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The CALLISTO and ReFEx flight experiments at DLR - Challenges and opportunities of a wholistic approach

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ABSTRACT

The German Aerospace Center (DLR) is currently preparing two reusable launch vehicle (RLV) flight experiments for flight - a singularly unique and valuable position in Europe. While CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations) in cooperation with CNES and JAXA aims at investigating the challenges associated with propulsive vertical take-off, vertical landing, ReFEx (Reusability Flight Experiment) aims to investigate the other end of the RLV spectrum with a fully aerodynamic mode of return and horizontal landing. The goal of both experiments is to gain experience with designing, building, operating and flying RLVs, de-risk and mature the necessary technologies involved and gather data so as to provide a basis for future European RLV development and optimization.

The paper will describe both projects and their status in detail as well as highlight some of the differences and similarities of the two approaches. This will lead to the identification of key applicational areas of the two.

1. Introduction

In December of 2015, the first vertical landing of an orbital-mission rocket stage marked a paradigm change in the way payloads are brought to orbit. At the time it was not clear how quick and drastic this change would be, but now eight years later, reusable launch vehicles (RLV) with rapid turn-around capability (not seen in the first RLV – the Space Shuttle) have become a normal and regular occurrence.

While the regular re-use of stages is still the mainstay of one company (SpaceX), many are now following at varying stages of development. Electron for example, a small launch vehicle no less, has just recently re-flown an engine for the first time, from a recovered stage. With the goal of full stage re-use in the near future [1]. The type of development also varies between partial (Neutron, Firefly Beta, Spectrum, Maiaspace) and full reusability (Starship, New Glenn, Terran R, Firefly Gamma).

While initially the argument behind the development was simply “reduce costs of space access” and which has been shown to be the case (to varying degrees depending on mission design) [2], many new aspects have become apparent once the technology became mature enough. Among these are aspects such as higher reliability of flight proven systems, increased cadence while keeping the (expensive) manufacturing lines small, higher responsiveness (rockets in storage are available on short notice) and increased versatility (the same rocket type can be used for low energy missions in reusable mode or high energy missions in expendable mode for instance at end of life) and not to forget sustainability.

There are basically two main routes to achieve reusability, be it partial or full. They are propulsive or aerodynamic return (or a combination thereof) and both are viable options and have been demonstrated in the past with for instance Falcon 9 and the Space Shuttle respectively.

But the suitability of the two options depends heavily on the set of requirements driving the launch vehicle design, as well as on the technological capabilities to fulfil those requirements. Both approaches have their individual technological challenges with respect to mission design and operations, guidance and control, aerothermodynamic environment, propellant management, landing system, as well as recovery and refurbishment operations after flight. As these key technologies are

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under active development, there is still significant uncertainty in their technical and economic viability under full-scale operational conditions. For example, during the Space Shuttle program the effort to refurbish the orbiter's thermal protection and main engine increased significantly beyond initial expectations, rendering it as a major driver for costs and operational constraints [3]. This illustrates that there is not one optimal RLV design but that the application and the technological capabilities always has to be kept in mind.

DLR has performed an extensive analysis of the different RLV-first stage return and recovery methods for future full-scale applications with different propellant combinations all launched from the European space port in Kourou [3].

To gain more insight on the actual challenges of each approach DLR has embarked on the challenging task of exploring both ends of the RLV methodology spectrum, by conducting (or co-conducting) two flight experiments. These are CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations) conducted in cooperation with CNES and JAXA, which is focused on vertical propulsive landing technologies (see Fig. 2), and the other being the Reusability Flight Experiment (ReFEx) which is focused on an entirely aerodynamic means of return (see Figs. 1 and 3).

As such CALLISTO covers the vertical take-off, vertical (VTVL) landing spectrum, which is now regularly applied for the recovery of first stages and ReFEx covers the vertical take-off, horizontal landing (VTHL) which is now often selected for concepts and tests of reusable upper stages, due to the high energy dissipation need. Of course, both concepts can be applied to any stage or even be combined (see Starship [5]), depending on overall mission requirements, where mission explicitly includes the entire end-to-end process from manufacturing all the way to recovery and refurbishment.

Interestingly all RLV, be they VTVL (Vertical Take-off and Vertical Landing) or VTHL (Vertical Take-off and Horizontal Landing) aim mostly to fly under similar specific conditions, see Fig. 4. This figure shows both the descent trajectories of the CALLISTO and ReFEx experiments as well as a DLR internal study (RLV C4 [3]) and operational missions like a Falcon 9 mission to GTO with a down-range-landing (DRL). For the Falcon 9 DRL mission aerodynamic and propulsive phases are distinguished through highlighting of start and end points of re-entry and landing burns. As can be seen in Fig. 4, the re-entry trajectories of the majority of the shown vehicles enter a dynamic pressure envelope of 5 kPa–50 kPa. It should be noted that CALLISTO is focused on the main manoeuvre of a VTVL first stage returning to launch site and hence it is not necessary to cover the full flight domain of a reusable VTVL first stage performing a down range landing. ReFEx is focused on hypersonic to subsonic flight and covers these parts of the RLV corridor [6] which is typical in particular for VTHL.

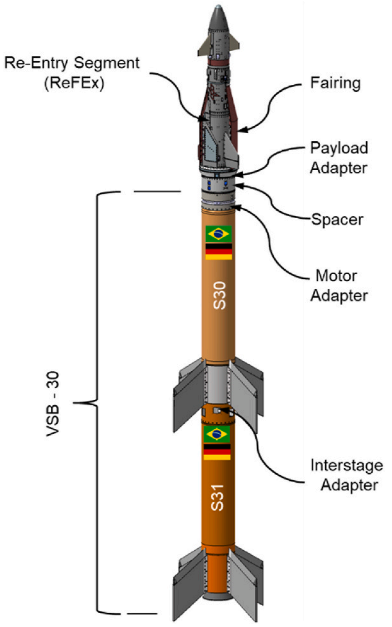

Fig. 1. ReFEx launch configuration on VSB-30.

This puts DLR in the unique position in Europe to be able to gain design, development, manufacturing as well as operational experience in both approaches. In addition, flight data from both experiments will be invaluable to validate methods and models. The goal is to have the knowledge base available to advise other stakeholders in Europe on how to develop the right next generation RLV for Europe.

2. Structure of the paper

This is an overview paper of the CALLISTO and ReFEx flight experiments and is structured in the following manner.

The next section (3) gives an overview of the two projects as an introduction to readers, who might not be familiar with them. It provides basic information on the missions and research goals.

Section 4 then focuses on the trajectories of the two projects, their differences and what can be learned by running two flight experiments using two different trajectory approaches to achieve the same final goal: safe landing of a RLV.

This is followed by a deeper look into the associated GNC methods to achieve these different trajectories and different vehicles in section 5.

Section 6 then focuses on the landing systems themselves, which is more CALLISTO focused since ReFEx is a one-shot experiment, not intended to be recovered after landing.

Section 7 then returns to a broader project perspective, highlighting some of the risk assessment methods used in the projects and how these can be influenced by the respective circumstances and assumptions they a based on.

Also, from a complete system perspective, section 8 gives an overview of the AIV methods employed to conduct the two projects.

Section 9 then finalises the paper with some conclusions and an outlook.

3. The CALLISTO and ReFEx flight experiments

3.1. CALLISTO

The CALLISTO project is a joint cooperation between the three national space agencies DLR, CNES and JAXA, which was initiated in 2017, with the main goals.

- To develop and mature technologies required for reusable VTVL rocket stages;
- To gather know-how, data and lessons learned about the system design of reusable VTVL launcher stages; and
- To gather know-how, data and lessons learned about the operation and refurbishment of reusable VTVL launcher stages on an active spaceport.

These goals shall be achieved by the currently ongoing collaboratively development, manufacturing, integration and test of a reduced-scale VTVL first stage demonstrator, the CALLISTO vehicle. This demonstrator has a length of about 14 m and a diameter of 1.1 m, with a maximum take-off mass of less than 4 tons. It is propelled by the Japanese LOX/LH2 Reusable Sounding Rocket (RSR), which provides re-ignition and deep-throttling capabilities in the range of 16–45 kN.

As shown in Fig. 2, the vehicle can be mechanically divided into five stacked modules [7].

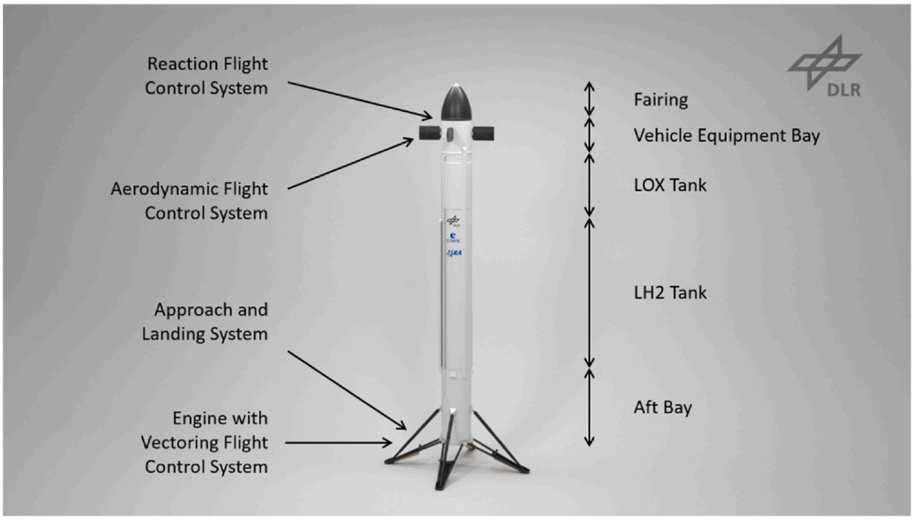

Fig. 2. Overview of the CALLISTO vehicle architecture; more details are available at [4].

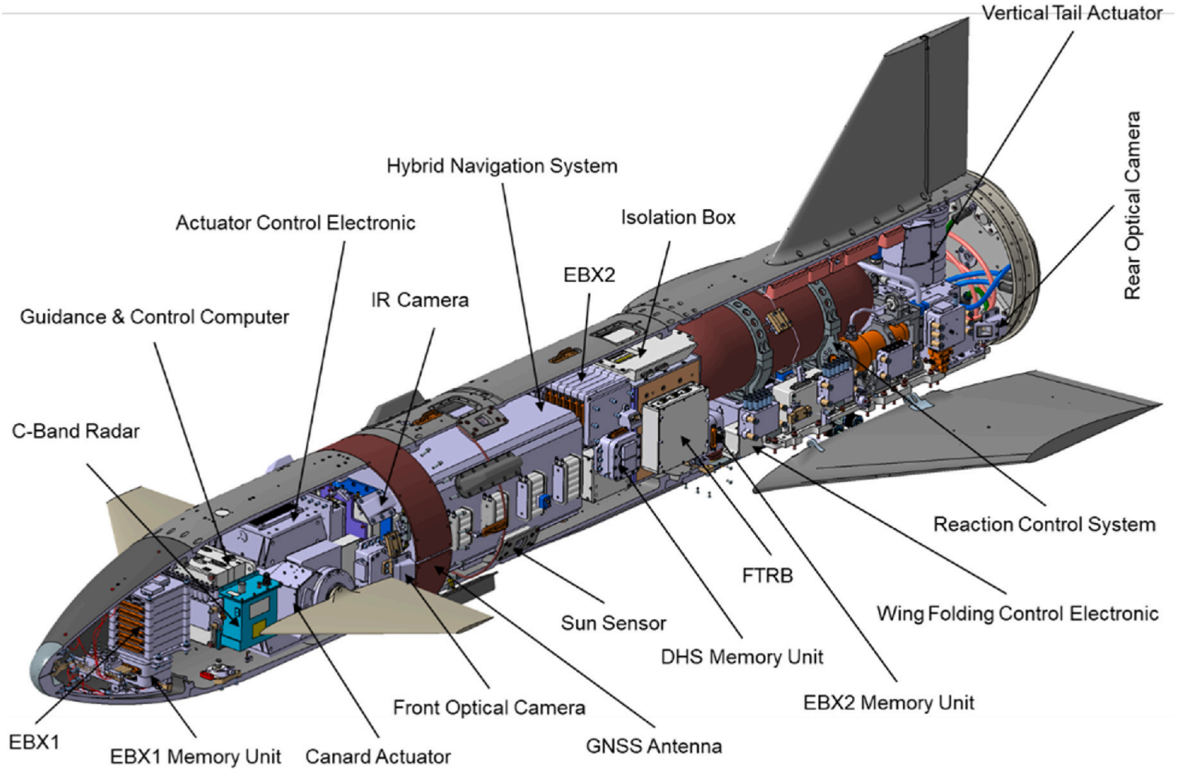

Fig. 3. ReFEx Re-Entry Segment cut-view with main systems.

- Nose Fairing Module, which ensures the forward aeroshape during ascent flight and houses the GNSS antenna and elements of the Flight Neutralization System (FNS);
- Vehicle Equipment Bay Module (VEB), which accommodates the Reaction Flight Control System (FCS/R), four deployable Aerodynamic Flight Control Surfaces (FCS/A) as well as avionic items such as the Hybrid Navigation System (HNS) and the On-Board Computer (OBC);
- LOX Tank Module and LH2 Tank Module, which both consist of the load-carrying propellant tanks equipped with fluidic and avionics equipment, plus two external cable ducts on either side of the vehicle;
- Aft-bay or Bottom Module, which houses in particular the RSR engine, the Thrust Vector Control (FCS/V) and the tank of the pressurization system, as well as further avionics and fluidics items, and provides also the interface to the external parts of the Approach and Landing System (ALS).

The CALLISTO vehicle will be operated from the European Space Port in Kourou (CSG), targeting the maiden flight in 2025. Therefore, the former Diamant launch pad, is being retrofitted by CNES to house the ground segment of the CALLISTO system. It will include a vehicle preparation hall, a launch pad and a landing area, as well as supportive infrastructure and equipment, see Fig. 5.

In total, CALLISTO is designed to fly up to 10 times, following an

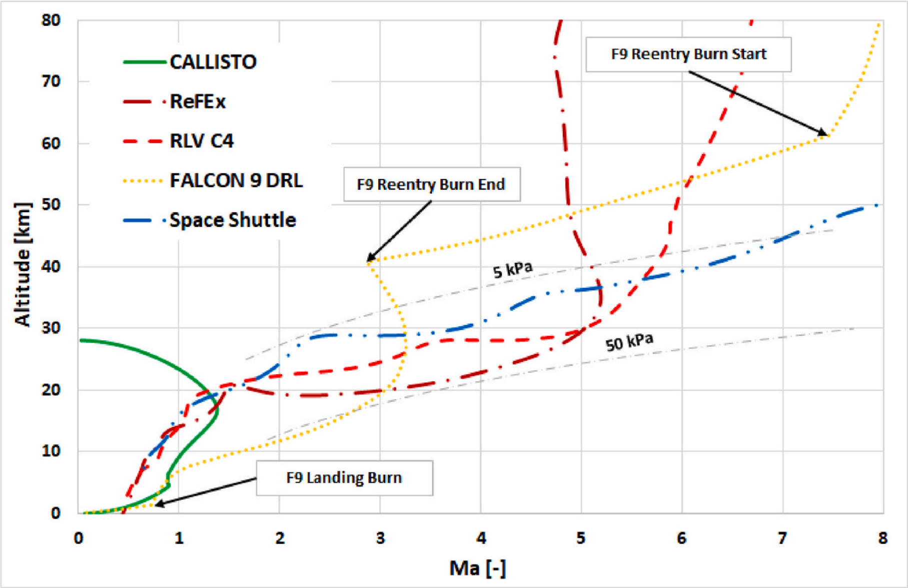

Fig. 4. RLV re-entry trajectories.

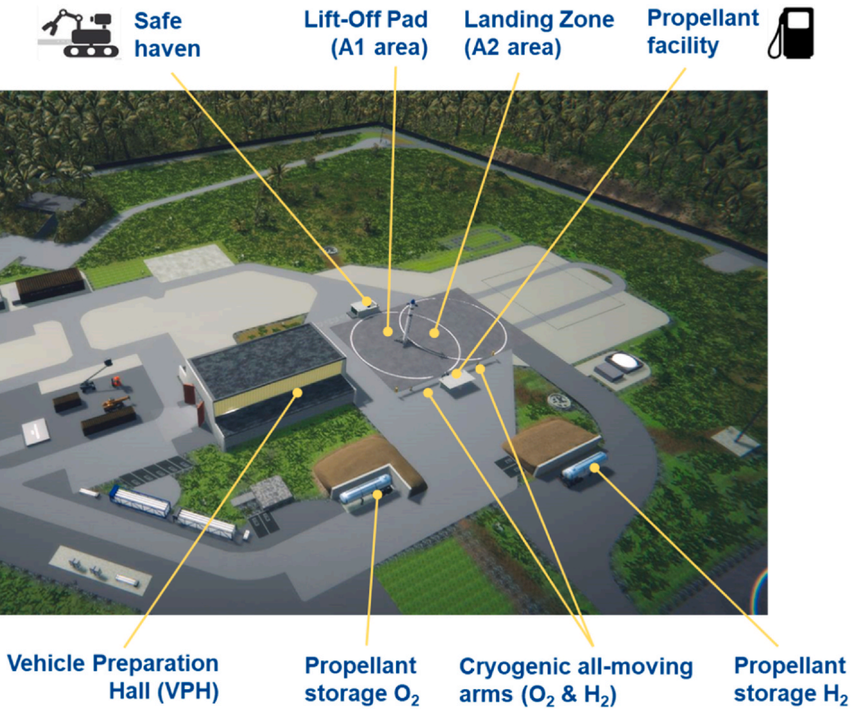

Fig. 5. Layout of the CALLISTO Launch Site after refurbishment of the Diamant launch pad under CNES responsibility [8].

incremental flight test campaign. Thus, the first flights are designed as low-energetic hop tests. This allows to continue the validation of the different subsystems of CALLISTO in an environment which cannot be reproduced in laboratory while these subsystems are not actively used yet or only within a limited range of their designed domain of used. Consecutive flights with higher altitude and velocity will then target more challenging demonstration objectives and extend the operational domain, until typical aspects, especially manoeuvres, of an operational VTVL mission profile will be resembled in the final demo flights. Fig. 6 displays the flight domain of the different flight energy classes defined in CALLISTO.

Fig. 7 illustrates a typical final demonstration mission for the CALLISTO vehicle. After lift-off the vehicle follows a powered, gravity-turn like, ascent trajectory, until the engine is throttled down. A boost-back manoeuvre is then performed. During the following unpropelled aerodynamic descent phase, the fins are deployed and the vehicle glides aerodynamically controlled back to the launch and landing site. Shortly before landing, the engine is re-ignited in-flight and the legs are deployed. After touchdown, the saving, recovery and refurbishment operations of the vehicle are conducted, using CALLISTO ground support equipment.

The preparation and the implementation of this project implies to solve a significant number of challenges, which is by the way also a goal of CALLISTO.

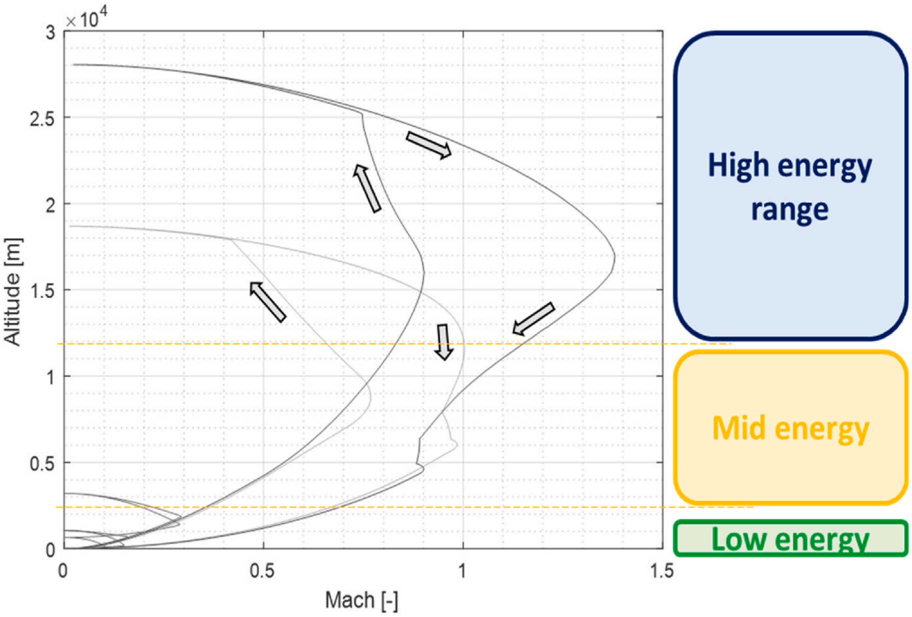

Fig. 6. Typical domain of the different flight energy classes of CALLISTO with exemplary flight profiles [9].

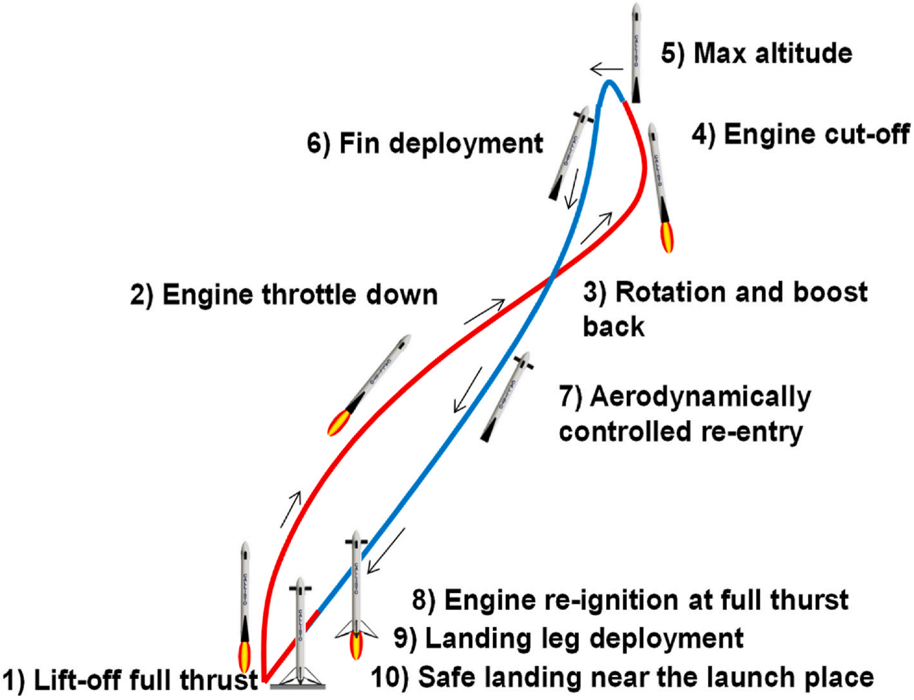

Fig. 7. Sketch of the typical reference mission profile of CALLISTO.

- Implement an efficient autonomous Guidance Navigation and Control System (hardware and software) for the whole flights, including the landing phase with a thrust to weight ratio larger than 1.3 [10, 11–13].
- Develop, build and operate a deployable, lightweight and reusable landing system. In particular the aerodynamic and thermal environment are challenging for the deployment mechanism [14,15].
- Manage the cryogenic propellant and limit unusable propellant during all the phases of the flight, to optimize performances and allow in-flight engine re-ignition [16,17].
- Characterize precisely the different configurations of CALLISTO (landing legs deployed/folded, fins deployed/folded, engine off/full thrust/throttled-down) for all the flight domain from aerodynamic and aerothermodynamic point of view. In particular the reduction of the uncertainties is decisive to exploit the vehicle at its maximum performance [18–20].
- Develop, build and operate a deployable, lightweight and reusable aerodynamic control system [21].
- Develop, build, operate, maintain and repair a vehicle and its structures to allow for multiple flights with an unique vehicle [22, 23].

CALLISTO entered phase D after the System Critical Design Review (CDR-S) conducted at the end of 2023. CALLISTO is benefiting of synergies with ReFEx in particular in the field of the GNC hardware with the Hybrid Navigation System and the On-Board Computer. Synergies exist as well for the aerodynamic control system which shares the design architecture with the aerodynamic actuator system of ReFEx.

3.2. ReFEx

Since ReFEx aims at the demonstration of technologies for aerodynamically controlled returning stages, the main mission requirements differ somewhat from the ones in CALLISTO, even though the final goal (stage recovery) is the same. As such the main mission requirements are (taken directly from Ref. [24].

- “The vehicle shall perform an autonomously controlled flight from hypersonic to subsonic velocities to a predefined point in space (latitude, longitude, altitude) with a predefined terminal velocity, following the typical Mach-profile as a function of altitude of an aerodynamically controlled stage.”
- “The vehicle shall perform a controlled heading change. The angle between a line connecting the apogee and the entry interface (EI) and a line connecting the EI and end of experiment (EoE) shall exceed 30°”
- “Reach a prescribed target point (EoE) within a certain accuracy (altitude, velocity and geographic position)”

Fig. 8 shows a rough mission event timeline. Since ReFEx is launched on a VSB-30 sounding rocket (provided by the DLR Mobile Rocket Base - MORABA), there are no intermediate experimental flights, with low power. The first flight covers the entire envelope. The main experimental phase starts upon de-spin and separation from the carrier vehicle.

Since the launch vehicle used to propel the experiment to flight conditions relevant for a first stage recovery is a sounding rocket it naturally provides higher than usual dispersion on the returning vehicle at the beginning of guided control (BoGC), as opposed to a fully TVC (thrust vector controlled) launch vehicle stage. The GNC system was designed to automatically cope with this situation and divert to a secondary landing site, which could be a very valuable asset for a future operational RLV.

To minimize the dispersion of the stage it is spun up during launch (through fin-canting and spin-up motors) and a yoyo-system is needed to de-spin the stack after burn-out. Prior to separation of the ReFEx re-entry segment itself, the triple-split fairing is jettisoned.

The next step in the sequence is to unfold the wings, which were stored underneath the fairing as well as unlock the exo- and intra-atmospheric flight controls. The reaction control system RCS as well as the canards and rudder were physically locked and prevented from operation during launch for safety reasons.

The initial hypersonic flight from about Mach 5 down to Mach 1.5 is conducted in an inverted belly orientation. This is done due to stability reasons. While this might seem unusual at first, it is the consequence of the aerodynamic shape and size of the vehicle (constrained by the launch vehicle). During high angle of attack (AoA) flight phases the rudder is in the wake of the body flow and becomes ineffective, leading to instability in the roll axis. In operational vehicles (such as the Space Shuttle) this was compensated for with a large hot gas RCS, that stabilized the axis during these phases of flight. For ReFEx there is insufficient space to add such a system. As such this unusual manoeuvre is flown as a demonstration of the capabilities to the flight controller, which would hence be easily capable of controlling a more benign operational stage. Once in the lower atmosphere and below Mach 1.5 it performs a roll manoeuvre to the “normal” belly-down position and continue the flight to EoE.

The EoE point is a predefined ellipsoidal volume in the atmosphere at an altitude of about 8 km and at which the vehicle will reach a velocity of below Mach 0.8. From this point onward, automated flight (and

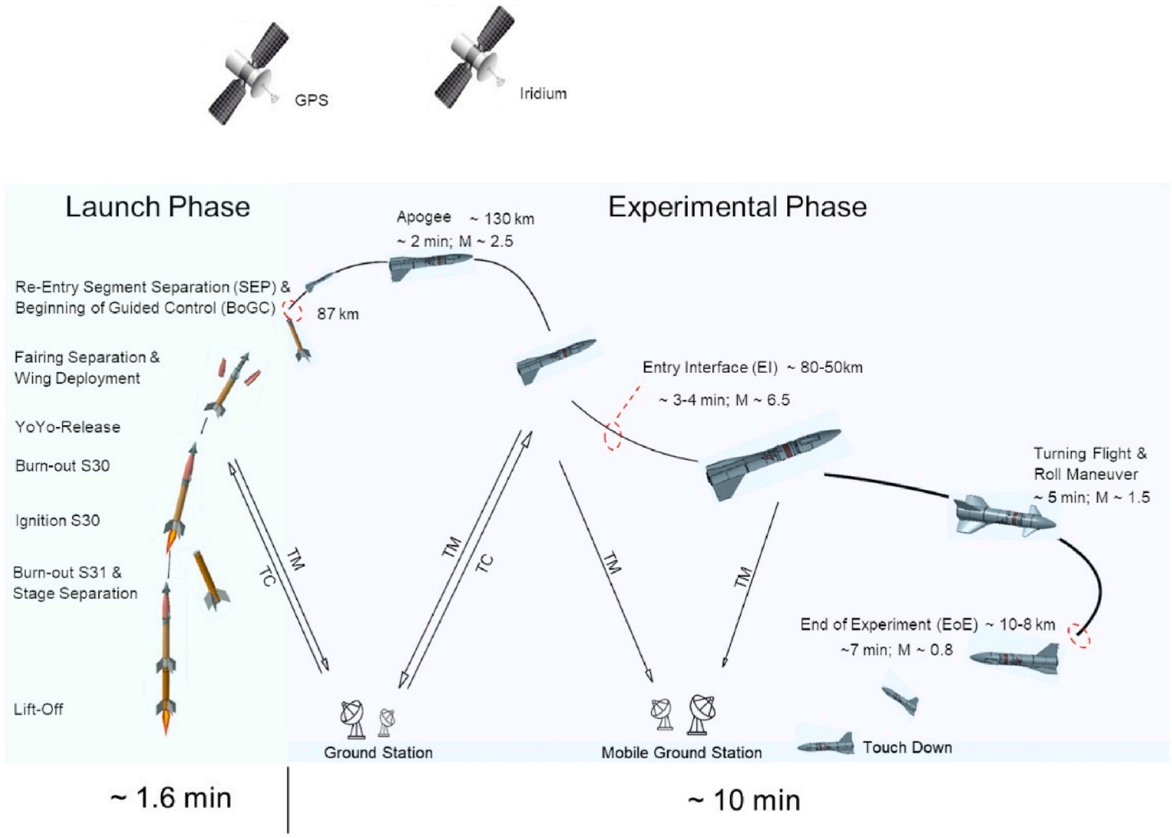

Fig. 8. ReFEx mission events and timeline.

landing) is an ordinary daily occurrence in civil aviation and is hence not part of the scientific goals of demonstrating fully aerodynamic RLV stage return.

However, the goal is to recover the vehicle and its data recorders after the flight and hence the flight continues to be guided, with the goal to both avoid certain difficult terrains as well as minimize impact energy in the final phases of flight.

4. Trajectories

4.1. *Differences between VTVL VTHL systems and flights*

The previous generation of reusable systems, led by the series of successful missions of the Space Transportation System (aka the "Space Shuttle") was relying on the Vertical-Take-off, Horizontal Landing (VTHL) idea. One of the main reasons for such a choice was the capability to fly longer ranges during the atmospheric entry due to the higher L/D ratio. As the Space Shuttle was orbital a large amount of energy needed to be dissipated before landing. Using the atmosphere to dissipate this large amount of energy is coming at a much lower cost than with a propulsive system, when propellant mass is concerned. Moreover, the technology required to perform a vertical landing of a large system was at that time not yet available, since it was only prototyped in 1993 with the first flight of the McDonnell Douglas DC-X flight, and made operational by SpaceX more than 20 years later. Therefore, the horizontal landing continued to be the main option to be explored even after the development of the Space Shuttle (e.g., the US programs X-33 and Dream Chaser, as well as with the IXV and Space Rider programs of ESA). All the programs were or are aiming at improving the historical limits of this technology, meaning the large refurbishment times between missions, the high costs, and the safety issues.

In the last decade, rocket stage reusability experienced a paradigm shift with the development, (and the repeated, successful validation) of the landing technologies for the SpaceX's Falcon 9 rocket, to the point that for SpaceX this is nowadays considered a standard operation during their missions, and they showed that the Vertical-Takeoff, Vertical Landing (VTVL) approach is also technologically and economically viable and competitive. The VTVL paradigm requires a completely different missionization, due to the 4 distinct phases the rocket must go through, as well as the allocation of part of the fuel for the landing stage.

Due to the different aforementioned paradigms, which are reflected by the design of CALLISTO and ReFEx, being a VTVL and a VTHL vehicle respectively, their trajectories and design thereof largely differ. While CALLISTO also actively performs its own ascent, ReFEx is delivered to about 90 km altitude by a sounding rocket and will only start its active part at separation from this launcher. Therefore, ReFEx trajectory design will only start with the exo-atmospheric phase whereas the CALLISTO trajectory is designed including already the ascent, as the same propulsion system should be used for ascent and descent.

Also, the approaches during the aerodynamic phases, even though present for both missions, strongly differ, resulting in very different trajectories. CALLISTO decelerates using its main engine, while its aerodynamic surfaces are employed for steering. ReFEx, on the other hand, does not have a main engine and, therefore, reduces its kinetic energy using its aerodynamic properties. Lastly the CALLISTO trajectory is designed for controlled vertical touch-down at a pre-defined landing site, whereas the ReFEx trajectory is designed for reaching a target position and velocity at the 'end of experiment', at about 8 km altitude covering a large downrange distance compared to CALLISTO and finally performing an uncontrolled landing afterwards. The following sections will give more inside into the trajectories designed and used for the two different missions.

4.2. *CALLISTO*

For what regards the flight trajectory, differently from ReFEx, for CALLISTO the flight campaign follows an incremental approach: starting from a very simple trajectory (the classic "hop" at few meters altitude) more and more functionalities and manoeuvres will be validated during the test progression with more demanding trajectories. The culmination of this approach is represented by a final (i.e., the "demo") flight, the demo flight, during which the rocket will encounter 4 distinct flight phases (ascent, boostback, aerodynamic descent and powered landing) requiring a corresponding set of guidance and control modes. Fig. 9 shows the Demo trajectory for CALLISTO, representing a Return-To-Launch-Site (RTLS) scenario, with the flight that will occur at the Guiana Space Center in Kourou.

After the ascent phase the boostback manoeuvre will change the attitude of the vehicle to obtain through the thrust direction an inversion of the horizontal component of the velocity vector. At the end of this phase, after reaching the apogee of the trajectory, the Main Engine Cut Off (MECO) command is issued and the aerodynamic descent starts. Here only aerodynamic surfaces, in the form of four fins, can be used to steer the vehicle while deep diving into the atmosphere. Upon reaching a given altitude the Main Engine Ignition Command (MEIG) #2 is issued, and the final powered landing phase begins. The completion of the pinpoint landing will represent the successful end of the mission.

4.2.1. *3-DoF trajectory reentry calculation*

The first step is the design of the 3-DoF Trajectory. In this phase the mission objectives are considered, and CNES trajectory design team performs all the required iterations to come up with a feasible solution. In this phase the resulting 3-DoF trajectory is for DLR an input rather than an output. The reason for this workflow resides in the complexity of having a solution that does not only satisfy all the mission requirements, but can also be approved by the safety authority of Guiana Space Center. In fact, it is easy to understand that severe measures of safety have to be considered to be authorized to fly in Kourou. CNES's multi-decennial experience in that sense is an important contribution to streamline the workflow of the project. This phase terminates with the delivery of the end-to-end 3-DoF trajectory to each partner.

4.2.2. *6-DoF trajectory reentry calculation*

Once the 3-DoF trajectory is delivered, an elaborated pre-processing is performed. Specifically, a set of operations to augment the trajectory and obtain a representative 6-DoF reference solution is performed. Specifically, the following actions are performed.

- Smoothing of attitude profile: 3-DoF trajectory might contain discontinuities due to separated computation of the segments

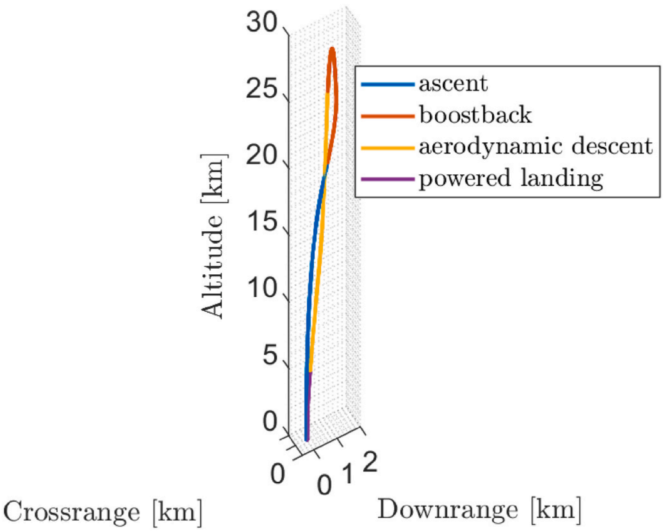

Fig. 9. Callisto return-to-launch-site scenario trajectory.

representing the end-to-end solution. A simple smoothing technique based on detecting outliers in the attitude profiles, and replacing them with the average of contiguous elements of attitude ensures the generation of meaningful attitude profile along the entire trajectory

- Trimmability analysis: the 3-DoF solution does not include explicit trimmability analysis: in other words, while the trajectory is designed in a way that it will be trimmable, the actual trimming values in terms of fins and TVC (thrust vector control) deflections are not provided. These variables are however needed for both improving the accuracy of 6-DoF closed-loop analysis and for control design purposes. Therefore, a trimmability analysis along the entire trajectory is carried out by determining for each phase what the fin and TVC deflections required to generate a meaningful controlled torque are. While for the phases without fins the computation is quite straightforward, during the aerodynamic phase the trimmability requires solving a set of nonlinear equations representing the total torque generated by the rocket.
- Variables conversion: the original solution is provided in a minimal number of reference frames, fundamentally an inertial one, and a earth-centered one. However, position, velocity, acceleration and attitude information are required in different reference frames, for instance, to properly compute several forces and torques. These computations are also computed at this pre-processing stage, making therefore easier for the G&C to readily access information in the desired format during the closed-loop analyses.
- Finally, a set of extra-variables is computed based on the chosen models, and stored for design and analysis purposes. Examples are the atmospheric density, temperature and pressure, the Mach number, the center of mass, the moment of inertia, the reference aerodynamic forces and torques, among the others. These variables make the verification of the behavior of the closed-loop results easier to understand, and the inclusion of uncertainties for each of the key elements to be considered straightforward.

The outcome of the 6-DoF Trajectory reentry calculation is represented by all the variables and the parameters of interest that characterize the end-to-end scenario of CALLISTO.

4.3. ReFEx

The trajectories for ReFEx where calculated using two simulation tools. One from a GNC standpoint using a 6-DoF simulation and one from a purely trajectory/mission perspective using a 3-DoF simulation.

This was done for two main reasons, firstly the 6-DoF simulation was not initially available at the project start and a corresponding aerodynamic database needed to be produced. Hence, the 3-DoF simulation allowed for initial estimates using simplified models and quick design iteration.

In addition, the 3-DoF code has a lot of heritage and was validated against several real missions, while the 6-DoF simulation was a new development. As such the two tools could be used in a dissimilar software development approach (different development teams) to validate the results of the 6-DoF code, which is key for later sophisticated flight safety analyses.

4.3.1. 3-DoF Re-entry trajectory calculation

The trajectories are calculated using a DLR in-house trajectory simulation and optimization tool. This tool allows the calculation of ascent and descent trajectories flown by launchers, spacecraft and re-entry vehicles through the solution of the equations of motion of a point mass (3DoF). The trajectory control is done via the angle of attack and bank angle, i.e. time histories of AoA and bank angle need to be provided as an input for trajectory calculation. The numerical integration of the equations of motion is performed with a Runge-Kutta-78 method. Different central bodies, as well as atmospheric and gravitational models can be selected. For this work, the WGS84 reference ellipsoid along with a gravity model with four zonal harmonic coefficients are employed. A constant mass of 375 kg is used for the simulation of the ReFEx flight experiment re-entry trajectory. The 3DoF trajectory simulations are performed in open loop, without including a guidance and control logic.

The resulting nominal re-entry trajectory for a vehicle mass of 375 kg is shown in Fig. 10. It shows altitude and nose stagnation point heat flux over Mach number. The cold wall nose stagnation point heat flux is calculated for the ReFEx nose radius of 0.05 m with an empirical relationship. After separation from the launch vehicle ReFEx is climbing to a maximum altitude of more than 130 km before re-entering the atmosphere with a flight path angle of around −44°. The maximum nose stagnation point heat flux of 364 kW/m^2 is encountered at an altitude of 28 km and a Mach number of 4.8. Maximum dynamic pressure of 41 kPa occurs at an altitude of 22 km and a Mach number of 3.7. The bank reversal is clearly seen as a break in the altitude profile at Mach 1.5.

4.3.2. 6-DOF Re-entry trajectory calculation

ReFEx does not follow the cumulative approach explained for CALLISTO, but instead consists of only one demonstration flight. This uniqueness is driven by the difficulty to isolate later parts of the mission and by the hard touch-down, after which the vehicle will not be fit to fly.

An overview of the mission is shown in Fig. 8, where the launch and experimental phase are identified. ReFEx is launched using a roll-stabilized unguided rocket, which drives several of the challenges for the GNC algorithms explained in the next sections. The vehicle is spun down before separation, which happens at an altitude of around 90 km. Due to the high altitudes, during this first part of the experimental phase the aerodynamic forces in the vehicle do not have a meaningful effect, leading to a ballistic trajectory. This drives the need of incorporating a Reaction Control System (RCS), to control the attitude of the vehicle during this phase. Soon after reaching the Entry Interface (EI), the vehicle can be controlled using its aerodynamic actuators (two canards and a rudder). During this part of the flight, the objective is to use the aerodynamic forces to correct the trajectory in order to reach the target. The target or End of Experiment (EoE) is defined at an altitude of approximately 8 km. From this point onwards, the objective is to avoid no-landing zones and minimize the impact energy.

The figure below (Fig. 11) shows a trajectory simulated in 6-DoF and with the GNC algorithms in the loop. All the phases previously explained are clearly visible. The trajectory flown is based in a precomputed nominal trajectory (see Ref. [25]) which is updated (see section 2.3.1) to ensure the target is accurately reached.

4.3.3. 5 GNC

Guidance, navigation and control (GNC), is needed to ensure the vehicle is realizing (*control*) the desired flight path (*guidance*), requiring

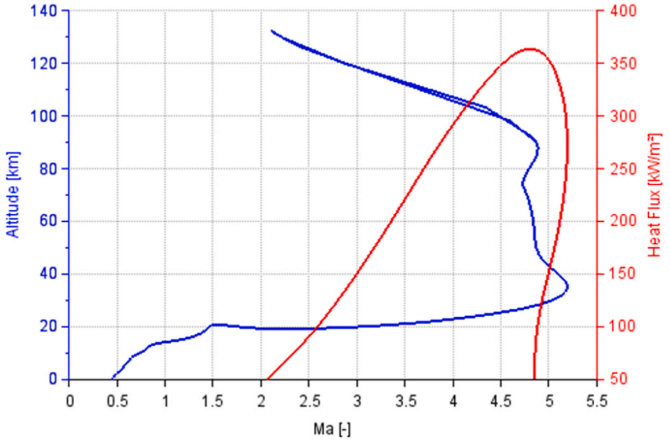

Fig. 10. Nominal ReFEx re-entry trajectory for a vehicle mass of 375 kg.

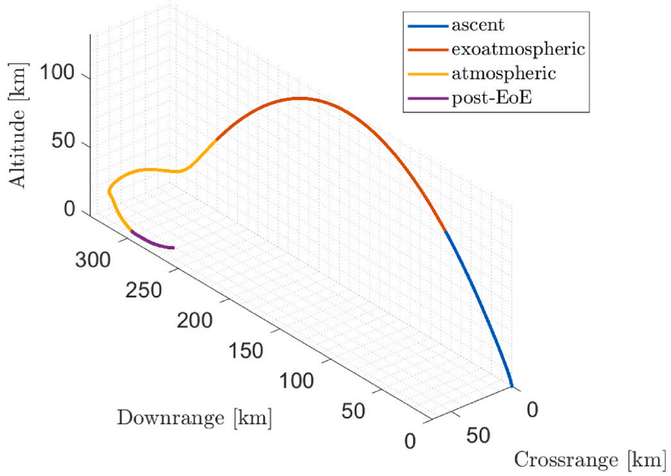

Fig. 11. ReFEx mission phases and events.

knowledge of its current position and attitude (*navigation*).

The GNC overall architecture for ReFEx and CALLISTO are depicted in Figs. 12 and 13.

The pose of the vehicles is estimated using DLR's Hybrid Navigation System (HNS). The HNS consists of a processing unit and different sensors, some internal to the HNS, others mounted in other places of the vehicle. The sensor measurements are used in the navigation filters running inside the HNS to compute the state estimate. While for ReFEx a two-layer approach is used to also estimate the wind velocity, in CALLISTO this is not required to successfully fly the mission.

The computed state estimate will be passed to the Guidance and Control system running on the onboard computers.

The Guidance and Control system will then compute the required actuator actions, which the actuators will execute influencing the vehicles state. This process is a continuously executed loop where the navigation closely monitors the vehicles state as the guidance and control try to realize the planned trajectories.

While the navigation system for ReFEx and CALLISTO are based on a common baseline and therefore feature many similarities, the Guidance and Control systems of the two missions are very different due to the different objectives as already discussed in Sec. 2.

One key difference between the Guidance and Control modes is represented by the guidance update logic. As ReFEx is launched using an unguided, passively stabilized rocket, this phase is not of interest for the guidance and control algorithms of the payload. After separation and during the exoatmospheric phase, there is time to perform a major trajectory update, correcting for the state error at separation (see 3.2.2). This is followed by periodic trajectory updates throughout the atmospheric re-entry, in order to correct for the model uncertainties and control and navigation errors. On the other hand, in CALLISTO a compound logic is required [26]: during the ascent and the aerodynamic phases an offline-computed reference trajectory is tracked, while the boostback guidance key parameters are computed online by means of a prediction/correction logic. The landing trajectory is computed online in the proximity of the second MEIG (Main Engine IGnition) event through the use of Sequential Pseudospectral Convex Programming (SPCP) techniques. Then, an asynchronous call is performed in case of disturbances causing violations of position and/or velocities. The remaining parts of the GNC scheme, i.e., Control Allocation, 6-DoF Navigation Filter, and Definition of Command, are from the logical point of view similar, despite showing clear differences due to the different scenarios.

4.4. Navigation for REFEX and CLT: the HNS

As already introduced, both missions will use DLR's Hybrid Navigation System (HNS) [27] for navigation purposes. The HNS is a highly flexible system which uses the same core design which can be adapted for mission specific needs, with ReFEx and CALLISTO just being two of its possible mission scenarios.

The HNS is designed to be very robust while at the same time minimizing weight and volume, all being important design drivers for space missions and launchers.

The core of the HNS is a tetra-axial IMU built from four COTS gyroscopes and four COTS accelerometers, which allows for partially redundant measurements. The HNS contains its own processing unit, which at minimum runs all the navigation algorithms, but can run further tasks.

As discussed ReFEx and CALLISTO feature quite different mission profiles, each of them putting different demands on the navigation system:

ReFEx will encounter high rotational rates due to the use of a passively stabilized rocket. This compounds with the scale factor of the gyros, leading to a considerable degradation in the attitude estimation. Whereas CALLISTO does not encounter high rotational rates.

ReFEx further suffers from a reduced observability of the attitude, due to a lack of observability of the rotation around the sun direction, during the exoatmospheric phase whereas CALLISTO can observe attitude angles during the ascent but has limited observability around the roll axis, in the final phases before the first burn manoeuvre also the observability of pitch and yaw decreases. All of them becoming observable as soon as non-inertial accelerations are acting on the vehicle.

Due to ReFEx exploiting its aerodynamic shape for generating lift, it

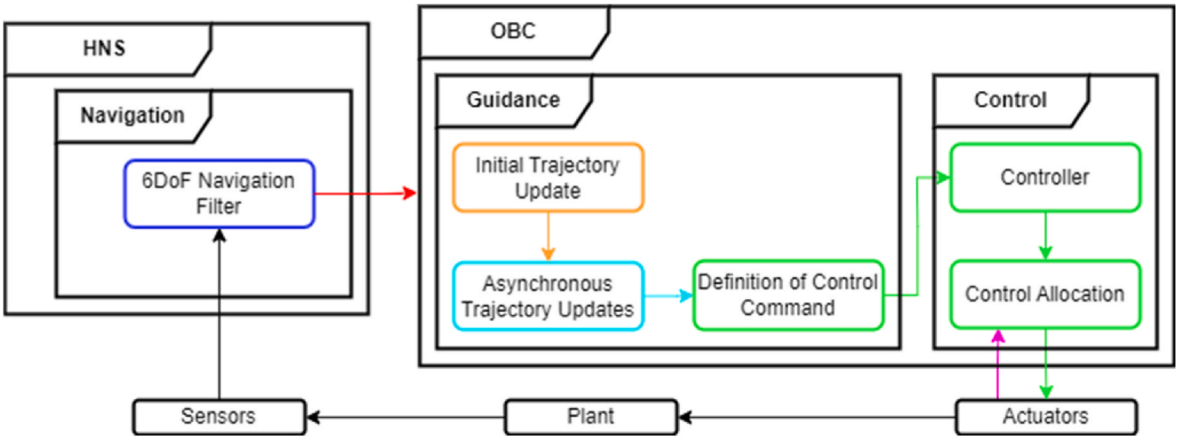

Fig. 12. CALLISTO high-level GNC logic.

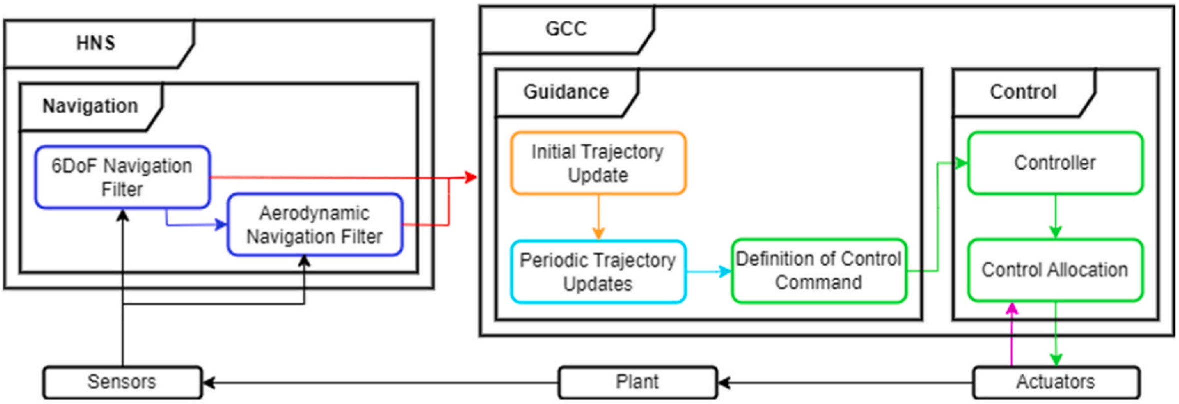

Fig. 13. ReFEx high-level GNC logic.

has large sensitivity to wind. A high accuracy is needed in the aerodynamic angle knowledge in order to keep the vehicle stable during the re-entry, as otherwise the wind can have a devastating effect if not estimated. This is not the case for CALLISTO as here aerodynamic forces are of lesser concern.

CALLISTO on the other hand however, will need to perform smooth vertical landings (partly without hovering), and is to be re-flown ten times, requiring these landings to be highly accurate, both in the horizontal and vertical components. It is very important that the altitude above the landing pad can be estimated very accurately. ReFEx on the other hand does not require this information as a hard landing is performed.

Due to these different mission requirements, ReFEx and CALLISTO need different sensors in addition to the IMU: ReFEx uses a flush air data system (FADS) for estimation of aerodynamic quantities, sun sensors to estimate the attitude and GNSS, while CALLISTO only uses GNSS as sensors, employing the DGNSS concept to deliver the required horizontal accuracy and using the RTK concept for obtaining accurate altitude information during the final phase of the flight.

Since both sensor suits are different they require the use of different navigation filters. ReFEx even relies on a two-stage set-up where the second layer is used to estimate the wind velocity based on the output of the first filtering layer. However also these filters are built from a common library source which will reduce implementation and testing efforts and allows for (partial) verification of one mission for the other.

4.5. Guidance & control

In terms of guidance and control CALLISTO and ReFEx can be thought of as complementary to each other: on the one hand CALLISTO wants to be the driver to develop the technologies required for first-stage reusability. On the other hand, ReFEx, while flying a trajectory for a winged first stage can also be seen as an effort in further developing reusable technologies for a fully reusable second stage, since the guidance principle remains the same. Hence it is an extension of the original idea that drove the development of the Space Shuttle first, and the several vehicles that were studied later on, including NASA's X-33 [28], DLR's SHEFEX-3 [29], Sierra Space's Dream Chaser [30], and ESA's IXV [31], among the others. It follows that, together, they will provide a rich dataset of information for the operative reusable space vehicles.

4.5.1. CALLISTO

The GNC of CALLISTO can be decomposed by looking at the navigation system, that is, the HNS described in Sec. 2.4, and the Guidance and Control subsystem. This last one is particularly challenging because of the complex mission scenario that reusable rockets must deal with [32]: each flight phase has its own constraints, as well as its own actuators set, meaning that highly specialized solutions must be developed for each of them. During the ascent phase the rocket must satisfy strict requirements in terms of Q α envelope, typical of any launch system. The boostback phase of CALLISTO must be accurately planned to make sure the rocket will not fly too far from the prescribed interface with the aerodynamic descent starting interface, while at the same time being capable of delivering the microgravity conditions required to meet propellant management demonstration objectives.

During the aerodynamic descent phase the rocket will experience large dynamic pressure and wind gusts, and must keep the position and velocity error under a given corridor with limited control capability (represented only by the aerodynamic fins) to ensure the feasibility of the forthcoming pinpoint landing manoeuvre [32].

Finally, the landing phase itself will occur in the presence of non-negligible aerodynamic effects. The corresponding guidance and control subsystems must cope with these effects and counteract further uncertainties and disturbances while meeting the strict final requirements to perform a successful touchdown event. This compound scenario requires coordination of the different guidance and control modes, as well as a dedicated Mission Vehicle Management (MVM) logic, able to smoothly handle all the transitions, and the corresponding changes of G&C modes.

4.5.2. ReFEx

The Guidance and Control subsystems of ReFEx are also quite challenging, due to the particularities of the mission. More detail explanations can be found in Ref. [33].

With respect to the Guidance there are two main challenges: 1) the high state dispersion at separation, which is driven by the unguided rocket used and 2) the accumulative effect of the modelling errors and control and navigation errors during re-entry. These challenges drive the design of the Guidance algorithms, which implement the following functionalities: 1) perform a major update of the trajectory to compensate for the initial dispersion, and 2) conduct minor periodic updates of the trajectory to compensate for additional errors. Both algorithms follow a similar principle, being based in a simplification of the optimal control problem into an unconstrained optimization problem. The validity of this approach as well as a more detailed explanation can be found in Ref. [32].

In relation to the Control subsystem, the main challenges are originated by the actuators used. The RCS characteristics define upper limits in the thrust and, thus, in the torque, as well as a maximum amount of fuel [34]. The aerodynamic actuators interfere with the rest of the vehicle, leading to an underactuated vehicle for certain combinations of Mach and angle of attack [35]. Furthermore, the transition between the two types of actuators, each with different properties and limitations, is not trivial. The Control algorithms are classified in two axes: 1) depending on the functionality and 2) depending on the actuators used. The table below gives an overview of the control approach used for each combination, as well as references were more detailed information can be found. In the table, INDI states for Incremental Nonlinear Dynamic Inversion, and PWPF for Pulse-Width Pulse-Frequency.

Functionality \ Actuators	RCS	Aerodynamic actuators
Controller (commands a torque based in the commanded and estimated attitude)	PD-Controller [36]	INDI [33]
Control allocation (Translates the commanded torque into actuator commands.	PWPF [36]	INDI-based [33, 35]

5. Landing systems

5.1. CALLISTO

For vertical landing, the CALLISTO vehicle is equipped with a deployable landing gear, namely the Approach and Landing System (ALS). It resembles a configuration similar to those of SpaceX′ Falcon 9 vehicle. The four legs consist of each of a telescoping primary strut and a secondary strut. The structural components are made of carbon fiber and titanium and are protected by a thermal protection system. During the initial ‘hop’-test flights, they remain permanently in a deployed configuration and are folded during the higher energy flights and are deployed shortly before touchdown. Fig. 14 shows the layout and the different configurations of the ALS. Unfolding is driven by a helium pressure vessel providing sufficient gas pressure for the telescopic primary strut.

A Deployment Control Unit (DCU) orchestrates the unfolding event sequence by opening the valves of the helium gas system and firing the launch lock and release mechanisms (LLRM). In order to test the unfolding, a dedicated test stand was set up at the Landing and Mobility Test Facility (LAMA) of the DLR Institute of Space Systems in Bremen. This test stand features a pulley counterweight system connected by a spring wire to the footpad in order to simulate the external environment during the final descent phase. This test is complemented by single leg touchdown tests which uses a rail-guided drop tower to set-up different landing orientations and impact energies. Both functions ‘deployment’ and ‘touchdown’ have been subject to intensive testing during the development phases. The following Fig. 15 gives in impression of these test-set-ups. The number of landing legs was reviewed by the design team and several pros and cons were identified. One of the top functional requirements of any such landing system is to provide dynamic stability against tip-over of the vehicle. Stability is determined by the ‘stability-distance’ which is the closest distance between the vehicle’s center line and a line between each pair of footpads. To achieve the same stability-distance as a four-legged system with a three-legged system, the legs must be longer. A three-leg systems tends to have less mass than a four-leg system despite the individual leg’ higher mass and also the lower number is a pro in terms of reliability. The most striking disadvantage is, that the stowed leg system, folded and locked against the vehicles aft-bay, requires a taller aft-bay for a three-leg system. A taller aft-bay structure by far out-weighs the small mass advantage of the three legs alone. Consequently, a four-leg landing gear significantly contributes to a lower vehicle system mass. A further advantage of the four-leg system is its symmetry, which allows to use half-models for the aerodynamic analysis of the landing gear aerodynamics. As deployment aerodynamics is quite complex due to various interacting flow pattern, a computationally reduced effort in its calculation enable more analysis of these safety critical events in a given schedule and budget frame.

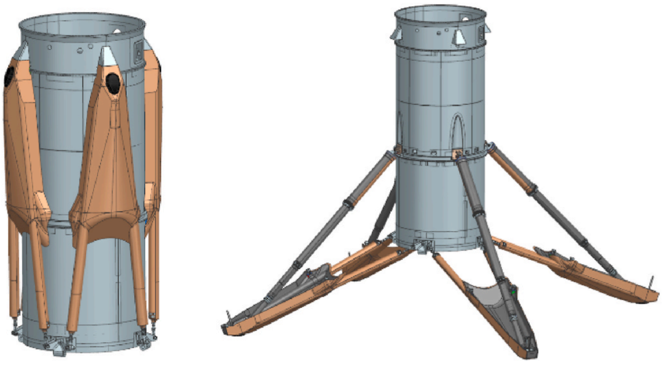

Fig. 14. ALS in folded (left) and deployed (right) configuration including thermal protection seen in brown-orange colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5.2. ReFEx

The question of the best recovery method for an RLV-stage is subject of intensive debate and also to systematic investigations [3]. Most attractive conditions for high performance missions are offered by Down-Range “Landing” (DRL). While the vertical landing of Falcon 9 first stages on a (relatively large) barge in the ocean has been established, a similar horizontal landing in the sea is hard to be realized.

However, the patented “In-air-capturing” (IAC) is an attractive procedure which intends catching the winged reusable stages in the air, and tow them back to their launch site without any necessity of an own propulsion system. The idea has been extensively investigated in DLR- and EC-funded projects by simulations and lab-scale flight demonstration. Most recent results on this technology achieved in the H2020-project FALCon are described in Ref. [37]. System studies indicate that IAC offers very good performance and hence has the potential to allow one of lowest launch cost of all RLV-first stage recovery methods [37]. Further, using “in-air-capturing” for the final recovery of the next generation ReFEx-flight demonstrator off-shore while still in the air will reduce operational constraints and improve safety on ground.

6. Risk assessment and flight safety

6.1. CALLISTO

In the course of the CALLISTO project a trilateral joint risk register is in place to announce and track technical and programmatic risks. The CALLISTO team conducts regularly a trilateral joint workshop to exchange on such matters, this is, if not intermediate wise scheduled, the point in time to re-evaluate the existing risks and to discuss the validity of associated actions, its status and potentially an update of them. Meanwhile each partner is obliged to enter new risks wherever necessary, e.g. as a result of identified risks during reviews or because of geopolitical crisis. Those risks are affecting as a minimum either joint interfaces, budget constraints (technical and programmatic wise), vehicle design and risks on functionality and operations and are therefore trilaterally to be discussed and to be mitigated. The main objective of the risk register and its trilateral discussions is to make the project partner aware of such risks and the tool to mitigate those to an acceptable level by reducing the likelihood of a risk cause. Key for such a joint risk assessment process is the solely contribution by each partner to work on the associated risks, commonly defined.

Risk management alone is for sure not sufficient to cover other aspects contributing as a risk for such a project with many parties – apart from the three partners – involved into the success of the mission goals. Aspects such as safety is for example treated differently following a process by safety authorities of JAXA and CNES; in charge for safety of their respective premises, at which CALLISTO will be prepared and verified for flight, especially at Noshiro Test Center and Guiana Space Centre (CSG). DLR is contributing by following the applicable rules, defined by partners and the relevant – but independent from CALLISTO project – safety authorities. As the flights of CALLISTO will take place at

Fig. 15. Development models of the ALS mounted on the deployment test stand (folded, left, and deployed, middle) and on the drop test stand in ‘landed’ condition, right.

Guiana Space Centre (French: Centre spatial guyanais; CSG), the Guiana Space Centre in French Guyana, CNES will be in charge of flight safety and therefore the rules of the French Law (Decree regulating the Operation of the Guiana Space Centre Facilities [38]) will apply.

For flight safety authorities and the underlying processes, the mission success – meaning the CALLISTO Vehicle can perform its maneuvers, resulting in achievement of mission goals, or not – is not key, but how the Vehicle design can be improved to serve demands on safety for operations and public health. For such feared events a flight neutralization system is in place to terminate the Vehicle in case it shows an abnormal behavior endangering public health. Safety reviews with an incremental scope of aspects to be analyzed and documented, are performed within different phases from the beginning of the project until the end of flight campaigns.

To release the Launch System for a flight, commonly known Flight Readiness Reviews (FRR) are performed. Those Reviews shall be supported by a Flight Worthiness Assessment, based on a global Flight Worthiness Report associated to the (Launch) System. This report is compiled of various flight worthiness reports prepared by each subsystem and considers the effect of any potential deviations of the underlying functional chains (e.g. electrical or fluidical) on key functionalities to operate the vehicle. This process will support the analysis for acceptance of a “go for flight” decision at the time of FRR. “To do so, in addition to safety aspects, the data have to demonstrate, with an acceptable level of likelihood, the success of the mission, taking into account all hazards and deviations encountered during each phase of the project [39].” Further details on the Flight Worthiness Assessment for CALLISTO can be taken from Ref. [39].

6.2. ReFEx

The objective of the risk management process in ReFEx is to maximise the probability of programme success by anticipating possible problems, identifying opportunities and by taking cost effective actions to improve the current situation, margins and working efficiency before launch of the mission.

Within ReFEx, the risk identification and management process is not seen as an isolated task, but is integrated into the normal day-to-day engineering and management flow, making risk management not a somewhat isolated and theoretical task, but is a lively discipline within the project. As such, the PA manager takes part in discussions and engineering decisions. Risk management is not limited to the initial program phases, but continues until phase E.

The general procedure of the risk management process is the following. Risks are identified, analyzed and if possible, eliminated. If this cannot be achieved, sources or consequences of risks shall be mitigated, and in those cases where even this cannot be achieved e.g. due to cost restrictions, the technical and programmatic management level must be aware of these risk contributing items and must have all information at hand either to accept the risk or to initiate further steps for further assessment.

All the information is taken into a risk register, in which the identified and assessed risks (technical, organisational, safety related, etc.) are described, according mitigating actions defined, as well as status updates and due dates recorded.

By having established regular risk meetings between Project Management and Product Assurance/Risk Management, it is ensured that risks within the project and their related actions are tracked and monitored. During these meetings, newly identified risks are assessed and mitigating actions defined, as well as decisions on the further handling of existing risks are made. Due dates for the completion of mitigation actions help to keep long-term projects such as ReFEx on track. Implementation and communication of these actions is done by Project Management to ensure that these additional tasks are implemented in the schedule to avoid project delays.

For the successful conduction of the mission measures must be taken to ensure a safe flight of the flight experiment. This includes extensive analyses on the trajectory from payload adapter detaching to re-entry segment touchdown by means of Monte-Carlo simulations. In addition, a detailed Failure Modes, Effects and Criticality Analysis (FMECA), including a Failure Response Mode (FRM) approach has been conducted to identify possible FRMs that can lead to a deviation from the nominal trajectory. This in turn feeds into the trajectory simulation cases to provide casualty expectancies [24]. The individual risk on a per flight basis has to be lower than about 10^{-6}, i.e. a likelihood of causing a casualty of less than one in a million. Additionally, the goal of the analysis was to prove a probability of less than 10^{-4} for collective third-party risk. Both thresholds are specified and mandated by the Australian Space Agency (ASA) Flight Safety Code [40].

The conducted FMECA includes a failure probability prediction and shows a probability of failure occurrence of 23.2 % for the mission. With this failure probability the casualty numbers required by the ASA Flight Safety Code can be met [41]. Thus, it can be concluded that the flight experiment can be conducted safely and within the ASA rules.

Finally, a manual Flight Termination System (FTS) is incorporated into the design of ReFEx. This system is fully independent from the internal systems of the experiment and is powered by a separate energy source. A manual termination signal from range head will activate the FTS. Once activated, it ensures an aerodynamically unstable configuration of the vehicle, leading to a close to ballistic trajectory from this point forward. The technical means of inducing the state of the vehicle are the rudder which is spring loaded to passively revert to a full deflection angle (end stop position). Only as long as power is supplied to the actuator - against the force of the spring - it will remain in the commanded position. Should power fail for any reason, the rudder will move to the end stop position.

7. AIV

7.1. Model philosophy

CALLISTO uses a classical QM-FM model philosophy on system level for both the Top- and Bottom Block Assemblies in separate campaigns. The VEB Top Block QM campaign is designated to take place at DLR premises. All Subsystems FMs are manufactured separately and are then are shipped to the respective integration facilities in Switzerland and Japan. The FM final assembly will take place at the Guyana Space Center prior to the first launch campaign. A protoflight model approach is used for part of the ALS and for the LH2 tank.

ReFEx uses an “inverse” 2 + 2 hybrid protoflight model philosophy on system level to cover the boundary conditions implied by the sounding rocket launch vehicle, combining 2 stripped-down qualification models, one protoflight- and one ground reference model. Final launcher integration will take place at the Koonibba launch facility in

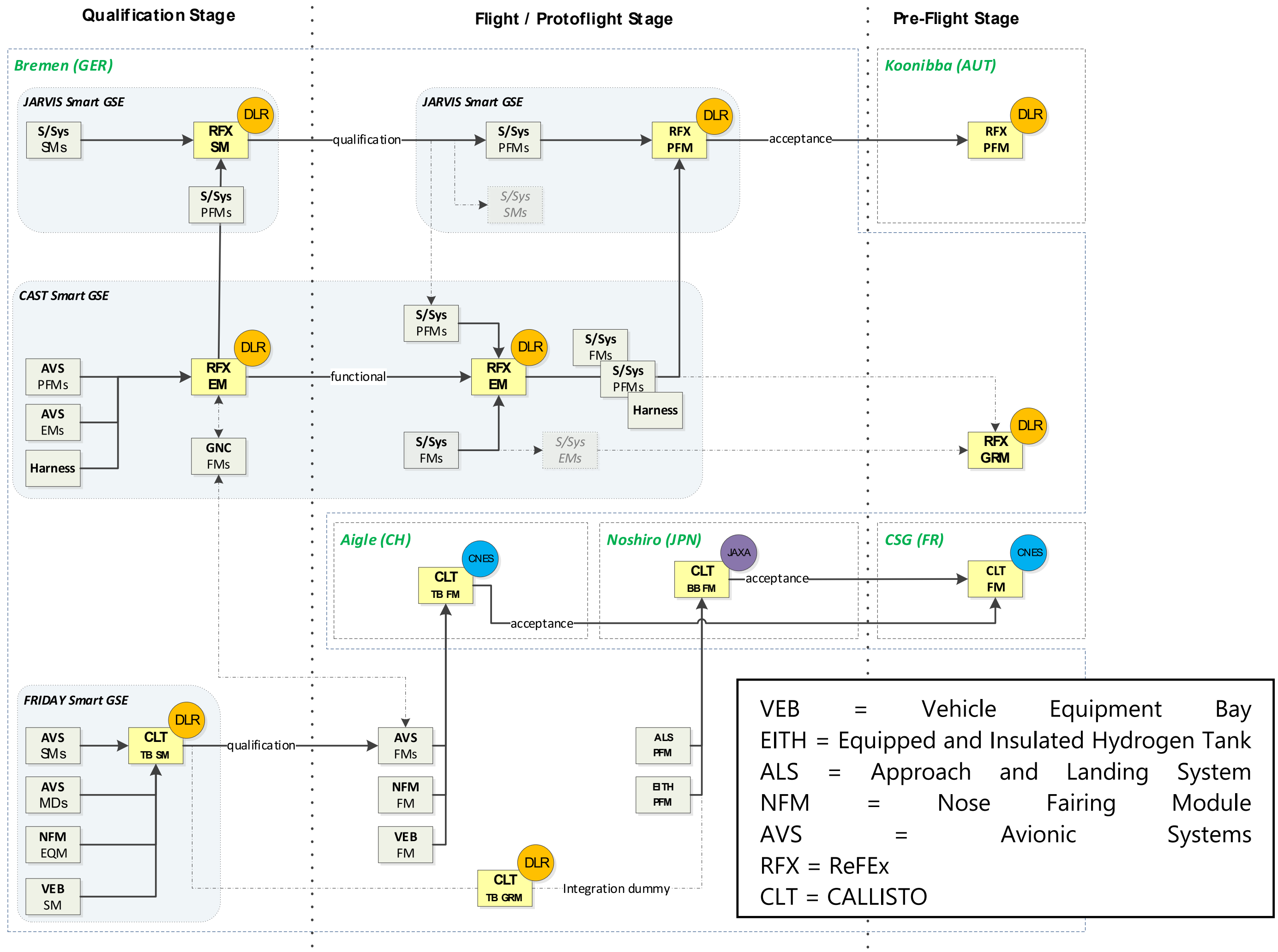

Fig. 16. AIV model philosophy and synergies of CALLISTO & ReFEx.

Southern Australia. Since the Guidance System on ReFEx and CALLISTO are shared technology, the ReFEx EM campaign is used to pre-qualify the AOCS capabilities for further usage on the CALLISTO project. Both model philosophies and the resulting synergies are shown in Fig. 16.

7.2. *AIV approach*

Since it is very challenging for a research organization to manage two large scale flight missions in parallel, the ReFEx and CALLISTO AIV campaigns at DLR make use of a number of synergies to optimize workforce and material. An overview of the applied methods and technologies to enable the teams to manage the complex and entwined AIV campaigns are given in the following sections.

The campaigns consist of the following programs.

- EM Campaign (ReFEx) with attached GNC development and verification program (Synergy)
- SM Campaign (ReFEx), environmental verification at external facility
- SM Campaign (*CALLISTO* Top Block), environmental verification within DLR premises

System integration campaigns will adapt lean manufacturing approach derived from the Toyota Production System (TPS) [42]. This includes.

7.2.1. *Cellular just-in-sequence manufacturing*

- System assembly breakdown to manufacturing cells (CAST, ReFEx, *CALLISTO*)
- Standardized, interchangeable sets of off-the-shelf tools for every integration cell
- Process synchronisation of all integration cells to optimize the campaign timeline (“Just in sequence” approach)
- Integration tree designed to allow maximum interchangeability of integration along the campaign sequence to cover delivery delays and subsystem non-conformances
- Synchronisation of MIPs/KIPs accordingly (mandatory and key inspection points, respectively)
- One integrated team for both projects grouped for competences

7.2.1.1. *Equipment and processes.*

- High flexibility and low lead times in ground support equipment design and adaption due to the use of a Smart GSE approach

- Reduction of highly specialized tools and measurement equipment in favour of simple, multi-functional solutions

- Use of rapid prototyping for structure design change fit checks

- Use of rapid prototyping for GSE and tool design

7.2.1.2. *Workload management.*

- All subsystem engineers are directly involved in all AIV processes regarding their respective subsystem.

- Short daily shift kick-off meeting (“Obeya”) including all AIV teams, subsystem engineers and PA to directly discuss current status, problems, procedures and processes.

- Decision responsibility for all AIV related topics during the running campaign is concentrated on the respective AIV team leader to reduce hierarchy drag.

- All involved engineers have to be able to perform all basic tasks to react flexible in cases of illness, absence or staff rotation.

7.2.1.3. *Integrated AIV team.*

- Utilization of one combined team for all flight projects at the DLR Institute of Space Systems

- CIP (continuous improvement process) towards AIV process database in direct feedback with PA

- Usage of heritage processes from AISat, MASCOT, InSight, CompSat Eu:CROPIS and MMX

- Integration of PA into the AIV teams for close involvement to gain shorter response times for NCRs

- On-the-fly modification for integration procedures with Red-, Yellow, Green-Tag-System to indicate open work, deviations and comments in the procedure document

7.2.1.4. *In-house synergies.*

- Use of In-House equipment and facilities to minimize transportation effort and costs

- Direct involvement of the Advanced AIV working group to quickly deploy newly developed technologies (Smart GSE, Augmented Reality)

7.2.1.5. AIV technologies. The ReFEx project serves as pathfinder mission for the application of newly developed AIV methodologies in the frame of the Advanced AIV research focus of the DLR institute of space systems. The CALLISTO SM/QM campaign is making direct use of the validated methodologies developed for ReFEx. The applied technologies are:

Product and Engineering Data Management: An AIV centered Information Database (ENIGMAS – Engineering Information and Ground Operations Management System) serving as single source of truth for all relevant engineering data, such as CAD models, interface descriptions and photo documentation. This also enables AR-supported process control.(See. Fig. 17)

Smart GSE CAST (Core Avionics System Test Bed): A general-purpose test facility for avionic architectures. The system consists of a set of EGSEs for power supply, RF communication and command infrastructure which is connected with a Bench Carrier MGSE over a standardized interface, allowing test automation. The Bench Carrier MGSE uses a metal grid surface to accommodate the electrical components and provide a common electrical ground. CAST is used for both AVS validation of ReFEx and the design and development support for the ReFEx and CALLISTO GNC architecture (see Fig. 18).

JARVIS and FRIDAY: Two heavy duty industrial robots have been introduced as multi-purpose 6-DoF MGSE platforms. These platforms provide sufficient motorization margins to handle medium-sized space hardware and allow a set of in-line verifications, such as mass determination without spanning operations. Furthermore the 6-DoF capabilities are a huge benefit in operator ergonomics. For ReFEx a KUKA KR500 with a 2830 mm extended position is used. (JARVIS – Joint Assembly Robot for Versatile Integration of Spacecraft). For CALLISTO, a similar model with 600 kg payload is deployed (FRIDAY – Flexible

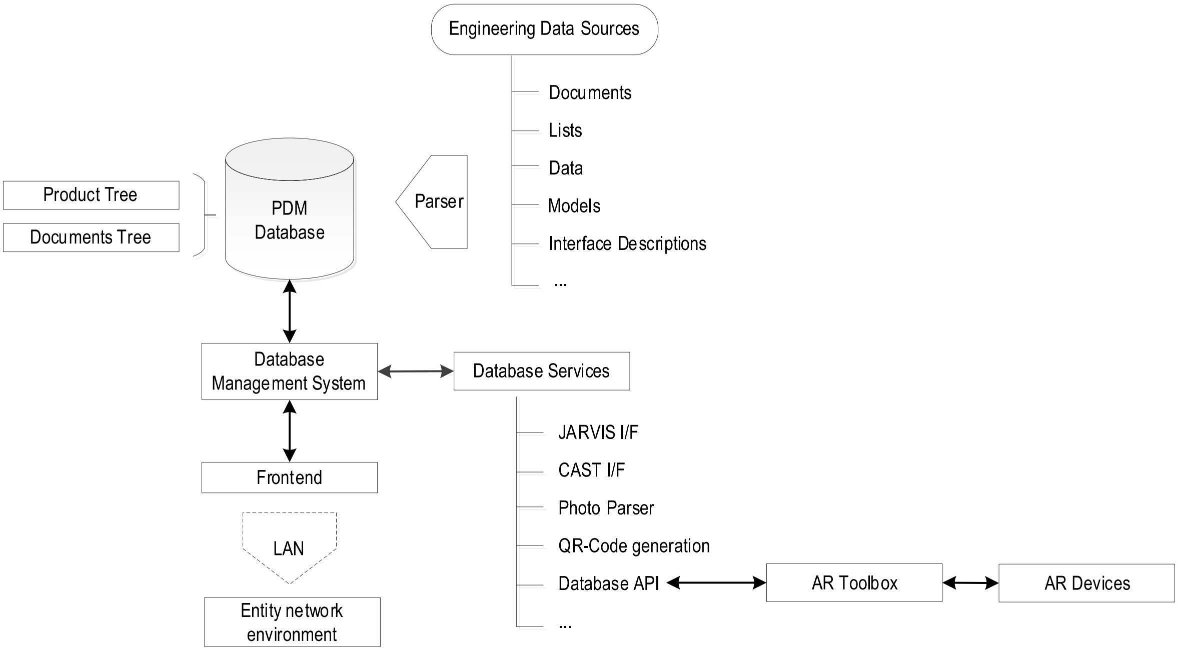

Fig. 17. ENIGMAS functional block diagram.

Robotic Interface for Dynamic Assembly of Spacecraft and paYloads). It is foreseen to mobilize the CALLISTO system to add shop floor transport capabilities. An overview of the integration facility setup is given in Fig. 19.

8. Conclusion and outlook

Within the last few years RLVs have shown their potential not only to reduce launch costs but also provide benefits in other areas such as reliability, responsiveness and direct observability of incremental technological improvements. This has led to a number of new launch vehicles adopting RLV technologies during their development, leading to a trend of more operational RLVs in the future. In general, there are two methods to provide the necessary forces to return a reusable stage safely to the ground. This can either be done by propulsive means or by using the aerodynamic forces acting on the vehicle. Often times these methods are combines to some degree, depending on the application at hand.

With the CALLISTO and ReFEx flight experiments DLR is investigating both of these options in detail. The goal is to gain experience with the technologies involved, de-risk them and also form a decision matrix depending on specific application and supported by actual flight data. This know-how will be very useful in making the right decisions for the future RLVs in Europe.

The paper highlighted some key technologies involved and investigated in each of the flight experiments, with a focus on GNC technologies. It can be seen that the knowledge gained will complement previously gained flight data at DLR nicely and form a comprehensive database, singularly unique in Europe, from which an informed decision on the best future RLV options can be drawn.

CRediT authorship contribution statement

Peter Rickmers: Project administration, Writing – original draft, Writing – review & editing. **Etienne Dumont:** Project administration, Writing – original draft, Writing – review & editing. **Sven Krummen:** Writing – original draft, Writing – review & editing. **Jose Luis Redondo Gutierrez:** Visualization, Writing – original draft, Writing – review & editing. **Leonid Bussler:** Visualization, Writing – original draft, Writing – review & editing. **Sebastian Kottmeier:** Visualization, Writing – original draft, Writing – review & editing. **Guido Wübbels:** Validation,

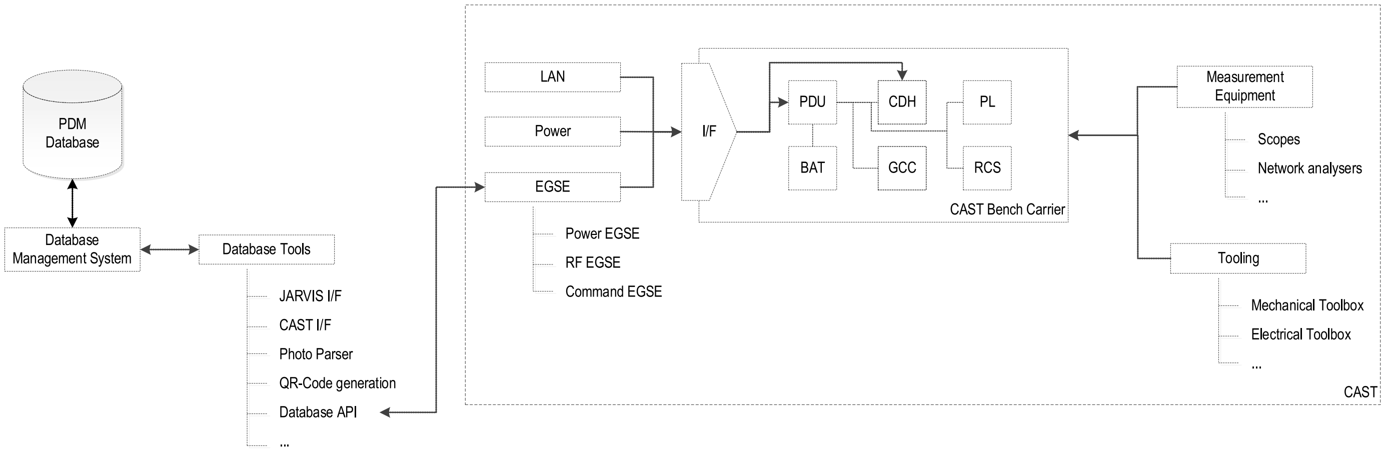

Fig. 18. CAST functional block diagram.

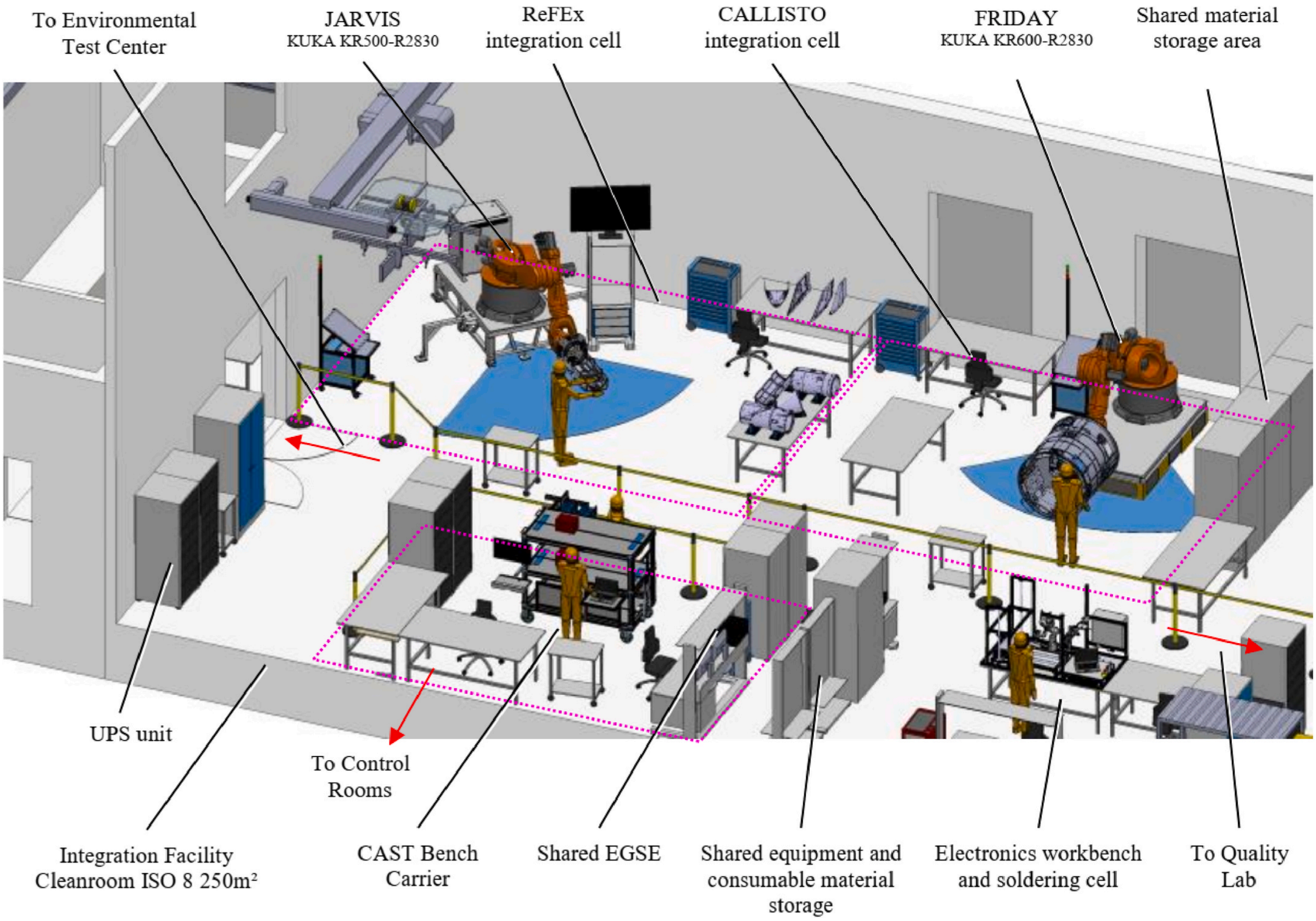

Fig. 19. DLR Institutes of Space Systems AIV Facility layout.

Visualization, Writing – original draft, Writing – review & editing. **Hauke Martens:** Validation, Writing – original draft, Writing – review & editing. **Svenja Woicke:** Validation, Visualization, Writing – original draft, Writing – review & editing. **Marco Sagliano:** Validation, Visualization, Writing – original draft, Writing – review & editing. **Janis Häseker:** Writing – original draft, Writing – review & editing. **Lars Witte:** Visualization, Writing – original draft, Writing – review & editing. **Martin Sippel:** Validation, Writing – review & editing. **Waldemar Bauer:** Visualization, Writing – original draft, Writing – review & editing. **Hendrik-Joachim Peetz:** Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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