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CALLISTO demonstrator and Operations in CSG – French Guiana: status of scenario

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The CALLISTO vehicle is a flight demonstrator for future reusable launcher stages and their technologies. 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 knowhow includes Products and Vehicle design, Ground Segment set up, and post-flight operations for Vehicle recovery then reuse.

Concentrating on operations in CSG and facing numerous and unique constraints [R1], CALLISTO Project has revisited several top requirements and Operational Requirements as well during design maturation process. Main evolutions include, for instance:

- The increase of turnaround time between flights,
- Landing on ground (close to Lift-Off Pad) instead of a barge in open seas.

Anyway, the initial core choices of Architecture design and Concept of operations [R1] were confirmed. Taking into account feedbacks from Vehicle and Ground Segment designers, several innovative choices were introduced especially robots [R2] in charge of:

- Reconnection of Safety-critical functions after aborted Lift-Off and landing,
- Disconnections of these same functions ahead of Lift-Off,
- Initial inspections after landing.

Having in mind that the campaign and the set of flights at CSG is supposed to be completed in one row and that Vehicle lay-out optimization is performance (in flight) driven first, the risk in drifting of operations duration must be mitigated.

A fair balance between the operational efficiency during ground phases and the inflight performance shall be mastered early in the course of development and ahead of major design decisions for Vehicle design.

Several key drivers provide degrees of freedom, as

- The devoted effort ahead of the French Guiana Campaign for (i) validating operations to be conducted in CSG and (ii) training of staff as well,
- The life time of products and their mean time-in between failure and then planning of maintenance and its duration,

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- The level of effort allocated to re-check flightworthiness between flights impacting the revalidations testing time line,
- The Vehicle limitations vs. natural environment resulting in availability constraints and then possibly undesired waiting phases.

The Concept of Operations maturation and challenges regarding flight preparation and Maintenance & Repair Operations (M&RO) definition are detailed in this paper.

Abbreviations

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
CFRP	: Carbon Fiber Reinforced Polymer
CONOPS	: Concept of Operations
CSG	: Guiana Space Center
ELM	: Multi-Launcher (launch) Complex
EQM	: Engineering & Qualification Model
FCS/A	: Flight Control System/Aerosurfaces
FCS/R	: Flight Control System/Reaction
FCS/V	: Flight Control System/Vectoring
FM	: Flight Model
GHe	: Gaseous Helium
GN2	: Gaseous Nitrogen
HP	: High Pressure
HQ	: Headquarter
LH2	: Liquid Hydrogen
LOX	: Liquid Oxygen
LP	: Lift-off Pad
M&RO	: Maintenance & Repair Operations
MGSE	: Mechanical Ground Support Equipment
NTC	: Noshiro Test Center
OCC	: Operational Control & Command (center)
PDR	: Preliminary Design Review
QD	: Quick Disconnector
RLV	: Reusable Launch Vehicle
SM	: Structural Model
SOCQ	: Safety and Operational Coordination Quarter
TPS	: Thermal Protection System
VEB	: Vehicle Equipment Bay
VEH	: Vehicle
VPH	: Vehicle Preparation Hall

1. Introduction: CONOPS top requirements

CALLISTO is a demonstration project of recovery and reuse of core stage(s) of space launch system: it is research, technology and system demonstration oriented. It takes off and lands vertically at same place (or very nearby from Lift-Off Pad) and is supposed to be flown several times in a row. It will be operated in CSG, the European spaceport located in French Guiana.

When compared to a Heavy-class Launcher (weight at take-off beyond 700 metrics tons and height as much as 50-60 meters tall), CALLISTO is a small vehicle: 3+ metric tons at lift-off and 10-15 meters high.

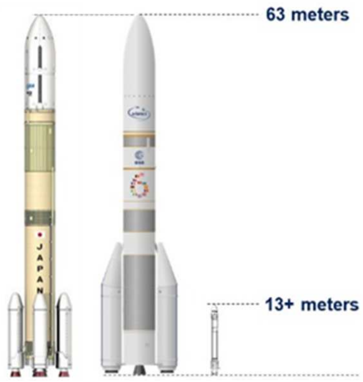

Figure 1 : CALLISTO sizes vs. Heavy Lift Vehicle

From operations standpoint and according to background history of CSG and its heritage in operating launch systems for 50+ years, to have vehicle returning back home and getting

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it flying again are the brand new life phases to manage.

The top Level requirement for duration of flight campaign in French Guiana is 9 months in total, including a period of 6 months dedicated to flights. The additional 3 months are mainly devoted to combined tests for validating interfaces in between the ELM, the Launch Range and the Vehicle.

Maximizing the number of flights over this fixed period remains obviously the target taking into-account several constraints including Launch Range availability which manages several launch campaigns for other customers. This top requirement coupled with a cost reduction approach led also to avoid landing downstream on a barge.

Thus, this makes it possible to carry out the entire campaign at same place. Vehicle recovery operations are greatly simplified and above all not very different from one mission to another.

The Operational Requirements of the CALLISTO project have been revisited accordingly. They have been adjusted and clarified according to the life phases resulting in 80 requirements, instead of 60, and simplified as well (10 requirements removed).

2. Ground segment: brief description

CALLISTO Vehicle is operated at CSG in French Guiana inside Launch Complex dubbed ELM (French acronym for Multi-Launcher Launch Complex) located nearby Ariane 5 Launch complex. It takes benefit from:

- retrofitted installations of Diamant site operated in the seventies or more recent Ariane installations,
- and services offered by CSG Launch Range for Launch systems operated locally.

The area devoted to CALLISTO operations has been optimized and is now frozen including one Lit-Off Pad and Landing zone nearby.

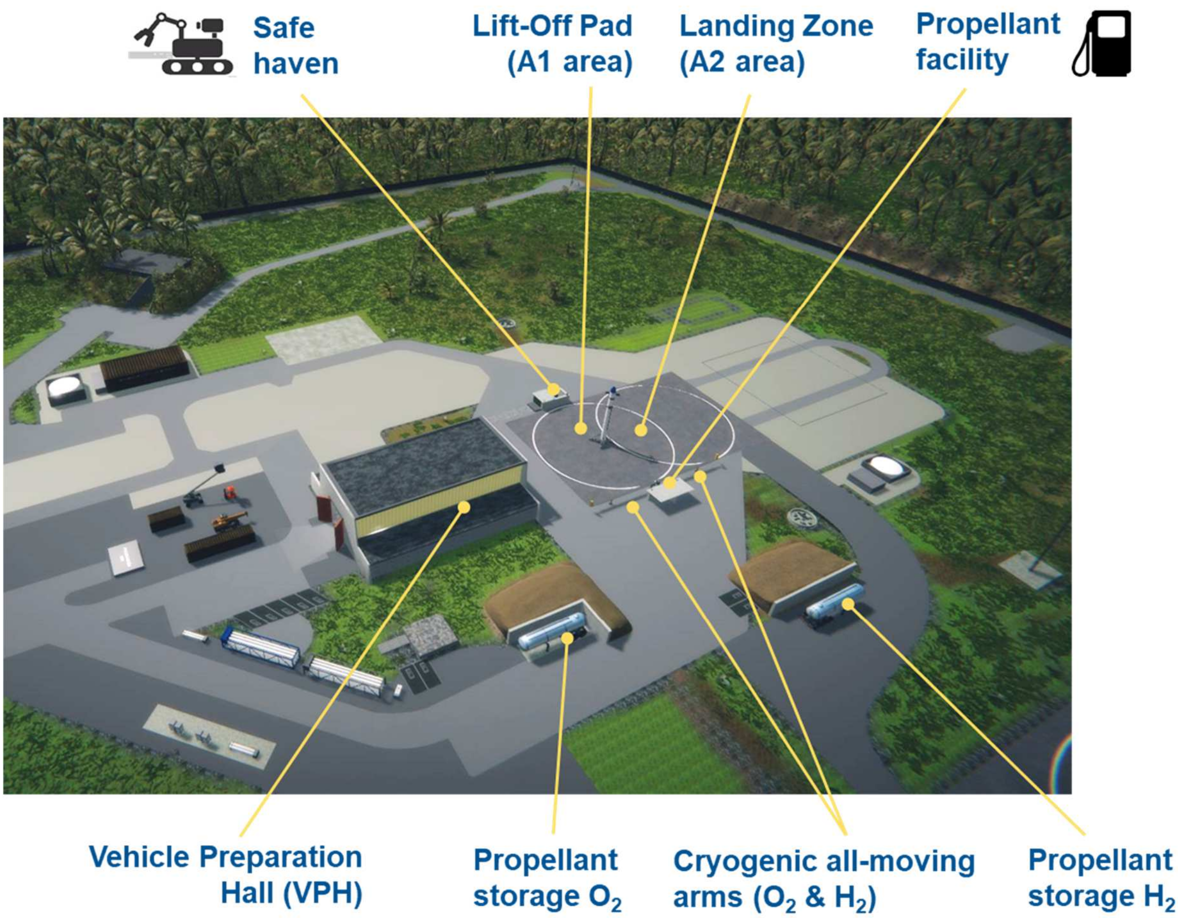

Figure 2 : Lay-out of CALLISTO site at ELM

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3. CALLISTO Vehicle at a glance

The CALLISTO vehicle is a single stage architecture and features a rocket propulsion system mixing liquid oxygen and hydrogen with a turbo-pump fed engine. Its Flight Control System combines (i) an engine Thrust Vectoring (FCS/V), (ii) a set of 4 aerosurfaces (FCS/A) located at vehicle's top and (iii) a Reaction Control System (FCS/R) as well. The FCS/A is electrically powered for unfolding maneuver during flight and then surface deflections. The FCS/R is a cold gas and pressure fed/blow down system. Its Landing System features a set of 4 fully deployable (landing) legs being pneumatic powered.

It is designed to have a capability to reach the transonic speed regime using a single rocket engine and to return to its home base and being reused several times. The vehicle configuration with the aerosurfaces and the landing legs deployed is figured below.

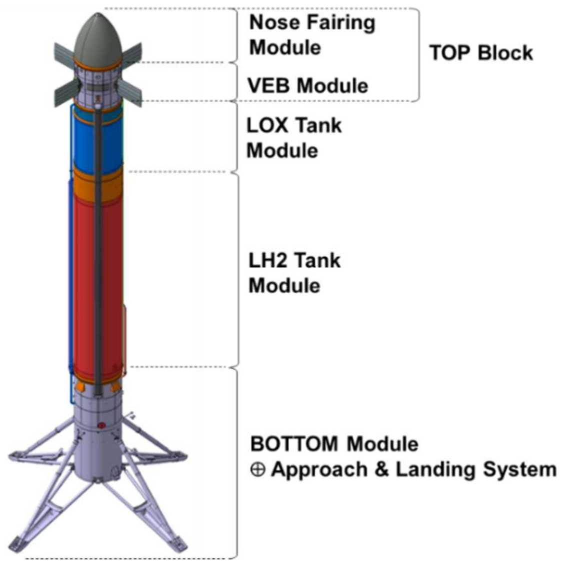

Figure 3: Vehicle configuration with FCS/A and ALS unfolded

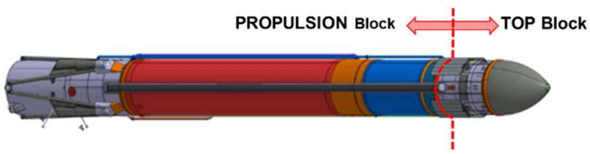

Figure 4: Vehicle TOP Block vs. Propulsion Block

For the sake of comprehension of M&RO optimization regarding products design, 2 Vehicle systems are described below:

- ALS legs thermal protection
- FCS/A actuators

ALS legs thermal protection

All experimental and commercially available returnable rockets that perform a vertical landing on unfolded landing legs require a thermal protection system (TPS) that protects the supporting structure from thermal overload throughout the flight. Due to the mass sensitivity and the costs of such a system, cork was chosen as the TPS of the landing legs in the CALLISTO project. In Europe, this material is already available with a large flight heritage.

Landing legs of CALLISTO are a CFRP made structure that transmits the mechanical loads and that is protected by a bonded cork layer absorbing thermal loads. This ablative cork layer is consumed by the thermal loads occurring during the flight and must be checked and, due to mass limitations, replaced after each flight.

FCS/A actuators

The 4 aerosurfaces are unfolded during flight and refolded after landing. These maneuvers are achieved by two consecutive rotations. For each aerosurface, a dedicated actuator is used. The first rotation is actuated during unfolding and transformed to a linear motion. During the unfolding sequence the main actuator will also turn the aerosurfaces by 90° in order to reach a neutral position from flight control perspective. During descent phase the aerosurfaces are used for vehicle control and thus their deflection needs to be controlled as well. This is achieved by the main actuators. The chosen actuator architecture has a significant impact on maintenance operations, because the harness that connects the unfolding actuator to the control is subjected to a twisting motion of 90°during unfolding and to continuous movement during the normal operation by additional.

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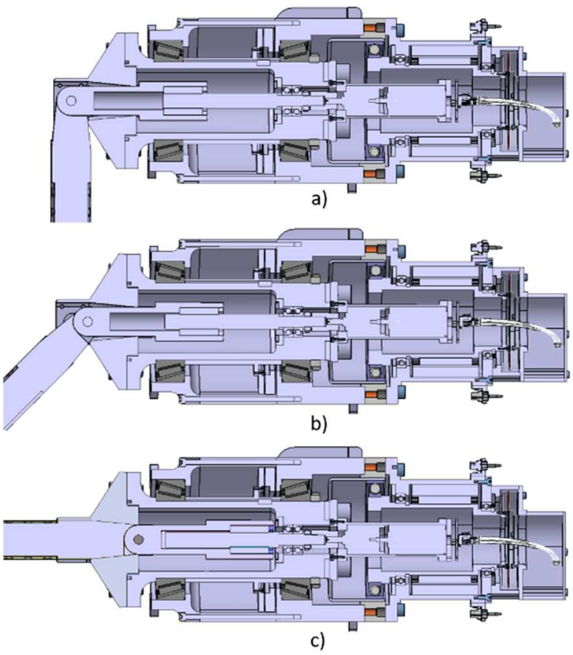

Figure 5 : cross-section views of the FCS/A actuator and aerosurface root for a) folded position b) 45°first unfolding rotation c) 90°first unfolding rotation with flexible harness in white at the right side of the actuator

4. CALLISTO life cycle overview

Concentrating on Vehicle only, the CALLISTO life cycle encompasses all the steps from the design and product manufacturing up to flight completion.

The life cycle presented below figures life phases starting from testing Vehicle in Noshiro Test Center which is operated by JAXA.

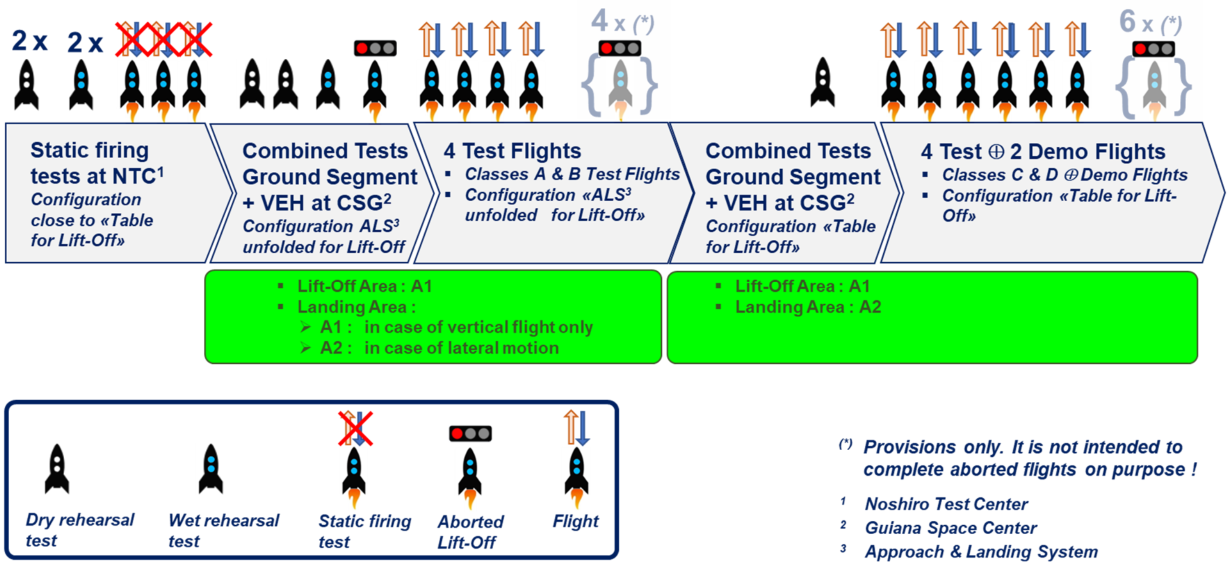

Figure 6 : CALLISTO life cycle – view starting from NTC tests

For keeping Project schedule shortened and validate operations as soon as possible ahead of CSG period at same time, life phases ahead of NTC period are useful for helping in having a vehicle configuration and GSE as close as possible to CSG one(s).

Especially, for TOP Block, it was decided to rely on testing Models of Nose Fairing Module (EQM) and VEB Module as well (SM) for Vehicle version to be operated in Noshiro Test Center (hot firing tests). Thanks to this decision and from (1) mechanical oriented operations stand point and (2) Vehicle-To-MGSE interfaces standpoints, fidelity in between NTC and CSG operations is maximized: vehicle transfer in between various locations and vehicle erection (and the other way around) e.g.

On the other hand, development of TOP Block Flight Model (including acceptance testing) can be completed in parallel. Afterwards, the TOP Block combining VEB and Nose Fairing Modules is transported straight from Europe directly to French Guiana.

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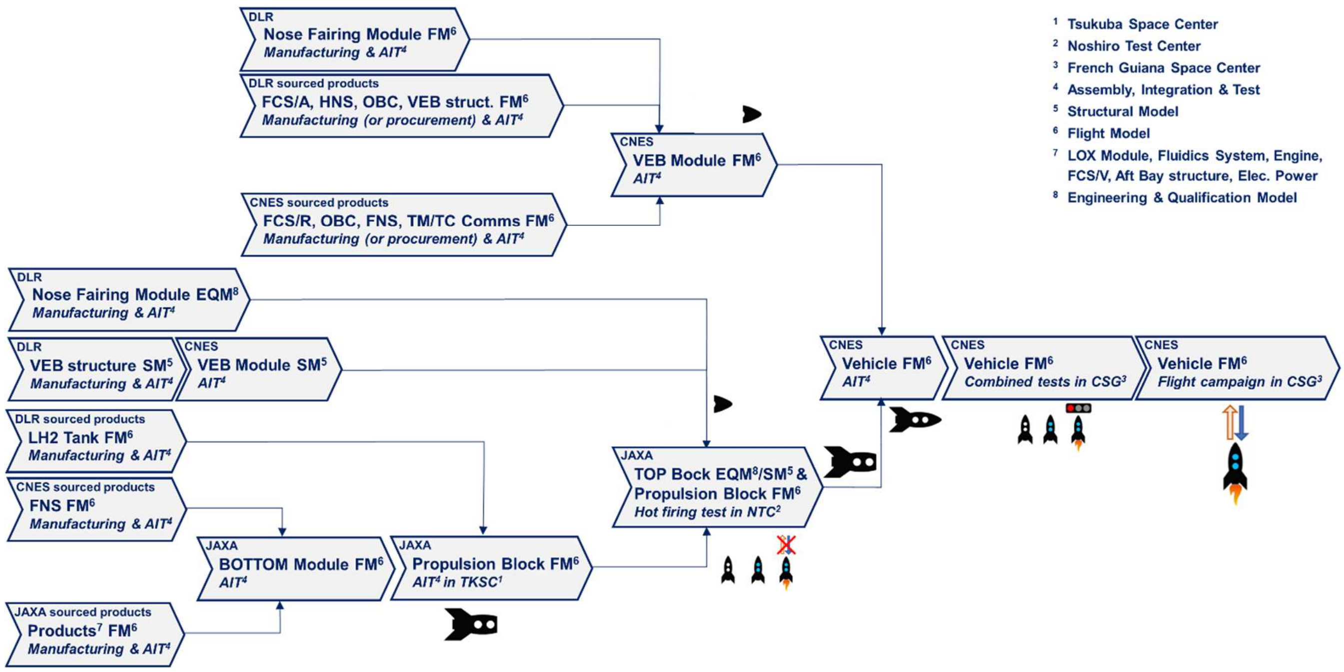

Figure 7: CALLISTO life cycle – Vehicle integration view

5. Optimization of operation duration in CSG: few examples

From the set of CALLISTO top requirements, 2 are to be highlighted as they deeply structure the specification cascading:

- Performing the flight test campaign in CSG, without disrupting commercial launches is a strong constraint and simultaneously an high value opportunity for an operational demonstration.
- Achieving the maximum number of flights over constrained period of time (6 months).

Both top-down requirements and bottom-up feedback from Product Owners were compared and then CALISTO Architect team reassessed specifications according to “best estimate” operation plan. In parallel, Vehicle design choices were as much design-to operation reoriented as possible pending other design drivers (optimization of Vehicle mass budget e.g.).

Concentrating on operations themselves, some assumptions were revisited:

- a reduction in health control operations after first flights lessons learned,
- some Launch range tasks to be completed ahead of flight reduced or erased in case of mimicked flight,
- an optimized contingency margin,
- the "learning curve" effect over flight campaign duration.

For the sake of comprehension of operation optimization, two examples are detailed below:

- Operations carried-out on Propulsion Block without the TOP Block,
- FCS/A actuators M&RO and integration

Operations carried-out on Propulsion Block without the TOP Block

Purpose of optimizing this life phase is to manage in parallel two parts of the Vehicle independently. This provision is essential to reduce the duration of the operation plan, optimize human resource, and limit the risk of time drift.

The operations require data communication between the functional products of Rocket Propulsion System located in the Propulsion Block and Avionics products located in the VEB Module:

- LOX and LH2 Tank Module Electrical check-out,

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- BOTTOM Module and Engine Electrical check-out,
- RPS Fluidic checkout,
- RPS Fluidic flushing.

To carry out these operations as described above, there are two possible options: use of (1) devoted EGSE instead of Vehicle avionics products or (2) Vehicle avionics products models being spare models. Depending on selected option that impact costs as well (EGSE procurement vs. additional avionics Flight Models), time reduction of operations is as much as several days.

FCS/A actuators M&RO and integration

After flight completion, disassembly of the FCS/A actuators is a regular planned maintenance operation between 2 flights.

During disassembly and then reassembly, the VEB Module must be rotated for an easy access, and furthermore, due to the criticality of these operations, no other operation is possible. Then the opportunity to get this operation removed would be welcome for reducing the time between flights.

Then it would impose to increase life duration of these items and number of “reliable” cycles.

That is the purpose of the dedicated validations performed on the flexible harness strongly twisted during unfolding and inclination of aerosurfaces. Consequently, preliminary tests of different harness configurations were conducted on a test rig to choose a configuration that would resists best the challenging life cycle.

Figure 8 : Left to right: different harness configurations; modified test rig for shaker operation; broken wire

A harness of several individual bundles with 3 wound wires performed best. Then the test rig was installed on a shaker to apply additional stress induced by the severe vibrational environment of CALLISTO Vehicle.

So, taking in account the objective of M&RO duration reduction, several harness specimens are tested under conditions close to the operational environment to qualify the harness reliability for as many consecutive flights without replacement.

In parallel to the work for getting products hardened, a functional validation without dismantling the actuators is under investigation.

Operations at VPH

The operation plan at VPH includes three primary phases, two being ahead of flight and the third one afterwards:

- an initial phase lasting 7 days, carried-out on the Propulsion Block on one side and on the TOP Block on the other side,
- a second phase of 6 days with the assembled vehicle beside the Nose Fairing Module which is integrated to Vehicle over very last moment ahead of transfer to Lift-Off Pad,
- a third phase (2 days) after transfer from the Landing Pad back to VPH.

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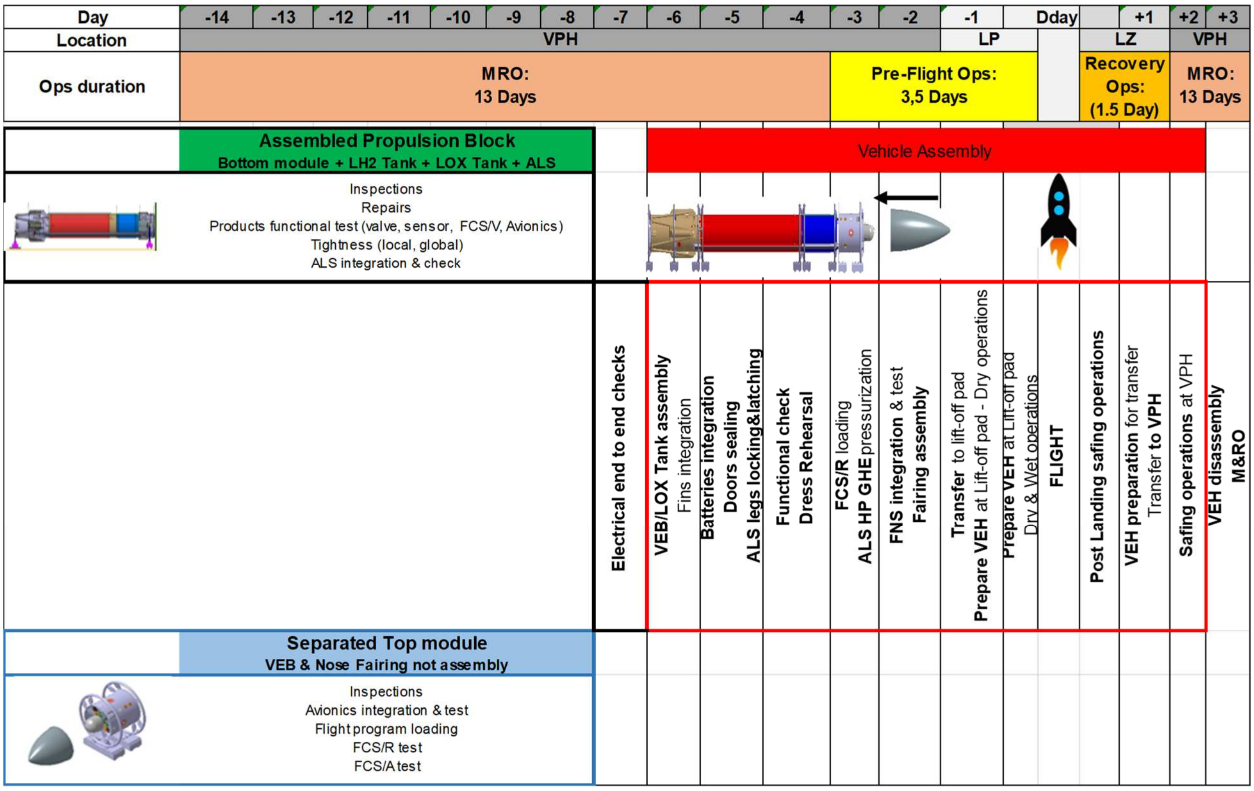

Figure 9 : set of main operations at VPH

Concentrating on reloading operation of electrical batteries ahead of (next) flight, two options are under investigation:

- One option derived from legacy Expendable Launch Vehicle heritage: reload the dismounted batteries in a devoted area,
- Another option is to get reloading operation with installed battery (inside VEH)

This second option would be time-optimized on one hand. On the other hand, this operation is riskier with possible damage to surrounding items.

ALS legs thermal protection is a product under severe thermal environment during descent phase that requires a planned maintenance after flight. This example of M&RO is detailed below as a particular attention on test during design has been applied to improve the process and assess operation duration.

ALS legs thermal protection M&RO

To validate the replacement of TPS cork, bonding and refurbishment tests are performed at DLR Institute in Stuttgart.

Cork material was glued onto a secondary structure model, cured and then removed from the CFRP supporting structure in the final step to represent the M&RO cycle.

TPS (cork) bonding operations ahead of flight:

> Pre-cut cork sheets are applied to the CFRP structure with an adhesive system and cured under vacuum and room conditions. Prior to flight, the cork must be coated with an external coating to fulfil the electrostatic properties and to protect the cork from the natural environmental conditions such as rain.

Post-flight operations and removal of the TPS (cork):

> After the flight, the TPS system will be replaced and tests were carried out as follows.
>
> The partially used cork is removed from the CFRP surface with sharp-edged tools in the first step, then the adhesive residue must be removed in a second step with a sanding tool. This results in a roughened surface that provides good properties for the bonding of a new layer of cork.

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Figure 10 : Bonded Cork Sheet, (a) after bonding, (b) during removal, (c) after sanding

These tests enable to assess the duration of replacement of complete TPS for 4 ALS legs.

6. Operations at Lift-Off Pad

After transfer to Lift-Off Pad, the Vehicle is erected and positioned on its ALS legs or on the lift-off table vertically (depending on the Test Flight) with a crane.

Based on JAXA's RV-X experience, erection technics is optimized for simplifying MGSE design. RV-X, the Reusable Vehicle - eXperimental, is a JAXA's rocket reusability flight test bed. RV-X has one 4-ton class LOx/LH2 engine, 1.8m diameter and its total length is 7m. Constructed at JAXA Sagamihara branch near Tokyo, it was transported horizontally to Noshiro rocket testing center. Then, erection was conducted with two cranes. RV-X has two hard-points around the nose section and two around the tail, along with its longerons. Those hard-points and 3m-lifting beams at the end of the crane boom are connected by slings (see figure below).

Figure 11 : Preparation of RV-X erection with 2 cranes

For CALLISTO, this method will be applied with 10-15 meters slings and the lifting beams with 25 ton-class mobiles cranes at both Noshiro Test Center and CSG. This TWO-crane operation is commonly used in the civil-engineering industry. The first step consists of lifting the Vehicle horizontally from its supporting device, supporting devices are removed, then the Vehicle is tilted by the front crane until vertical position.

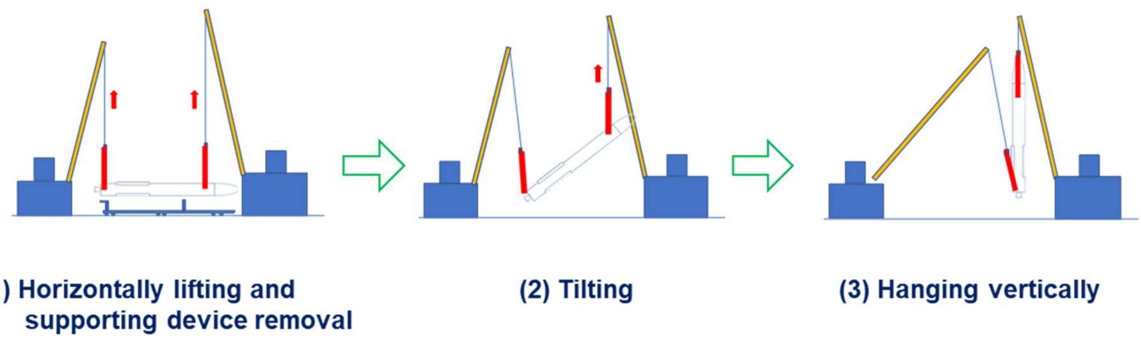

Figure 12: Main steps of CALLISTO Vehicle erection at Lift-Off pad

Initial preparation of the Vehicle is completed at Day-1 with especially Robot operations, and then the final preparation is performed at Day-0 at Lift-Off Pad including cryogenics propellant loading.

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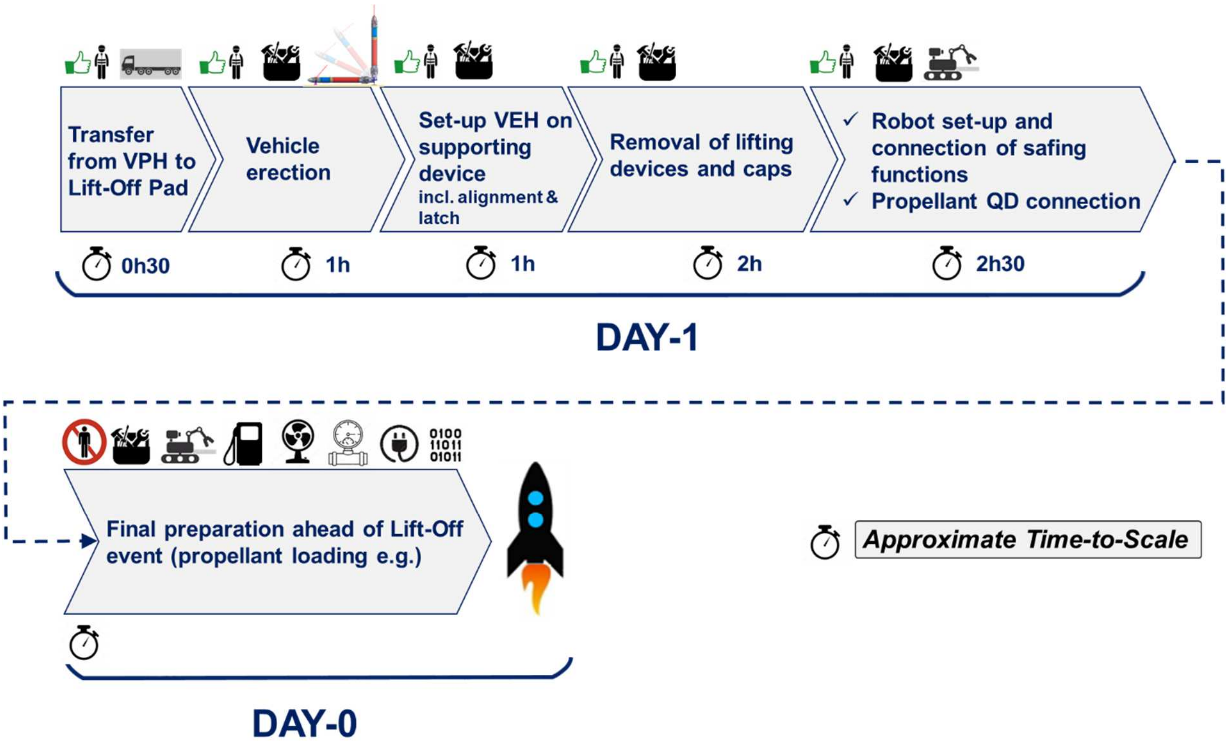

Figure 13 : Set of main operations at Lift-Off Pad ahead of Vehicle Lift-Off event

Operations at Landing Zone

The introduction of the Vehicle safing concept relying on Robot use is a major evolution in the design of operations (see [R2]).

After landing, Vehicle operations are broken down in 4 primary (life) phases:

- Phase 1: Automated sequence for Vehicle safing and remote-controlled operations (from Operation Control/Command Center) to clear authorization for Robot access. Link in between OCC and Vehicle is wireless communications.
- Phase 2: Robot reconnecting Vehicle safing-critical functions
- Phase 3: Draining and flushing of Vehicle Rocket Propulsion System
- Phase 4: after GO for staff access, preparation for Vehicle transfer back to Vehicle Preparation Hall

The following principles are key input for phasing and detailing content of operations:

- The time line for getting safing-critical functions of Vehicle available has to be paid careful attention. It directly impacts electrical power budget required on-board Vehicle and then Vehicle mass budget accordingly. In addition, the conditioning function of “closed compartments” of Vehicle (TOP Volume, Inter-tank volume, BOTTOM volume – see Figure 3) is to be ON rapidly for avoiding damage to heated items supposed to remain healthy for next flight(s).
- Ahead of tank full draining, any closing of the LOX or LH2 tank vent lines results a in a tank pressure increase and then safe state is at stake.
- The Vehicle has to be in safe mode ahead of GO for staff access. It means that the Rocket Propulsion System has been fully drained and cleaned with neutral gas.

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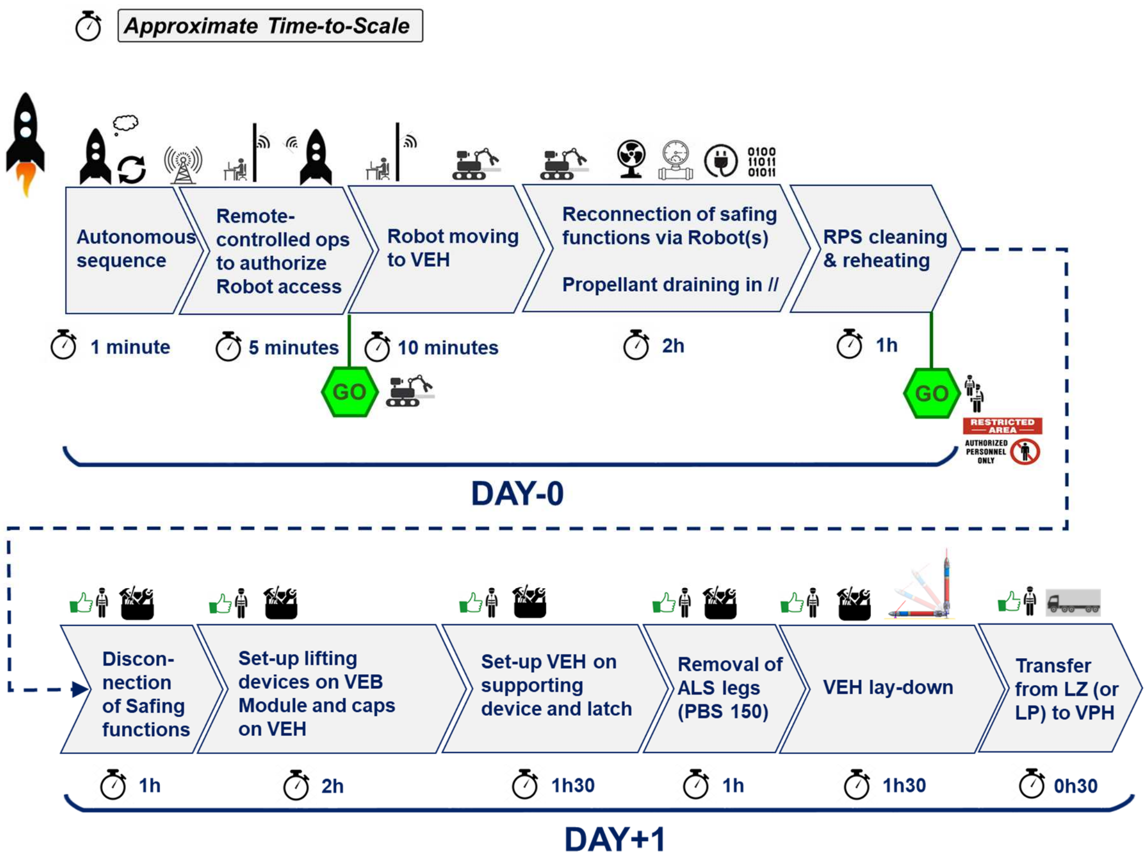

Figure 14 : Set of main operations at Landing Zone after flight completion

7. Summary and conclusions

CALLISTO project being a reusable rocket demonstrator, ground phase operations are a major challenge according to specificities of the Vehicle and the post-landing safing phase.

The definition of the CONOPS is part of the activities assigned to the CALLISTO System Architect. One role is to ensure overall consistency between the top objectives of the project and the requirements cascaded to the products for ground phases.

The CONOPS strongly depends on the definition of Vehicle operations and interfaces between the vehicle and the Ground Segment. It has to take into account technical risks, human factors and the environment.

As a conclusion, the Concept of Operations is now framed and stabilized and its optimization is Work in Progress. Some changes either to Vehicle design or improvements in operation performance impact it. For instance, the use of robots during the critical phase of post-landing operations leads to update the operation scenario for some life phases in CSG (see [R2]).

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