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CALLISTO – A safety demonstration of future reusable launcher stages from CSG

*Pierre MEZARD * – Dr Nathalie CESCO * – Nicolas PRALY * – David MONCHAUX **
*Thierry CLAUZON * – Jean DESMARIAUX **
** CNES Space Transportation Directorate,*
52 rue Jacques Hillairet 75612 Paris Cedex France

Abstract

The CALLISTO vehicle is a flight demonstrator for future reusable launcher stages. The program involves three countries and their space organizations: CNES for France, DLR for Germany and JAXA for Japan. The first tests will be conducted in 2024 from the CSG, Europe's Spaceport for commercial launches.

It is a unique opportunity to demonstrate that a launcher stage can be flown with a Return-To-Landing-Site trajectory, recovered and reused from the CSG in compliance with state-of-the-art safety regulations.

From Ground-based operations safety perspective, as the Vehicle is integrated and tested up to hot firing tests in Noshiro test Center (NTC), a Design-to-safety approach has been established so that the Vehicle design copes with both Japanese and French safety standards.
This led to compare and to customize JAXA and CNES safety practices and to set cost effective solutions adapted to the programmatic constraints and the heritage of NTC and CSG test facilities. In particular, remotely controlled capabilities via robot have been introduced for managing safety-critical operations at Landing Pad in CSG.

From Flight safety perspective, CALLISTO vehicle flight test campaign is built around an incremental opening of flight domain, from Low Altitude hops to High Energy flights featuring Drag-Landing-Point manoeuvre and transonic re-entry. Compared to expendable launchers, the Vehicle neutralization strategy has to be tailored in accordance with the flight phases -ascent, high altitude manoeuvre and re-entry-.
As such, Flight Safety Corridors have been specified as constraints for the GNC so that the Vehicle remains within safe cinematic limits. This provides a clear framework for the performances of the two Flight Software developed in parallel by CNES and JAXA/DLR.

Besides, CALLISTO is also a chance to develop a Flight Termination System embedding innovations to enhance safety and cut operating costs. These novelties deal with GNSS-based localization, small-sized Smart Detonators and extensive use of COTS.

Aim of this paper is to detail how CALLISTO team tackles these challenges and opportunities, paving the way for future reusable launcher stages to be operated from French Guiana.

1. Introduction

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

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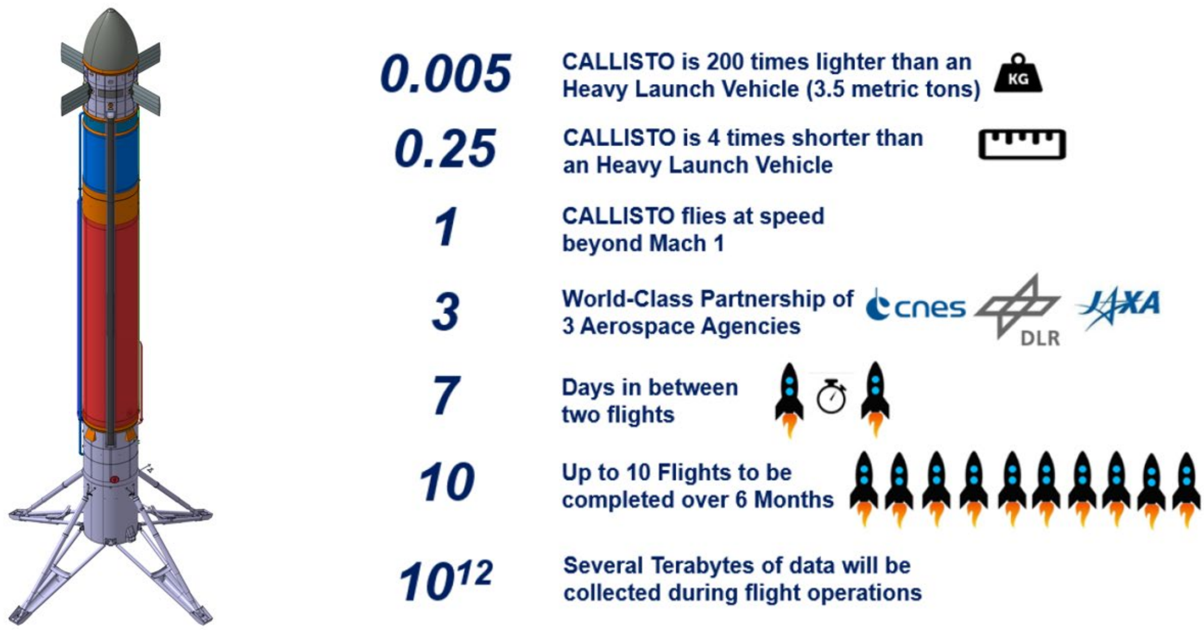

Figure 1 : CALLISTO by numbers

It is a unique opportunity to demonstrate that a launcher stage can be flown with a Return-To-Landing-Site trajectory, recovered and reused from the CSG, in compliance with state-of-the-art local safety regulations.

The recovery and re-usability of CALLISTO vehicle raise significant safety-related challenges, both from ground-based operations and in-flight perspectives. This paper provides an overview of some of these challenges and the associated solutions.

The proposed concepts shall cope with both the demonstrator mind set of CALLISTO –limited resources, reduced-scale, single flight model- and the very ambitious goals to pave the way for future re-usable launchers to be operated from CSG. [1]

In term of safety, this means to find a proper balance between securing the feasibility based on flight-proven solutions as well as introducing the key innovations that will enable the re-usability to become a reality over the next decade in French Guiana.

Among these novelties, the introduction of remotely operated robots to avoid having staff close to non-safe vehicle back from flight after landing , the concept of Flight Safety Corridor to secure in-flight safety performances early in the development and the introduction of Smart Detonators in the Flight Termination System are detailed in the next paragraphs.

2. Ground-based operations safety

2.1. CNES and JAXA Safety standards for ground-based operations

As the Vehicle is integrated and tested up to hot firing tests in Noshiro test Center (NTC) operated by JAXA in Japan and then flown from CSG, French Guiana, the Vehicle design shall cope with both Japanese and French safety standards.

On the Japanese side, the regulations are split in between "Management" (JAXA Management Requirements or JMR) and "Design Requirements" (JAXA Engineering Requirement Guidelines or JERG). [2]

On the French side, although the regulations could have been customized thanks to the demonstrator and sub orbital nature of CALLISTO, the Project Team has decided to make it compliant with the French Space Operations Act (FSOA) [9] as a core objective of the Project.

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The FSOA sets up a consistent regulatory framework to authorize and monitor space operations under French jurisdiction or for which the French Government bears international liability as a Launching State.

The goal to apply FSOA-related requirements to CALLISTO is to demonstrate the capabilities to fly and recover Space transportation vehicle from CSG under the most demanding safety standards and to pave an easier way for future (operational) vehicles.

A Design-to-Safety approach has been implemented to design a vehicle fitting both JAXA and CNES safety regulations. The outcomes are gathered in the CALLISTO Vehicle Design Rules which provide in a single document the set of safety requirements to be applied at Vehicle and Product levels as well.

This has been the opportunity to benchmark safety practices between the two Agencies on some specific topics such as electrical batteries charging when installed on vehicle and Maintenance and Repair Operations strategy for fluidics items in between two flights. [3]

2.2. Overview of CALLISTO Ground based operations

The vehicle Flight Model is integrated in Tsukuba Space Center of JAXA and transported to Noshiro Test Center (NTC) in Japan for dry and wet rehearsals and vehicle hot firing tests as well. The vehicle is then partly disassembled for transfer to French Guiana Space Center (CSG) where final combined testing will be completed ahead of Flight period itself. [3]

The following figure summarizes this approach as well as giving details about the different classes of flights that are planned at CSG.

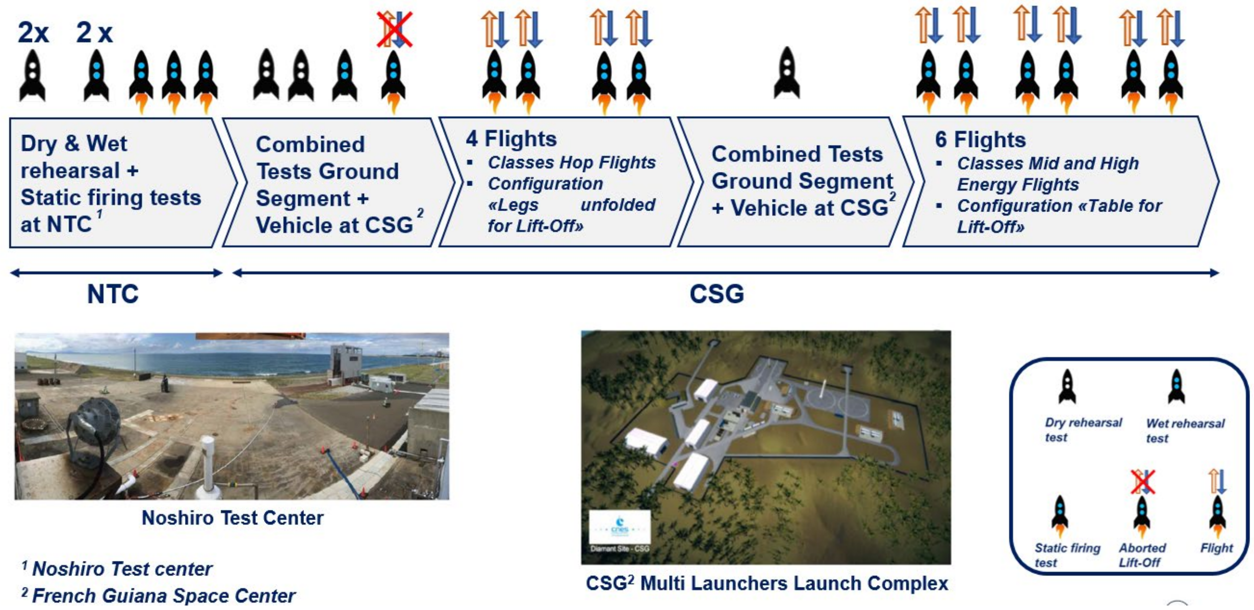

Figure 2 : NTC and CSG test plan overview

2.4 Operations at Noshiro Test Center (Japan)

At Noshiro Test Center, test tasks concentrate on Vehicle electrical and fluidics operations. From fluidics perspective, they encompass:

- Rocket propulsion system checks,
- Connection and disconnection tests of Ground Segment-To-Vehicle Fluidics interfaces,
- Filling, outgassing and drain operations of propellant tanks and fluidics system as well,
- Hot firing tests.

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These operations will benefit from the re-use of the ground installations of RV-X (Reusable Vehicle - eXperiment) Project [8].

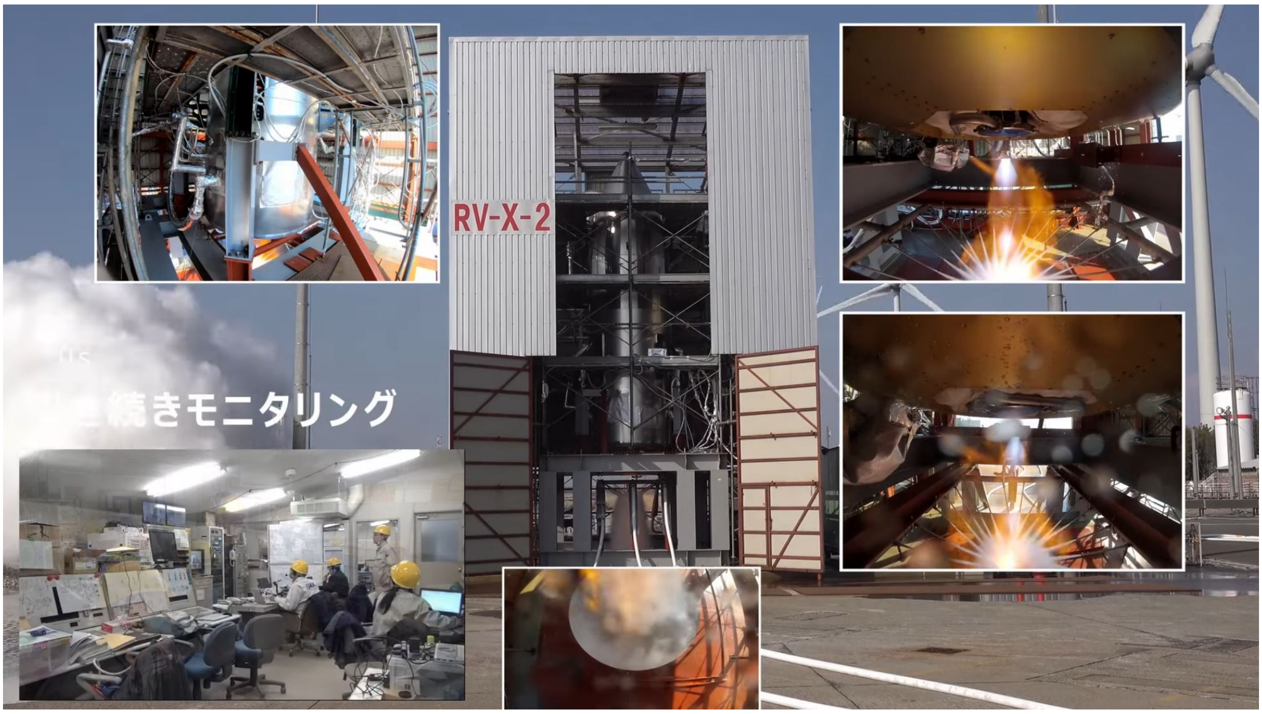

Figure 3 : RV-X hot firing tests in NTC [3]

The ground test setup includes:

- A torch to burn propellant during engine ignition sequence,
- Water discharge and trench for acoustic damping and thermal loads reduction,
- Gas detectors around vehicle and on facility, and gas collectors at outgassing vent port levels for management of explosive atmosphere and local thermal conditions.

These items are key for mastering induced environment and mitigating risks at Vehicle and Ground installations levels.

2.3. Solutions for operations safe at CSG (French Guiana)

CALLISTO operations at CSG will be performed at ELM (Multi Launchers Launch Complex). ELM is located at the launch complex which hosted the first launcher -dubbed “Diamant”- lifting off from CSG in the early seventies.

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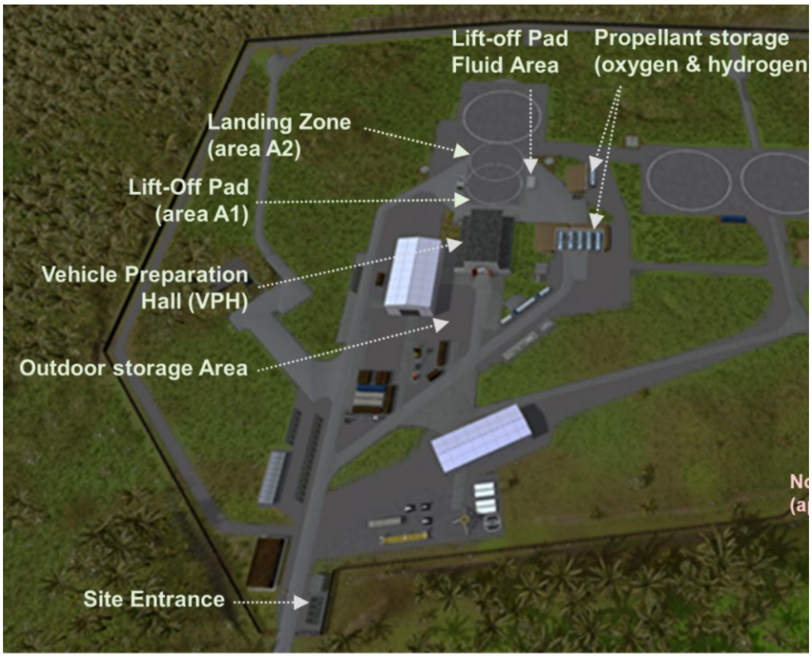

Figure 4 : ELM Launch complex – focus on primary installations for CALLISTO

Centre Spatial Guyanais (CSG) test activities involving the vehicle Flight Model are initially focused on the combined testing between vehicle and ground segment and then the flight period itself. From a fluidic perspective, the test activities tackle:

- Rocket propulsion system checks,
- Connection and disconnection tests of Ground Segment-To-Vehicle Fluidics interfaces,
- Propellant fill, outgassing and drain operations,
- Simulation of an aborted lift off including rocket engine ignition.

The challenge is to keep the installations as simple as possible, in line with the CALLISTO demonstrator spirit and short duration of operations at spaceport, while ensuring adequate level of safety.

2.3.1 Simplification of launch and landing areas

Two configurations are contemplated at Lift off Pad (see figure below):

- Vehicle standing on its ALS[1] legs (legs resting on the ground) for a first set of tests,
- Vehicle with ALS legs in folded configuration and standing on a small-sized lift-off table for the rest of the tests.

[1] ALS : Approach & Landing System

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Figure 5 : two different configurations ahead of Lift off

At Landing Zone, one primary constraint is that the area shall be cleared from any obstacle. This constraint leads to two subsequent impacts.
Firstly, the vehicle design and the operational concept have to deal with the absence of water discharge, trench, and propellant collectors (especially during the first steps of the safing operations after landing).
Secondly, as the very first pair of Test Flights is vertical without planned horizontal movement, any obstacle shall be cleared from the lift off pad prior to landing.

Therefore, installing a torch, a water discharge capability, a trench and propellant collectors is not an option at Lift off Pad compared to NTC ground test setup.

The absence of water discharge and trench leads to an increase in thermal and acoustic environments at Lift-Off to both surrounding installations and Vehicle itself. These environments are computed relying on RV-X data [8].

Regarding the absence of torch and propellant collectors at CSG, the risks of fire in case of gaseous hydrogen and oxygen release over long durations (e.g. propellant tank filling and engine chill down operations) are characterized based on:

- Lessons learned from DC-X program conducted in the nineties [6],
- Modelling activities for gaseous propellant dispersion and thermal and pressure effects in case of ignition.

Besides, the reduced-scale of CALLISTO is an opportunity with respect to environment protection. Indeed and looking at the CALLISTO vehicle only, i.e. excluding hydrogen and oxygen storage installations, the on-board hazardous products quantities –i.e. hydrogen, oxygen, hydrogen peroxide and explosives- are below the ICPE (Classified Installation for Environmental Protection) thresholds that would lead to consider it as hazardous for the environment in case of accident. [7]

This helped to relax the need for Lightning Protection System when the vehicle is outdoor especially.

Legacy launch complexes at CSG feature a Lightning Protection System, usually composed of four lightning masts (see picture below), which provides a protection against damages to the launcher walls and against induced overcurrent flowing through the launcher towards the ground.

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Figure 6 : Four lightning masts surrounding Ariane 5 at launch pad

From a human safety perspective, the CSG weather forecast management allows staff to evacuate danger area in due time in case of lightning strike risk alert.

From a vehicle damage risk point of view, an assessment has been conducted considering CALLISTO vehicle exposure to lightning strike based on lightning strike impact history at CSG. This risk, estimated lower than 1 over 10000 for the short duration of CALLISTO CSG campaign, has been deemed acceptable with respect to the overall mission success target and other reliability figures.

Therefore, as a major accident involving the vehicle on its Lift-Off pad is acceptable from (i) human
Safety, (ii) environmental and (iii) flight reliability perspectives, no Lightning Protection System will be installed for vehicle protection when outdoor. [3]

2.3.2 Post landing safing via remotely operated robots

CALLISTO recovery introduces the need to have post-landing safing that would ultimately allows staff access to the vehicle under safe conditions.

At touchdown, the vehicle status is the following:

- The engine is on,
- There are residual propellants –hydrogen, oxygen, and hydrogen peroxide- stored in pressurized tanks,
- The Flight Termination System is armed,
- Electro static charges have been accumulated on the vehicle,
- The ALS four legs structural dampers have been crushed under touchdown loads so that the vehicle may rest in a non-fully vertical position,
- The vehicle has been submitted to various aerothermal fluxes during re-entry and at landing (braking boost maneuver),
- The vehicle is exposed to French Guiana environment e.g. humidity, temperature and ground winds.

Besides, electrical power and helium –both critical for vehicle safing- have been largely consumed in flight and the vehicle conditioning system, relying on gaseous nitrogen during ground phases, is not operating (no active system during flights).
Time is now running for:

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1. stabilizing the vehicle against rapidly divergent risks (fire, propellant boiling leading to self-pressurisation e.g.)
2. supplying electrical power, gaseous nitrogen and gaseous helium budget to manage mid-term divergent risks (thermal runaway, moisture contamination) and finalize propellant tanks cleaning.

The first step is achieved automatically at touchdown, triggering a sequence to:
- shutdown the engine for mitigating the risk of fire,
- set the hydrogen tank to outgassing and then prevent a risk of burst under self-pressurisation due to hydrogen boiling,
- keep pressure in oxygen tank and start helium injection to alleviate the risk of geyser effect, i.e. the creation of a massive bubble flowing upstream the oxygen feedline that can ultimately damage the vehicle.

The Flight Termination System is then remotely deactivated by Flight Safety Officers.

At this point, the vehicle is stable but the residual propellant are such that it is not yet safe for staff access. Indeed, the safety regulation for ground phases imposes that neither single nor double failures lead to catastrophic events, so-called Fail Safe / Fail Safe criterion.
As the main remaining risks come from residual propellants- hydrogen and oxygen-, the priority is to reconnect the Electrical GSE (Ground Support Equipment) and Fluidics GSE to provide vehicle conditioning and clean the vehicle. This is performed via remotely-operated robots.

From safety perspective, these remotely-operated robots allow to exclude staff from the danger area during any vehicle operation involving usage of cryogenic propellants ahead or after flight.
They ensure safety functions, independently from the vehicle and have the capability to work where a human cannot, putting the staff away from the danger area. They can adapt to various types of interfaces and provide an enhanced repeatability of operations, as well as approaching the vehicle despite the ground floor high temperature after landing. Thanks to their versatility, they are the cornerstone of the lift off and landing operations contributing to functions such as:
- Disconnection of GSE-To-Vehicle interfaces prior to lift off,
- Reconnection of GSE-To-Vehicle interfaces after landing and in case of aborted lift off,
- Visual and thermal assessment of Vehicle health,
- Gas detection (Oxygen and Hydrogen),
- Firefighting.

3. Flight safety

3.1 Flight Safety Corridor concept

CALLISTO will be the first vehicle to be recovered at CSG following a Return-To-Landing-Site trajectory. It is designed to perform a set of flights ranging from low altitude Hops to flights featuring High Altitude manoeuvre.

CNES on one side and DLR & JAXA on the other side are developing two independent Guidance and Control (G&C) software; the guidance function computes and evaluates the trajectory and possible offsets vs. planned path and the flight control function tracks the trajectory and manages possible in flight perturbations and then commands actuators.

On legacy expendable launchers, the flight safety assessment -i.e. the risk assessment on third parties and installations in case of vehicle failure in flight- is based on the outcomes of all other design activities, in particular trajectory definition, G&C performances and launcher characteristics e.g. structural design and Flight Termination System (FTS) architecture.

It is based on design iterations that converge along the development cycle up to the flight considering experience from one launcher to the other (e.g. Ariane 5 to Ariane 6, Vega to Vega-C) as well as the safety-by-nature configuration of the CSG geography and in particular down range areas: open seas of Atlantic Ocean from North to East.

Such method is not adapted to CALLISTO. The lack of in-flight experience regarding G&C achievable performances in particular for high altitude manoeuvre and re-entry and the development in parallel of 2 G&C systems led to adopt a Design-to-Safety approach designated as Flight Safety Corridor.

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The Flight Safety Corridor is a kinematic interface specification, expressed as position, velocity and slope errors versus nominal trajectory along each altitude.

On Flight Safety side, the Flight Safety Corridor is used to check as early as possible the acceptability of a given trajectory. This specification is the baseline to define the limits beyond which the flight is terminated. Flight safety assessment is performed to check that 1) the resulting debris fall within a safe area and 2) that the limits can be operated by the Flight Safety Officers in term of workload considering anticipated vehicle behaviour in case of failure (e.g. in case of malfunction turn).

On G&C side, the Flight Safety Corridor constraints are taken into account for the design associated with a reliability objective to overshoot the specification.

The main benefits from this approach are the following:

- It is safe by design: in case of vehicle excursion from the Flight Safety Corridor, the risk is to have a flight termination. However, it would occur under safe conditions and the consequences would then be limited to mission loss.
- It mitigates the risk to have a late showstopper in the development coming from Flight Safety: as the safety performances are specified early in the project, G&C can be designed to operate within a domain that takes into account all constraints : Loads, flight control capability, propulsion system capability and Flight Safety. The Flight Safety performances can then be monitored along the project.
- It allows CNES and JAXA/DLR G&C systems to be designed in parallel: on legacy launcher, quick design iterations can be set to check Flight Safety compatibility and to adapt, as required, trajectory and G&C performances. On CALLISTO, as 2 G&C systems are developed in parallel, with different strategies and performances, the adaptation of the trajectory to alleviate the Flight Safety risk for one G&C could degrade the Flight Safety performances of the other. Providing a clear Flight Safety Corridor applicable to both early in the development phase is a smart way to proceed.

The main challenge of the Flight Safety Corridor approach is to find the optimised balance between:

- An acceptable Flight Safety performance, considering that input for flight safety analysis such as vehicle characteristics and trajectories are likely to change along the development, and
- Achievable G&C performances that can match the Flight Safety Corridor with expected reliability.

This balance is challenging considering the lack of experience on achievable G&C performances e.g.
Nevertheless, the recently passed milestones are confirming the feasibility of what is one of the core objective of CALLISTO demonstration.

3.2 CALLISTO Flight Termination System highlights

The Flight Termination System (FTS)[2] is an in-flight safety system which allows to protect third parties, properties and environment. It provides, independently from the functional avionics, the localization of the vehicle to the Flight Safety Officers and, in case of vehicle failure, the FTS ensures the vehicle destruction before it becomes hazardous. Such systems are common on European launchers taking off from the Guyana Space Center. However, CALLISTO vehicle raised some new challenges because of its reusability, relatively small size and specific flight domain remaining in "close" area from CSG when compared to Launchers travelling to orbit either eastwards (GTO) or northwards (SSO).

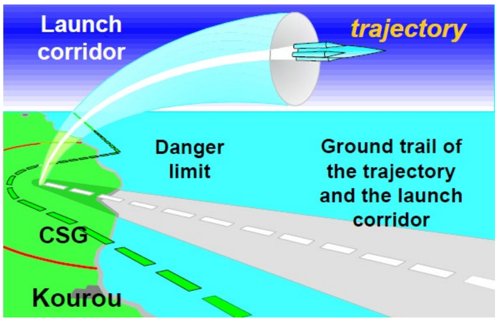

Figure 7: Termination domain principle during flight

[2] For CALLISTO, the Flight Termination System is dubbed Flight Neutralization System (FNS)

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The FTS architecture choice was therefore driven by new parameters.
For instance

- To ease the vehicle reusability, digital bus were preferred to classical pyrotechnical transmission lines [10],
- Innovative Localization system on board will be activated step by step with the opening of the flight domain from standard on-ground set of radar stations to GNSS system,
- Small antennas derived from COTS items,
- small and smart detonators integrating different functions were chosen to cope with the small size of the vehicle and its mass constraint,
- A new avionics flight safety kit is developed to manage all the onboard safety equipment units and its communications with the launch range,
- The Flight Termination System communication is fully digital.

Nevertheless, usual design drivers are also to be considered. The system shall be compliant with the Launch range safety rules. As CALLISTO is a demonstrator, its reliability has to cover the potential higher risk of vehicle failure . Therefore, the system combines flight proven solutions for the end-effect neutralization items and innovative solutions as listed previously.

Finally, the global architecture is figured below. It is a Fail Operational architecture with a segregation and redundancy of neutralization channels. The vehicle localization is performed with various sensors type (radar, GNSS, ground cameras…). The FTS configuration might be adapted depending on flight features (altitude e.g.).

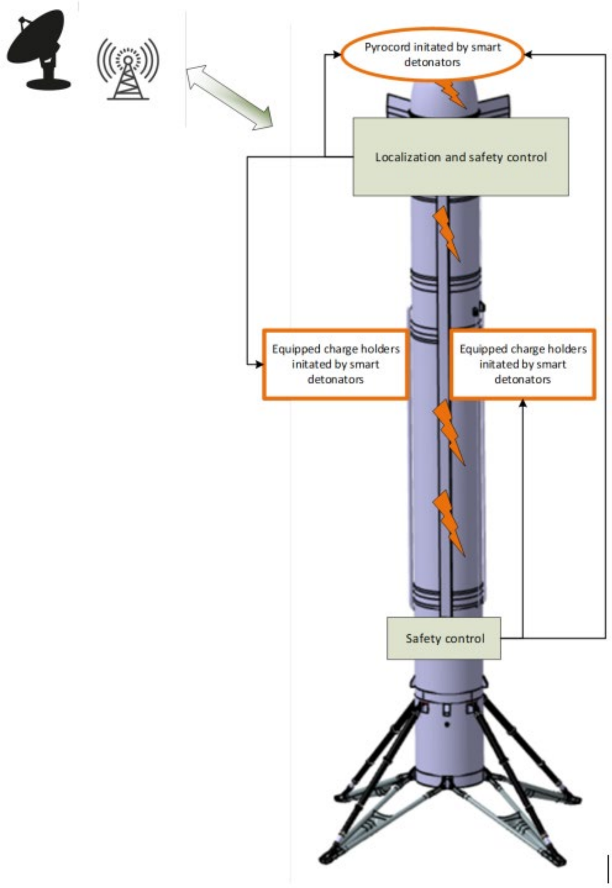

Figure 8: FTS Architecture – simplified view

4. Way forward

As the Flight Models products are on their way for manufacturing, the focus is moving toward the operational aspects. As an example, the Flight Safety Officers procedures have to be updated to cope with the RTLS trajectories including human factors (man-machine interface) and training aspects.

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From safety point of view, CALLISTO fuels the need for getting evolving the French Safety Operation Act (FSOA) for re-usable launchers. This work is performed in tight coordination with the FSOA office and CSG safety department.

Besides all technical achievements and in line with post Ariane 6 CNES strategy, CALLISTO project contributes to develop the excellence of the CNES Space Transportation Directorate engineers' technical skills. In return, they will be ready to support the private launchers initiatives to come to CSG.

Looking at the European launchers exciting times to come, CALLISTO team motto is to tackle as many questions as challenges on the roadmap toward next generation reusable launchers.

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