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Concept of Operations - CALLISTO demonstrator

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Abstract

In the frame of the preparation of future launchers generation aiming at a timeframe beyond Ariane 6's first flight in Europe or H-III in Japan, CNES, the French Space Agency, is involved in a reusable vehicle project called CALLISTO under an international partnership agreement with Japanese and German Space Agencies, namely JAXA and DLR
CALLISTO vehicle is a first stage-like (or booster) in-flight demonstrator about 13 meters high.

This paper will describe different studies focusing on the concept of operations. Its three main periods include vehicle assembly and integration in Tsukuba Space Center of JAXA first, then completion of hot firing tests of assembled vehicle in Noshiro Test Center, and finally a set of Test and Demo Flights from the European Spaceport in French Guiana and refurbish down time in between two flights.

The CALLISTO project features **a long list of specificities** and faces numerous and severe induced constraints that strongly drive the design of the concept.

The challenge in designing a concept of operations that meets ambitious specifications include:
-Perform as much as 8 Test Flights with increasing flight envelope and landing on 2 different areas,
-Perform 2 Demonstration Flights landing on a barge in open seas,
-Operate the campaign inside a launch range that is fully operational,
-Optimize the duration of flight campaign over half a year or so,
-Carry out the vehicle refurbishment in between two flights with very limited accessibility,
-Manage LH2 and LOX residuals inside propellant tanks at landing with as less as possible of on-board functions,
-Manage operations of H2O2 fuel of Flight Control System/Reaction (or RCS),
-Reduce the natural environment impact to operations.

Many constraints and very ambitious objectives mean that many studies are concluded including **trades-off** and the need of reaching an acceptable baseline when all criteria cannot be fulfilled at same time.
Meantime, CALLISTO offers also opportunities according to its reduced dimensions and the low mass of the vehicle when compared to operational mid or heavy launch systems.
Another opportunity is to benefit from and share lessons learnt from each agency experience.

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The design of the concept of operations up to phase B must cope with the definition of specifications at top level and at the same time reduce the possible options via architecture choices.

The flight campaign concept of operations definition is closely dependent on assembly operations performed in Japan. It is conducted within a small CNES Architect team who interacts with the Vehicle design offices, the ground segment teams in charge of facilities design, AIT responsible in a close partnership involving JAXA and DLR teams.

1. Introduction

CALLISTO is a small scale experimental demonstration project of a recovery and reuse launcher first stage. It takes off and lands vertically after a toss-back maneuver.
It will be tested in flight in 2022 from a selected site in the French Guiana Space Center.
The demonstration consists in exploring the complete life cycle, acquiring sufficient knowledge to assess critical technologies and quantifying the technical and economic interest of carrying out this recovery technique on a larger scale, larger flight envelope and recurrent operation of RLVs.

Phase A of the project started after the signature on 20 June 2017 at the Paris Air Show of a trilateral cooperation agreement between the Japan Aerospace Exploration Agency (JAXA), the Deutches Zentrum fur Luft-und Raumfahrt E.V (DLR) and the Centre National d'Etudes Spatiales (CNES).

This paper describes different studies focusing on the Concept of Operations (CONOPS).

2. CALLISTO and flight campaign overview

The main characteristics of the CALLISTO Vehicle are described hereafter:

Figure 1: CALLISTO Vehicle

Length: around 13,5 m
Diameter:1,1 m
Weight at lift-off: around 3,5 tons
Main Propulsion propellants: LOX/LH2
Full thrust: around 44KN
Reaction Control System (RCS) propellant: H2O2 (Hydrogen peroxide)
Approach and Landing System (ALS): 4 legs

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The main objective of the demonstration campaign is to perform, during a downrange trajectory, a toss back and landing maneuver in a 10m radius target after deployment of the feet and a braking re-ignition. In order to reduce the risk of a single attempt, the flight range is progressively widened during test flights period with a vertical trajectory. The initial lift-offs are performed with legs deployed, while the next ones are performed legs folded with their deployment during the descent as for the demonstration mission.
Thus, the campaign includes as much as 5 different flight paths.
As part of the cooperation agreement, the 3 partners have agreed to embark on the vehicle alternatively a flight software program provided by CNES and JAXA/DLR.
Each mission is carried out twice and in total the vehicle completes 8 test flights and 2 demonstration flights.
The duration of the flight campaign in French Guiana is fixed at 9 months in total, including a period of 6 months dedicated to flights. The remaining 3 months are mainly allocated to combined tests between the Ground Segment and the Vehicle.

3. Concept of Operations (CONOPS) - Activities in CALLISTO project

What is the scope of CONOPS activities in CALLISTO project?

There are certainly different ways to implement the CONOPS studies, depending on the characteristics of the project. Anyway the CONOPS studies refer generally to a description of how a set of capabilities may be employed to achieve desired objectives or end state.

From High Level Requirements listed below:

- Development and campaign costs
- Optimization of the duration of the campaign: by maximizing the number of flights over a fixed period of campaign
- The constraints of Vehicle mass and lay-out
- The propulsive system imposed with the couple LOX / LH2
- The application of the regulation of the Space Port facilities - [1],

defining the technical objectives of the campaign, the technical-economic constraints that have strongly guided the Concept of Operations, we intend to find in our CONOPS usual properties as:

- Organizations, activities, and interactions among participants and stakeholders
- Operational strategies
- Constraints affecting the CALLISTO Architecture including interfaces between the Vehicle and the Ground Segment, with potential impacts on their design.

CONOPS activities have started in phase A of the project (closed by System Requirements Review) with the objective of identification of the specificities, the stakes, the main orientations but also permanent design and programmatic drivers of the project.

From phase A, there are architectural choices that have required trade-offs or targeted studies to evaluate physical phenomena. This information is gathered in the CONOPS file in coherence with the first definitions of the Ground Segment and the Vehicle.

The current phase B (that will be closed by the System Preliminary Design Review), has identified 60 operational requirements grouped together in a specification document covering organization,

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operability, equipment accessibility, checkout logic and a list of constraints (mainly safety constraints). These requirements have been cascaded to the Technical Requirement Specifications of the products.

The 10 structuring choices include:

- The design of the Ground Segment infrastructure, with a single and compact area for preparation activities and test flights.
- The integration of the vehicle horizontally.
- The clustering of the interfaces with the Ground Segment at the bottom of the Vehicle.
- H2O2 filling operations for the RCS carried-out manually during the Vehicle preparation in VPH (see figure 7).
- LOX and LH2 propellant tank filling operations carried-out remotely (ahead of flight).
- Vehicle safing operations after landing carried-out in 5 steps using all possible modes: automatic, remote mode, manual.
- As little dependency on the Launch Range as possible in the flight data preparation and processing activities.
- A short duration of refurbishment between flights.
- Preventive maintenance between flights defined according to the criticality of the functions
- Checkout between flights favoring global controls.

Some of these design features of the CALLISTO project are closely related to the reuse of the vehicle. At this stage of the new project, we are also convinced that we have not identified them all, especially in the field of maintenance.

The relations between High Level Requirements and concept choices are shown in the diagram below:

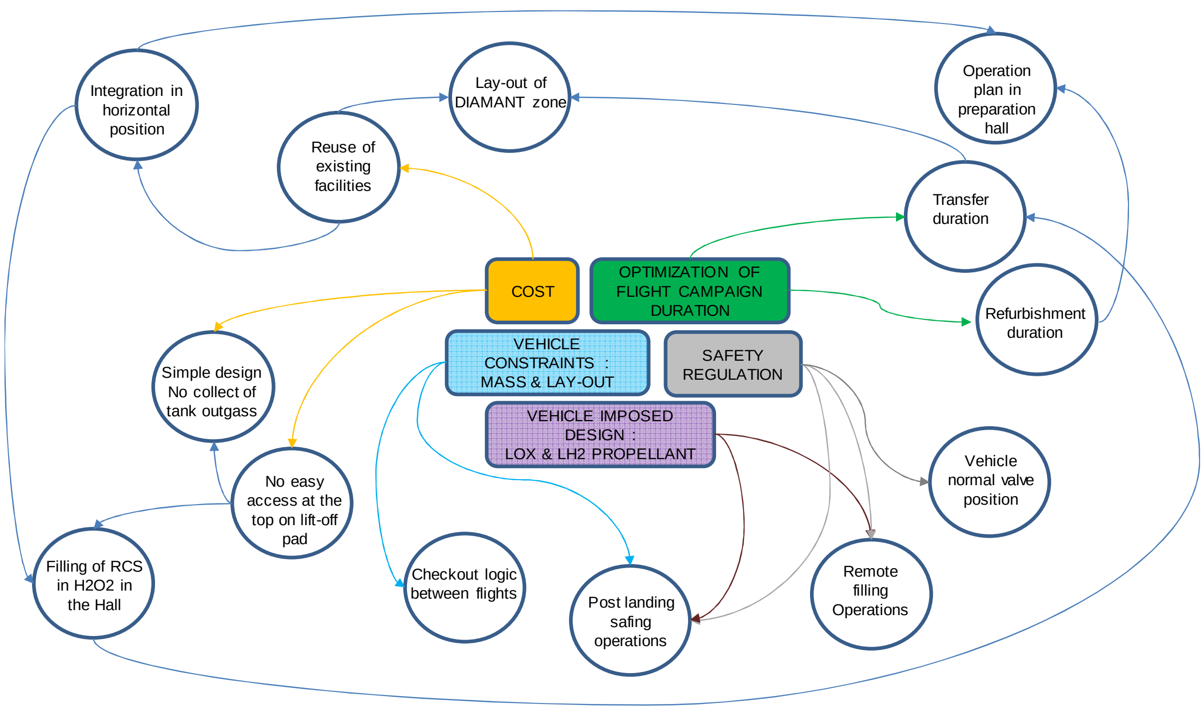

Figure 2: Relations between CALLISTO High Level requirements and concept characteristics

We will detail the content and the consequences of these choices in the sections dedicated to the life cycle, the ground means, the operations.

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4. CALLISTO life cycle overview

The CALLISTO life cycle encompasses all the steps from the design and products manufacturing to the Vehicle flights. Part of this life cycle is presented below, including Vehicle modules and Vehicle integration activities in France and in Japan (Tsukuba and Noshiro).

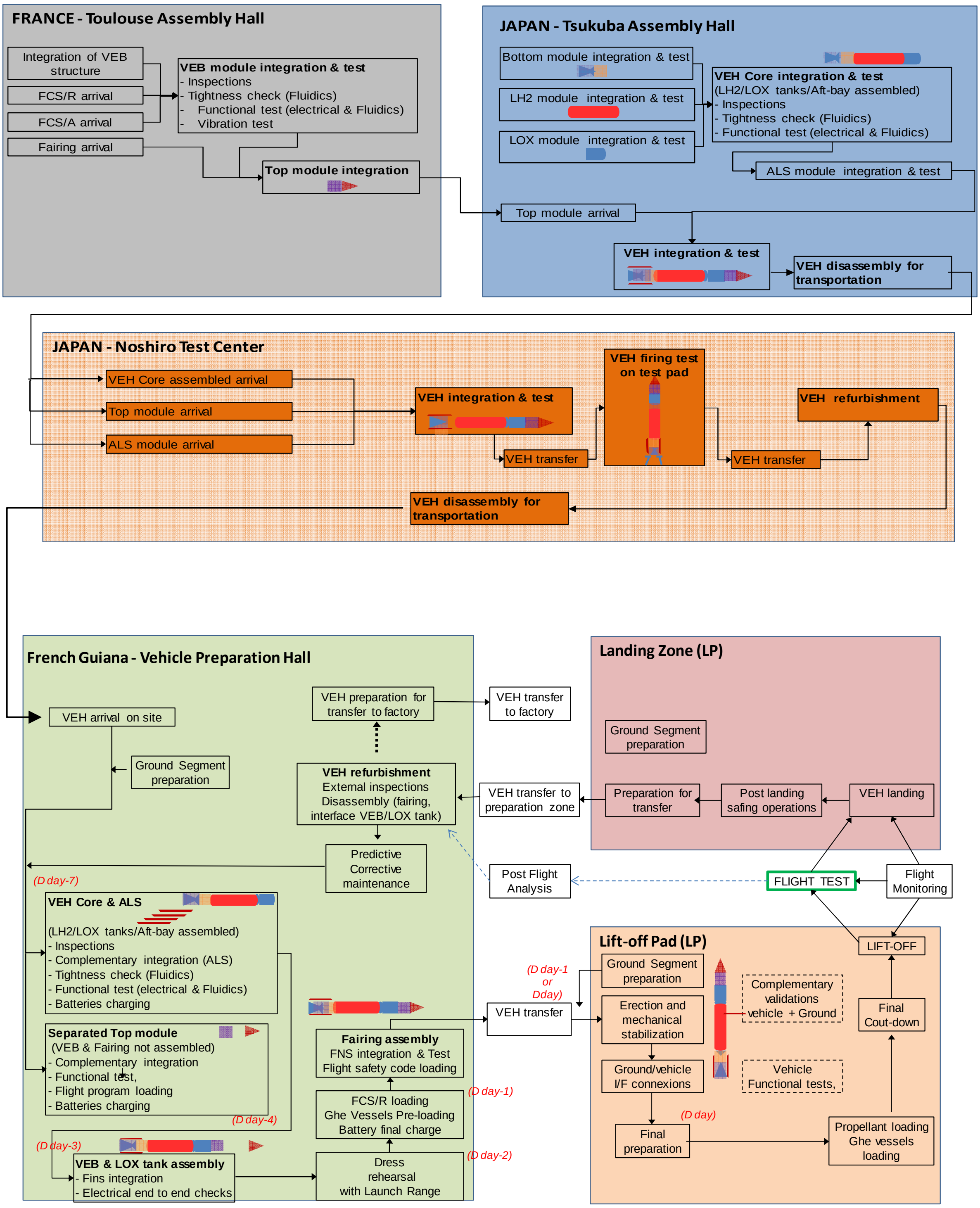

Figure 3: CALLISTO life cycle overview

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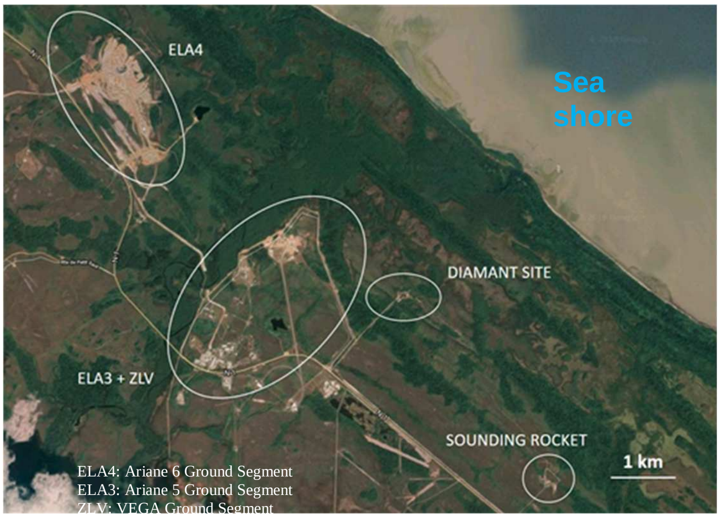
5. Optimization of the flight campaign duration

One of CALLISTO High Level Requirement is that the design of the Vehicle and the Ground Segment must lead to achieve the maximum number of flights in a given campaign duration.
From phase A studies, carrying out the flight test campaign in the French Guiana Space Port without disrupting commercial flights appeared as a strong constraint.
Based on assumptions and experience, a rough scheduling activity has been carried out incorporating a logic of validation tests between the Vehicle and the Ground Segment.
The result leads to an ambitious operational requirement of preparation and maintenance duration between flights: the minimum turnaround time between flights shall be 7 days, of which 6 days are dedicated to maintenance operations.
This duration is similar to the 1rts specification of Delta Clipper-X [2] turnaround time in the 90's.
This requirement leads to design the Vehicle in order to minimize change of configuration with heavy disassembly and to favor global controls in the checkout logic.

6. French Guiana Ground Segment overview

From DIAMANT to CALLISTO
After several studies and relevant trades-off, the decommissioned Diamant zone, inherited from the French launcher program of the same name, has been selected to carry out most of the activities.
Once the area has been chosen, the reuse after refurbishment of the facilities still in good condition has made it possible to confirm choice relevance.
The landing areas are located on the Diamant zone for the first 8 Test Flights, whereas the landing area is still under studies, located in open seas inside a quadrilateral area for the 2 Demonstration Flights (the 469 reference landing spot is at 22 km from Diamant site).



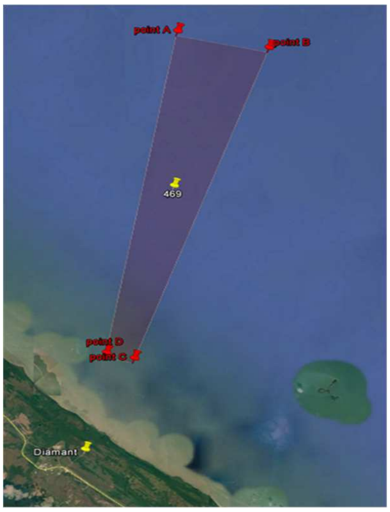


Figure 4 and 5: Diamant site (left) and open seas landing zone (right) locations

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The area as it was during the launch of the Diamant rocket in the 70's is presented below:

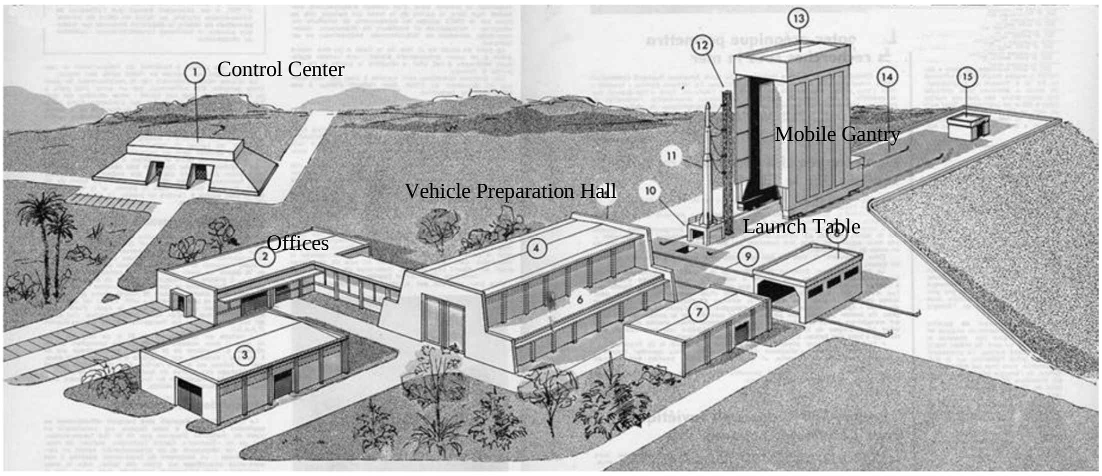

Figure 6: Diamant site in the 70's

The very interesting concept of the Diamant Zone was that it was compact with all the facilities gathered within a radius of 120m around the Launch Pad. From these facilities, the Vehicle Preparation Hall, the concrete slab, some buildings and the roads will be reused after renovation. This configuration offers the same advantages by regrouping the main facilities. The mobile gantry will be removed.

The area lay-out for CALLISTO operations is presented below:

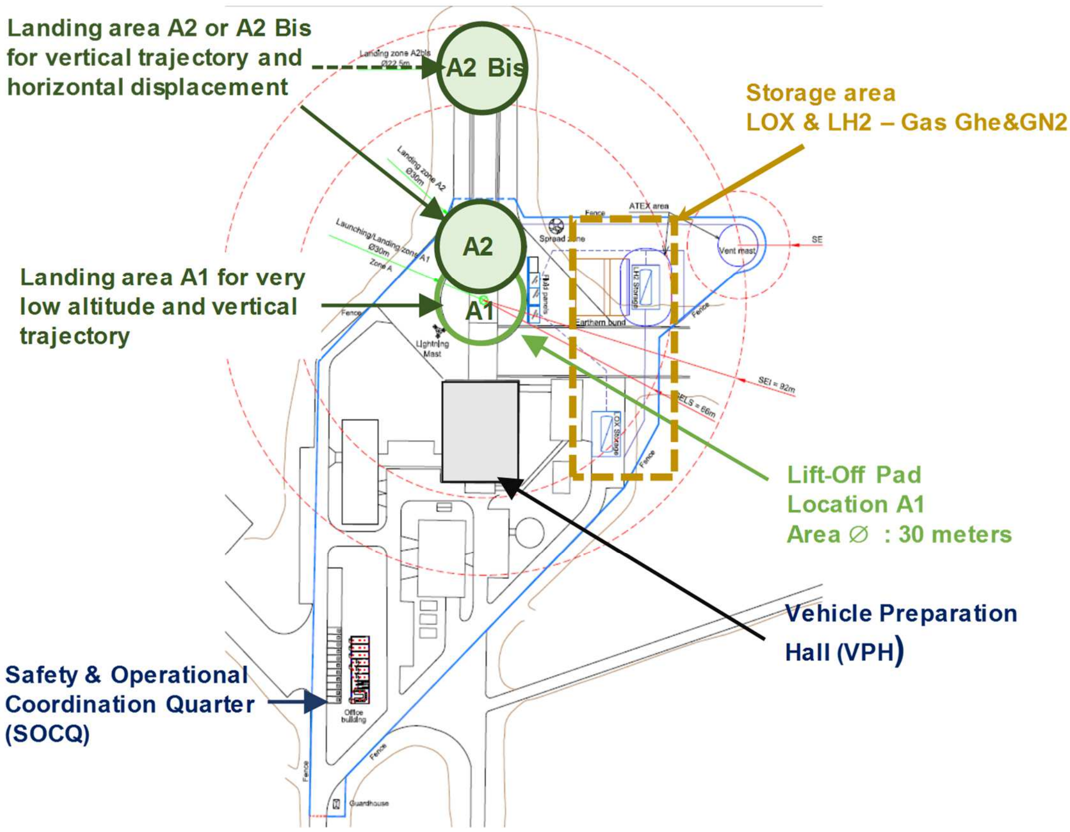

Figure 7: Lay-out of CALLISTO Diamant site

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3 areas are identified during the life phases of the vehicle inside the Diamant site of CSG:
- Preparation area (Vehicle Preparation Hall)
- Lift-off area (Pad on A1)
- Landing area on ground (on A1, A2 or A2bis areas, depending on the flight type)

A fourth one is the open seas landing area required for the Demonstration Flights. The type is still under analyze, either a floating barge or a fixed platform.

4 relevant additional facilities are required to carry out the operations and are part of the Ground Segment:
- Command Control Center (CCC), located at 3,5 km of Vehicle Preparation Zone (formerly CCC for Ariane program).
- Headquarter (HQ), localized inside the CCC to shelter campaign authorities and design authorities with communication means with their rear base.
- Safety and Operational Coordination Quarter (SOCQ) at the entrance of Diamant site.
- Launch Range.

This concept allows short distance between the different areas, therefore implies short transportation duration of the vehicle and optimization of the working hours.

7. Vehicle preparation in Hall

Horizontally integration concept

The small size of the vehicle, particularly the diameter, the availability of the Diamant Vehicle Preparation Hall and thus the possible economy of a gantry on the lift-off pad, quickly led to select the concept of a horizontal integration. Moreover, this choice is entirely compatible with the Assembly Hall at Tsukuba and with the Noshiro Preparation Hall in Japan (JAXA facilities).

The Vehicle is delivered in French Guiana in 2 main assembled parts, in containers transported by air from Japan on their integration carts

The elements are unloaded on their carts, and positioned in the Vehicle Preparation Hall then inspected, tested and prepared until assembly. At the end of the preparation, the RCS is filled also in horizontal position just before the transfer of the Vehicle to the lift-off pad.

Operation plan overview

The operation plan includes a 1rst part of 4 days carried-out on the assemble VEH core on one side and on the Top module on the other side and a second part of 3 days on the assembled vehicle except the fairing.
The transfer is foreseen to be carried-out at the end of Dday-1 or at the early hours of the day of flight.

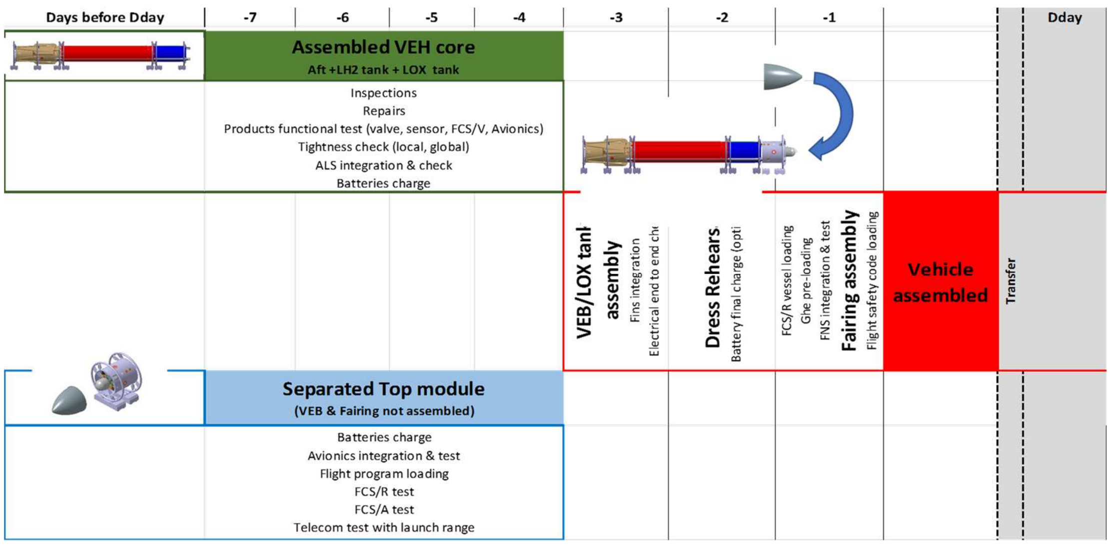

Figure 8: Operation plan overview of the Vehicle preparation in Hall

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8. Vehicle preparation on Lift-off Pad

Operations to prepare the Vehicle on the Lift-off Pad are described in the schematic hereafter:

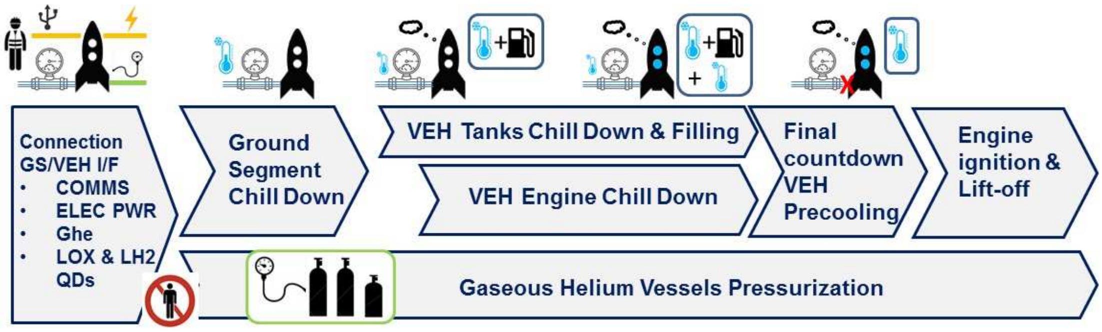

Figure 9: Vehicle main operations on Lift-off Pad

After transfer, the Vehicle is erected and positioned of its legs or on the lift-off table vertically (depending on the mission) with a crane. Then the operations of the countdown are started.
For safety reasons and for vehicle performance justification, the concept for filling operations is based on remotely operations.

Operation plan overview

It is foreseen to perform the complete countdown before lift-off in less than 5 hours and the post-landing safing operations in less than 5 hours also.
The time to go back to the preparation hall is short) in case of landing on ground (less than 1 hour and will be dependent on the recovery scenario and should be less than 2 days.

9. Post landing Vehicle safing operations

Vehicle recovery operations after landing are sequenced in 5 phases:

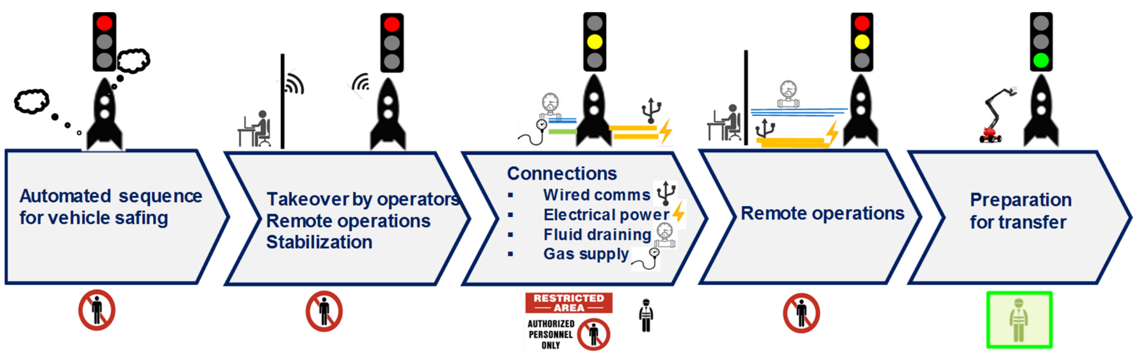

Figure 10: Post landing Vehicle safing operations

Phase 1: Automated sequence for Vehicle safing

The objective is to safe as soon as possible after landing the vehicle up to a stable state:
- Engine shut down and purged,
- LH2 tank and LOX tank isolated from the engine,
- LOX and LH2 tanks depressurized and in free outgassing
- Pyrotechnic components disarmed of the Flight Neutralization System.

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Phase 2: Post landing takeover of the vehicle by the operators and stabilization

During this phase, there is:
- First a complete vehicle status check
- Additional safing operations if needed
- A long phase of stabilization
- The monitoring of the vehicle.

The objective at the end of phase 2 is to obtain criterias required to authorize staff access and in particular the reduction of LH2 residual propellant that also implies a reduction of LH2 outgassing mass flowrate.

The duration of this phase 2 is assessed at around 1 hour.
The operations are carried-out by operators from the Control Center via wireless connection.
Particular attention will be paid to the risk of explosion and fire in the lower part of the vehicle, in the engine compartment, in the inter-tank compartment and in the Vehicle Equipment Bay.
Specific monitoring will be established on the necessary functions (pneumatic and energy) for the end of Vehicle safing operations.
Stabilization is to be understood from the point of view of pressure and heat.
Thus, some parts of the heated vehicle during the flight mission will return to an ambient temperature or cooled again by the presence of residual propellants. Other parts of the vehicle will warm up after the purge of engine lines.
During the stabilization, the monitoring should be maintained in intermittent mode and the normal position of the valves corresponds to the safety state of the vehicle. In particular, the tanks are in free outgassing.
So, no valve command is required in nominal case.

Phase 3: Connections by operators

To avoid increasing the Vehicle mass with equipment that is not necessary for the flight phase, the Vehicle autonomy is reduced to phases 1 and 2 necessary to obtain the access conditions of the operators. So first the objective of connections is now to provide to the Vehicle the main functions necessary to progress in the safing operations. The mechanical stability of the vehicle is improved by clamping Vehicle legs on the ground.

The authorization is limited to a reduced team of operators (between 3 to 5 people) and requires access means because the connectors are located between 2.5m and 3m from the ground. In the case of the demonstration mission with landing on barge, this autonomy duration also allows the operators to be able to reach the spot.

In second time, the objective is to provide the functions to remove completely the remaining propellants by LH2 and LOX fluidics connections to be able to drain and flush the tanks and lines

During this phase and until the end of connections, the monitoring of vehicle is continuous and performed only via WiFi mode. Indeed, the telemetry emission is switched off for operator safety. The weather conditions are also constantly monitored: speed and wind direction with a 30 minutes' availability, risk of lightning and rain hazard, and swell in the case of landing on barge.

Phase 4: Draining and flushing

The objective of this phase is to safe the Vehicle in a state allowing its transfer to the Vehicle Preparation Hall by:
- A complete removal of the residual propellants in LOX and LH2 tanks
- Flushing the LOX and LH2 tanks and lines in neutral gas
- Simultaneously depressurization of the GN2 RCS capacity and flushing RCS lines
- Depressurization the HP Ghe capacities.

Operations are carried out remotely from the control room after evacuation of the operators beyond the hazard distance.

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Phase 5: preparation for transfer back to Vehicle Preparation Hall

When the cleaning criteria have been obtained and the capacities depressurized in accordance with the safety margin, the Vehicle is now considered safe and the operators are authorized.

In case of landing on barge, 4 scenarii to go back to the Space Port are still under analysis:
- In vertical or horizontal position
- By sea on the landing platform or by helicopter.

The legs are dismounted before putting the vehicle back on its integration carts and then brought back to the Vehicle Preparation Hall.

Trade-off carried out to define the concept of post landing safing

The main trade-off carried out have focused on the Vehicle state at the end of phase 2 to authorize the staff access.
In fact, several constraints and objectives led to contradictory solutions with regard to the position of the vehicle's valves, energy consumption and risks (fire and explosion).

The application of the following principles has finally led to the choice of a currently baseline architecture:
- The safety state of the Vehicle at the end of phase 2 must be stable. Any closing of the LOX or LH2 tank vent line causes a tank pressure increase opposite to the safety state.
- A direct consequence of the previous principle is the presence of H2 and O2 clouds near the vehicle. The risks induced have to be analyzed in priority.
- The power consumption being a problem considering the batteries weight and occupied space and also in case of loss by simple failure (simplex architecture), the normal position of the valves must lead to the vehicle safety state.

10. Possible evolutions of the Concept of Operation

The Concept of Operations has been stabilized since phase A but it is not yet frozen.
Evolutions may be necessary to fit with Vehicle design modifications or to improve operational performance.
In this latter category, the use of robots in the critical phase of post-landing operations could lead to a fundamental review of the current Concept of Operations. [4]
The aim would be to reduce the duration of the post landing phase 2 operations described above, by freeing up the safety constraints and by drastically reducing the time due to the transportation of operators.
In this new approach, performing the connections of fluid and electrical umbilical with robots would impact the overall current logic, would question fundamental choices and release design constraints going well beyond the post-landing phase.
It provides opportunities
- to reduce the power and pneumatic budget of the vehicle to the benefit of a mass reduction
- to simplify the hot topic of compartments conditioning
- to diagnosis the Vehicle State with Ground Segment means

These tracks offer many innovations in the frame of operations on a reusable Vehicle. The feasibility to introduce these modifications in the Concept of CALLISTO Operations is already under analysis.

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11. Summary and conclusion

- On the CALLISTO project, a reusable rocket demonstrator, ground phase operations are a major challenge because of the specificities of the Vehicle and the post-landing safing phase and are part of the experience and know-how that must be transmitted to a future RLV.
- The definition of the CONOPS is part of the activities assigned to the System Architect. By nature, it participates therefore in ensuring overall consistency between the high-level objectives of the project and the requirements cascaded to the products in the frame of ground phases.
- The CONOPS is strongly related to the definition of Vehicle operations and interfaces between the vehicle and the Ground Segment. It takes in account technical risks, human factors and the environment.
- Robots could introduce much more than a simple innovation. It could change deeply the way to perform efficient operations while preserving the safety of the operators.

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[2] Translating SSTO system operability and supportability requirements into measures of system effectiveness – Delta Clipper program: AIAA 96-4247
[3] Description of Diamant program and facilities: http://www.cnes-csg.fr/web/CNES-CSG-fr/9849-ensemble-de-lancement-diamant.php
[4] EUCASS 2019 - Smart Operations in ATEX RLV Environment - Massimo FERLIN, Michal KURELA

Acronyms and definitions

AIT: Assembly, Integration, Test
ALS: Approach and Landing System
CALLISTO: Cooperative Action Leading to Launcher Innovation in Stage Toss-back Operations
CCC: Command Control Center
CONOPS: Concept of Operations
CSG: Centre Spatial Guyanais = French Guiana Space Port
FCS/R = RCS
GHE: Helium gas
GN2: Nitrogen gas
HP: High Pressure
HQ: Headquarter
LH2: Liquid Hydrogen
LOX: Liquide Oxygen
PDR: Preliminary System Review
RCS: Reaction Control System
SOCQ: Safety and Operational Coordination Quarter
RLV: Reusable Launch System
VEH: Vehicle
VPH: Vehicle Preparation Hall