to demonstrate the capability to recover a vehicle with toss-back trajectory. This goal implies many sub objectives each ones linked to the different phases of the trajectory such as in fly re-ignition, propellant settling and sloshing management, aerodynamic control, and precise landing. On board computer will have to use robust fly software for guidance, control and navigation during all phases.
- Second objective is to repair the vehicle and make it ready for the next fly with minimum turnaround and refurbishment effort. This is link to real goal of cost assessment of this task.
- Third objective is to fly with the same reused vehicle, with a capability of 5 flights, following a test plan defined for risk reduction of losing the vehicle and flight objectives.

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Main ground base objective is to demonstrate the ability of the French Guyana space center to operate a vehicle with launch and come back phases. Safety solutions and analysis considering flight and ground operations will be the main drivers for vehicle trajectory, takeoff and landing sites with minimum impact on vehicle concept.
First positive consequences of these objectives are the need to find new solutions and to experiment other engineering and project practices in order to fulfill the mission in time, cost and with the available human resources.

3. Callisto Vehicle System

3.1 General Design

The Callisto vehicle is a single stage vehicle equipped with a 40kN class LOX/LH2 engine, with thrust modulation capability of 40%. The main mission objective is to be able to perform a so-called "Tossback" flight profile, which includes in particular:

- A classical ascent phase
- A "ballistic" attitude change phase, so-called "tilt-over"
- A "boostback" flight phase which aims at targeting the landing site
- A guided reentry phase
- A final boost which enables to reach touchdown conditions compatible with the vehicle design

In fact, on top of this reference trajectory profile, several flight profiles are under investigations in order to establish a consistent flight test plan which would enable to incrementally reach the target profile.

As a consequence of this target flight sequence, the vehicle design is constrained from several points of view, namely:

- T/W ratio at lift-off
- Flight control and propellant settling during tilt-over maneuver
- Flight control during reentry
- Flight and ground safety

A preliminary design has been performed, assessing the feasibility of such a concept, with respect to technical and programmatically aspects. The following presents some main results of this design process.

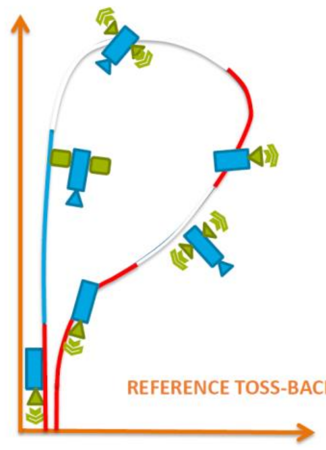

Figure 1: Reference Trajectory for Toss Back

3.2 Vehicle Layout:

Preliminary design studies showed that vehicle diameter has a major impact on performance, and shall result from extensive trade-off between accommodation (propulsion subsystem in particular) and mass.
The reference vehicle has a diameter of around 1m, with a total height around 13m. It is equipped with two main external features compared to a classical operational launcher:

- Deployable fins, which are folded during ascent and are unfolded during the ballistic phase before reentry : they enable to stabilize and control the vehicle during its atmospheric entry

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- Four landing legs, which are also folded during ascent and deployed very shortly before landing. A preliminary design has been done with the objective of ensuring both sufficient engine clearance with respect to ground and stability at touchdown.

The Vehicle ground/board interface prior to landing remains to be fully defined, but alternatives are currently being traded-off which could include classical interface at bottom of aft bay has well as local interfaces.

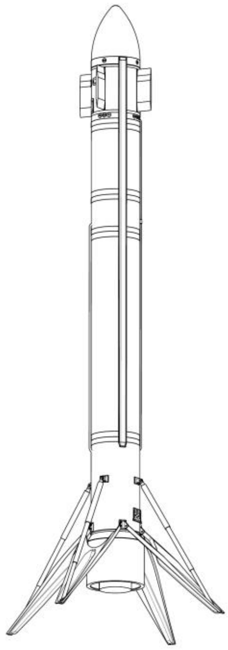

Figure 2: Vehicle Lay out

3.3 Vehicle Flight control:

Vehicle flight control is being deeply investigated in the course of current engineering activities, with dedicated emphasis on:

- TVC : to define what is the gimbal and gimbal rate need for all propelled phases
- RCS : to define what is the thrust requirement, total impulse, as well as thrusters lay-out which is of prime importance for RCS efficiency, and implies strong interfaces with vehicle lay-out responsible
- Fins : to define minimal area and deflection need, in order to ensure enough L/D range to meet accuracy objectives
- Engine : to define thrust modulation requirements to be able to perform the range of landing profile and ensure sufficient

CFD computations performed at aerodynamics level showed that vehicle configuration lay out **(Fig. 2)** is being stabilized by fins during the whole Mach range, also allowing some trim capability inside a given AoA range. Detailed studies are currently being performed to check whether the resulting L/D range is sufficient to compensate from dispersions which will necessarily be observed at beginning of entry. Illustration about such simulation campaign is given **(Fig. 3)**.

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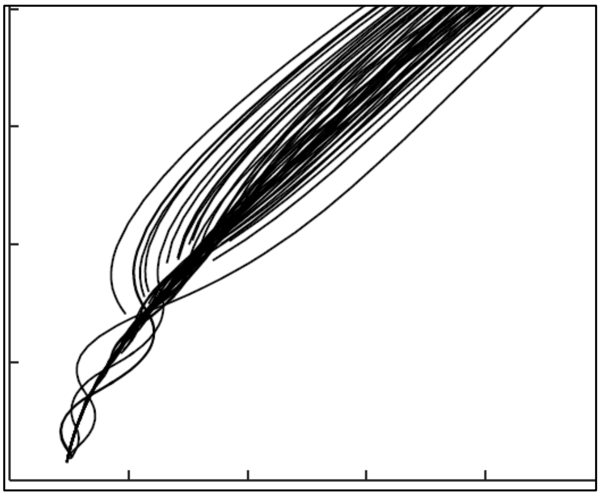

Figure 3: Illustration of reentry trajectory used in L/D ratio specification

Regarding RCS design, dedicated study are being performed to define what are the requirements to ensure controllability during the critical phase of "tilt-over", where a residual atmosphere remains. In this case, a compromise is to be found between tilt-over maneuver dynamics, propellant management and RCS capability. Co-engineering analysis, involving specialists of flight control and propellant sloshing are currently carried out. Typical criticality indicators are for instance the comparison between allowable torque and max aerodynamic torque encountered during maneuver, and the propellant location during this maneuver **(Fig. 4)**.

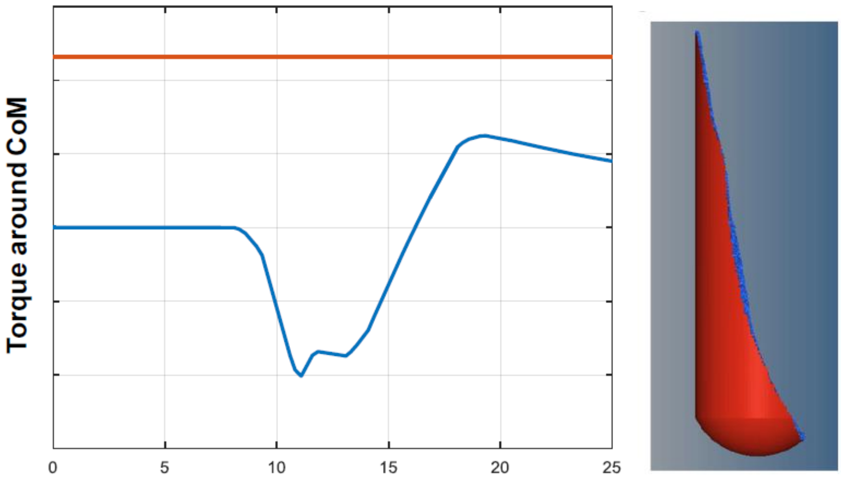

Figure 4: Aerodynamic Torque and propellant evolution

3.4 Vehicle Avionics:

One of the major challenges of the CALLISTO demonstration is to be able to define an avionic chain which is compatible with the specific requirements of vehicle reusability cycle, which includes in particular:

- Accuracy management through dedicated measurements, in particular with respect to Navigation. Indeed, the short duration of the last boost requires a very stringent knowledge of real-time vehicle states in order to be able to catch and compensate any errors through guidance and control
- Telemetry and Telecommand through the whole mission, with emphasis to be put on post-landing operations where the vehicle has to be put back to a safe status where humans can approach it.
- Flight safety during the recovery maneuver. Dedicated studies on vehicle ground and in-flight health assessment are being performed, as well as on vehicle neutralization strategy which directly impacts avionics at system level.

Preliminary avionics architecture has been proposed and is currently under system engineering design **(Fig. 5)**.

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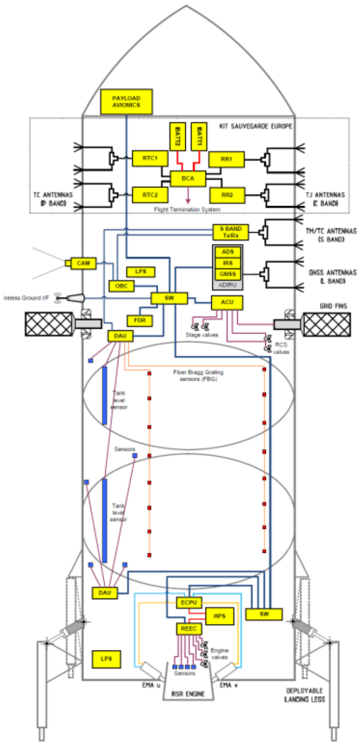

Figure 5: Preliminary avionics architecture

4. Callisto Ground Segment

In the goal of global optimization, the ground segment has to be adapted to this new objective. It is the reason why the imagined launch base for this demonstrator has been focused on reusability of infrastructures from previous projects, minimized new means and safety logic adapted.

The layout of French Guyana Space Center is the following **(Fig. 6)**. The positioning of preparation/lift-off and landing sites have been selected.

Figure 6: French Guyana Space Center

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4.1 Lift-off Sites

For Callisto studies, it was decided to give a strong priority to costs efficiency, and to look for possible re-use of the investments.
Major criteria to be considered for the selection were shortlisted as the following:

- Safety of assets and people :
  - Existing Infrastructures in operational use (Ariane 5 & 6 facilities, customer facilities).
  - Personnel (Guyana Space Technical Center, Kourou city).
- Costs containment :
  - Reuse as much as possible of already existing infrastructures (launch pad, preparation and revalidation buildings, access roads).
  - Avoid areas to be prepared from scratch.

With these constraints, “Sounding rockets” Site **(Fig. 7)** was the more appropriated.

Figure 7: sounding rocket Site

4.2 Landing Site

3 options are studied:

- The first one, the principle one, is situated near the launch pad, at approximatively 800m distance between the coast and the launch pad, in a free area. This zone has the advantage to be near the preparation and the revalidation building which implies a cost optimization for preparing the area to operations. The principal disadvantage is the reduced distance from the populated area with its intrinsic impact for what concerns flight safety aspects.
- The second one is a back-up solution area which is situated between Ariane 6 launch base and Soyuz launch base. The principal advantage is that this area is the best place on land in terms of distance from populated areas. The principal disadvantage of this area is that is very near from a floral and faunal protected zone. The possibility to test the vehicle demonstrator with this constraint is under investigation.
- The third one is a barge positioned on the sea near the Salvation's Islands. From a safety aspect, it’s the best one because far from any people. It could allow also proposing a big change for Guyana launch base exploitation but the costs would be very important for a demonstration. This solution could be the last back-up solution.

At the time of this paper, the first solution is the reference. This is mainly due to the fact that others locations are not sufficiently mature to challenge the first choice and more costly. Only concrete slab in order to have a strong surface for landing, without equipment, is considered at this step of the project.
In order to minimize the costs, which is the principle ground segment objective, all needed means have been required and defined on the simplest way.

4.3 Mechanic Means

The major functions to be insured are the following:

- To allow the Vehicle transfer between the Preparation Building and the lift off site.

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- To allow the Vehicle erection on lift off site and reverse operation on landing site.
- To allow the maintaining of the Vehicle in vertical position on the Launch Pad.

In order to insure these functions, some means are envisaged:
- A container with an integrated frame would be available to allow the transfer and the removal from storage of the vehicle in preparation building. It would be compatible with all constraints linked to the project (roads in Europe and French Guyana, boat or plane depending the choice of transportation to French Guyana, preparation building).
- One or two mobile cranes put up the vehicle in vertical position on the lift off site and setup in horizontal position after landing in order to transport it. The transport framework where the vehicle will be attached inside the container will have to be compatible with these cranes.
- A table for supporting the vehicle until lift-off. This table should also provide or minimally allow flexible and cables routing associated to :
  - Fluid connections.
  - Electrical connections.
  - Deflector positioning below the vehicle.

4.4 Fluid Means

Concerning the fluid, 2 main functions need to be insured:
- Vehicle filling (with LOX and LH2) with all associated rules for this kind of fluids for piping, evacuation and cooling.
- Vehicle supplying in terms of gas need (Helium and/or Nitrogen).

The major outcome of the design studies is that all tanks / capacities will be mobile. For LOX / LH2 tanks, it can be dedicated tanks adapted to these fluids (CRYOLOR trailer Ariane 5 type). For gas need, it will be bottles / racks capacities. Test panels will be setup to allow a good operating system for processes which are in current development. More detailed information is described in the processes definition which will be defined during the next step of the project.

4.5 Monitoring and Control system

The monitoring and control system configuration for Callisto demonstrator will be divided in 2 major parts linked with on-board avionic which is actually only partially defined and with means available on the space center:
- Power and digital front end on the space center (Electrical Ground Segment Equipment definition)
- Communications with radars and TM/TC ground stations.

The monitoring and control system addresses, in particular, the way and means to command and regulate the ground processes (fluid, electrical), and to control orders exchanged with the on-board systems during all ground phases up to lift-off, as well as after landing.
The logical will be as most as possible the same than for fluids, namely having mobile means. The actual assumption is to have a mobile control center situated in a dedicated truck which could be positioned everywhere around the vehicle. Flexibility of communication could allow answering to safety constraints in term of vehicle and ground installations monitoring, without implementing cables or radio station. On this side too, associated studies are in progress but concept principles are clearly established.

4.6 Conclusion on ground segment

The ground segment definition located in French Guyana and adapted for Callisto demonstration is in progress. Even if all solutions are not actually clearly chosen, concept principles to have a lift off site adapted and financially optimized are established. For CNES and particularly for the ground segment, the goal of this project is also to show that CNES is capable to change the current methodology in an ambitious cost objective, to operate Callisto vehicle during several flights but also to demonstrate that reusable rockets can be operated in future in French Guyana.
Nest step of the project will defined the concept of operation with more elements, providing the necessary input for starting some studies, especially on MRO.

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5. Summary and Conclusion

This paper presented CNES activity for reusable booster stage experiment and demonstration. This activity is currently run in the frame of inter-agency cooperation for short term in-flight demonstration with the goal to perform a system experiment with conditions close to a typical operational booster stage.

It presented the preliminary objectives, general concepts and reference design of Callisto demonstration, ground segment and vehicle.

With a short term demonstration, CALLISTO project will demonstrate, through a specific vehicle and the corresponding test plan, the feasibility of a toss-back mission with limited similarity.

In addition, the vehicle and ground operations will permit to provide elements on cost hypotheses linked to the refurbishment phase and the recovery strategy.

In this project, CNES is prime contractor for the ground segment and the vehicle system architecture. For CNES, this rule is similar to the one during the development of Ariane 5, many years ago but today with a complete new team, organization and working methods, taking into account lessons learnt and cost analysis of future launch system.

The feasibility phase is ongoing.

6. Acknowledgments

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7. ACRONYMS & SYMBOLS

AoA	Angle of Attack
ATD	Aero Thermo Dynamics
GLOW	Gross Lift-Off Weight
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
L/D	Lift-to-drag ratio
MECO	Main Engine Cut-Off
MGSE	Mechanical GSE
MRO	Maintenance Repair & Overhaul
RCS	Reaction Control System
TM/TC	Telemetry / Telecommand
TVC	Thust Vector Control
T/W	Thrust-to-weight ratio

References

[1] Dr. P. Baiocco, E. Louaas, E. Bourgeois, Ch. Bonnal, Th. Bouilly. *Reusable rocket stage experimental vehicle and demonstration*. IAC-16-D2.6.6