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ORIGINAL PAPER

CALLISTO: on the design and development of a reusable first stage demonstrator

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Abstract
CALLISTO is a collaborative project between JAXA, CNES, and DLR, focused on developing and operating a scaled reusable vertical-takeoff vertical-landing rocket stage demonstrator. This initiative is a crucial step for advancing reusable launch vehicle (RLV) technology in Europe and Japan. Significant strides have been made during the recently completed phase C of the project, particularly in aerodynamic modeling, guidance, navigation, and control design, landing dynamics, and flight domain definitions. These advancements facilitate the development of future operational vehicles and provide insights applicable to other RLV projects. This paper provides an update on the design and development status of the CALLISTO vehicle. It outlines the program objectives, focusing on mission design, vehicle life cycle, and their distinctions from legacy expendable launch vehicles in Europe and Japan. Details of the flight test plan, including in-flight experimentation, are elucidated, demonstrating incremental progress toward acquiring key technology and preparing for high-energy missions. Furthermore, the paper offers an overview of the CALLISTO vehicle's development status, highlighting key architectural features such as load-carrying structures, avionics, rocket propulsion system, flight control systems, and approach and landing system. It underscores the milestones achieved over the past years and the progress toward the first flights. With a flight test campaign to be performed at Europe's Spaceport in French Guiana, the CALLISTO project signifies a crucial step toward enhancing launch system affordability, competitiveness, versatility, and sustainability. This collaboration among three space organizations highlights the importance of shared expertise in advancing RLV technology and preparing for the next generation of launch vehicles.

Keywords CALLISTO · Reusable launch vehicle (RLV) · Vertical takeoff vertical landing (VTVL)

Abbreviations

AEDB	Aerodynamic database
AIV	Assembly, integration, and verification
ALS	Approach and landing system
ATDB	Aerothermal database
CFD	Computational fluid dynamics
CNES	French National Center for Space Studies
CSG	Guiana Space Center
DCU	Deployment control unit
DES	Detached eddy simulation

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DGNSS	Differential global navigation satellite system
DLR	German Aerospace Center
EMC	Electromagnetic compatibility
EKF	Extended Kalman filter
EQM	Engineering qualification model
FCS	Flight control system
FCS/A	Aerodynamic control system
FCS/R	Reaction control system
FCS/V	Thrust vector control system
FDR	Flight data recorder
FM	Flight model
FNS	Flight neutralization system
GHe	Gaseous helium
GN2	Gaseous nitrogen
GNSS	Global navigation satellite system
GNC	Guidance, navigation, and control
HNS	Hybrid navigation system
HiL	Hardware-in-the-loop
IMU	Inertial measurement unit
JAXA	Japan Aerospace Exploration Agency
LH2	Liquid hydrogen
LOX	Liquid oxygen
MRO	Maintenance, repair, and overhaul
MVM	Mode vehicle manager
NFM	Nose fairing module
NTC	Noshiro Test Center
OBC	Onboard computer
QM	Qualification model
RANS	Reynolds averaged Navier–Stokes
RF	Radio frequency
RLV	Reusable launch vehicle
RPS	Rocket propulsion system
TM/TC	Telemetry/telecommand
TPS	Thermal protection system
TRL	Technology readiness level
VEB	Vehicle equipment bay
VTVL	Vertical takeoff vertical landing
WTT	Wind tunnel test

1 Introduction

In recent years, reusable launch vehicles (RLVs) have gained significant attention in the global aerospace industry for their potential to significantly reduce launch costs and increase mission frequency. By enabling the reuse of key rocket components, RLVs offer the promise of more sustainable and economically viable space access. Notably, companies such as SpaceX have already demonstrated the commercial success of RLV technology, highlighting the growing demand for reusable systems to ensure competitiveness in the space sector. This shift toward reusability reflects a broader industry trend to improve cost-efficiency, enhance sustainability, and increase flexibility in space missions. Europe and Japan have increased efforts to remain competitive and meet the demand for cost-effective space access [1, 2].

In this context, the CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss-Back Operations) project represents a joint initiative between the Japan Aerospace Exploration Agency (JAXA), the French National Center for Space Studies (CNES), and the German Aerospace Center (DLR). It aims to master the technical and operational challenges associated with vertical-takeoff vertical-landing (VTVL) systems through a reusable technology demonstrator vehicle. By leveraging the expertise of these three space organizations, CALLISTO serves as a platform to mature key technologies that will contribute to future reusable launch systems. This collaboration represents a unique example of international cooperation, bringing together technical expertise from Europe and Japan to address the challenges of reusability in space launch vehicles [3].

CALLISTO's primary objective is to advance RLV technology by designing, testing, and operating a reusable first-stage demonstrator, focusing on areas such as GNC, landing systems, propellant management, aerodynamics, and thermal protection. Unlike traditional expendable launch vehicles, CALLISTO is designed for multiple reuses, introducing challenges in maintenance, refurbishment, and operational concept. The insights gained from CALLISTO will play a crucial role in informing the development of future reusable launch vehicles in both Europe and Japan.

Following the successful completion of the System Critical Design Review (CDR-S) in late 2023, the project is now transitioning from the detailed design phase to the assembly, integration, and verification (AIV) phase. In this context, this paper will present a detailed update on the recent development and implementation status of CALLISTO. The focus will be on key contributions from DLR, including the development of structural components, propellant management, GNC and flight control systems, landing system, avionics, and aerodynamics. By providing a comprehensive overview of the project's objectives and milestones, this paper aims to present the incremental progress toward demonstrating key VTVL technologies.

In the following sections, the paper will first provide an overview of the project's goals, mission design, and vehicle life cycle, before delving into the technical aspects of the individual subsystems of the vehicle. A status update on the most recent developments and progress achieved will also be presented, outlining the next steps toward the flight campaign. Finally, the paper concludes with reflections on the achieved progress and its broader implications for the future of RLV technology.

2 Project overview

2.1 Project objectives

The CALLISTO project was initiated in 2017 through a trilateral agreement between DLR, CNES, and JAXA, with the objective to develop and demonstrate reusable vertical-takeoff vertical-landing (VTVL) technology, which is viewed as a key enabler for reducing launch costs and increasing sustainability in space access.

CALLISTO focuses on both technical and economic goals. Technically, the project aims to advance key technologies, such as guidance, navigation, and control (GNC), propellant management, structures and actuators, thermal protection, and landing systems for reusable launch vehicles. Economically, the project seeks to optimize maintenance, repair and overhaul (MRO) processes to reduce costs and turnaround time between flights. Furthermore, to mimic real-world operational conditions as far as possible, CALLISTO has been designed in a mass-optimized way and will be operated from an active commercial spaceport, the European spaceport in Kourou, in parallel to the ongoing Ariane 6 and Vega C campaigns. These additional aspects imply further complexity, as well as operational and regulatory constraints on the project.

The CALLISTO program is building on the heritage of the three partners, which has direct implications on the sharing responsibilities as shown in Fig. 1. For instance, the RSR-2 engine used by CALLISTO is an improved version of the RV-X engine, developed by JAXA with MHI. The ground segment is situated at the former Diamant launch site at the Guiana Space Center (CSG) and is under CNES responsibility, which has an extensive experience in this domain for more than half a century. DLR is responsible for the development of several new launch vehicle subsystems, for example the approach and landing system (ALS) and the hybrid navigation system (HNS). Both subsystems are based on more than 15 years of experience in the domain of landing systems, especially on celestial bodies, and the design of low-cost multi-sensor navigation systems.

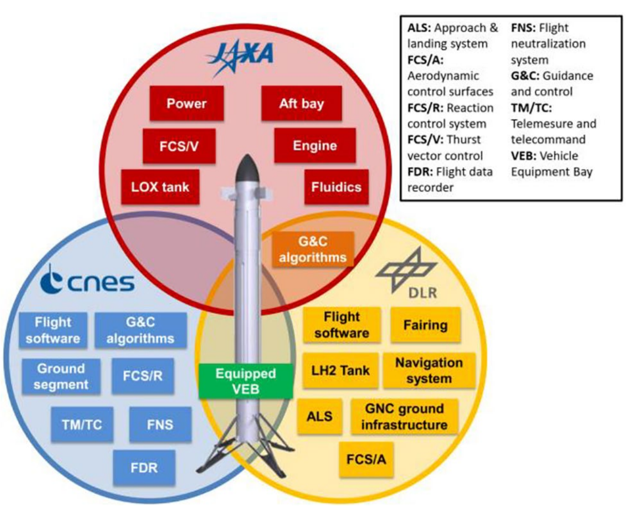

Fig. 1 Main subsystems of the CALLISTO vehicle, categorized by workshare between the project partners [4]

By the end of the project, CALLISTO aims to increase the technology readiness level (TRL) of key technologies and to provide valuable insights for the future design of reusable launch systems in both Europe and Japan. Furthermore, the project will generate critical data on economic feasibility, focusing on low-cost and timely maintenance, repair, and overhaul (MRO) operations between flights. This gained knowledge will allow to ease, de-risk, and optimize the design of future operational vehicles. In particular, it is expected that these key technologies can enable a significant reduction of cost per payload mass for mid- to heavy-lift orbital launch systems, and likewise for suborbital vehicles, by enabling VTVL recovery and reusability. While CALLISTO is a scaled vehicle, the demonstrated objectives (e.g., deep throttling and reignition, GNC and flight control, propellant management, landing dynamics, and MRO processes) are selected for their scalability to future operational first stages.

2.2 Mission design

The CALLISTO project is centered around the development of a reusable vertical-takeoff vertical-landing (VTVL) demonstrator vehicle, which integrates key technologies representative of the first stage of a reusable launch vehicle (RLV). The vehicle, which is 13.5 m long, 1.1 m in diameter, and has a maximum takeoff mass of under 4 tons, is designed to showcase and validate the potential for reuse and affordability in future launch systems. CALLISTO is powered by the Japanese RSR-2 rocket engine, capable of in-flight reignition and deep throttling, and uses liquid oxygen (LOX) and liquid hydrogen (LH2) as cryogenic propellants. The vehicle's flight control is managed by three distinct systems: the thrust vector control system of the main engine (FCS/V), a reaction control system featuring eight hydrogen peroxide propelled control thrusters (FCS/R), and an aerodynamic control system with four deployable fins (FCS/A). A deployable four-legged approach and landing system (ALS) is employed to ensure safe vertical landings.

The subsystems of the CALLISTO vehicle are organized into several functional architectures, which include the mechanical architecture, rocket propulsion system, flight control systems, approach and landing system, guidance navigation and control system (GNC), avionics, aerodynamics and aerothermodynamics, flight neutralization system, and conditioning system. An overview of the components of these subsystems can be seen in Fig. 1, also indicating the shared responsibilities between the project partners. Further details about the design and development progress of each subsystem will be presented in Chapter 3.

The test campaign for CALLISTO will consist of up to ten flights, conducted at the Guiana Space Center (CSG). These flights will incrementally increase in complexity, allowing the project to de-risk vehicle operations while progressively validating key RLV technologies. The flight classes range from low-altitude, low-energy tests aimed at final qualification of vehicle subsystems to higher-altitude, higher-velocity flights designed to validate RLV technologies in conditions representative of operational missions [5]. An overview of the flight envelopes for the different flight classes is given in Fig. 2.

In brief, the flight campaign starts with low-energy vertical hop tests to characterize the vehicle and to validate touchdown performance with the landing legs already deployed before lift-off [6]. It then progresses to medium-energy flights that expand the envelope and introduce in-flight configuration changes, such as unfolding of aerodynamic surfaces and landing legs, as well as basic lateral maneuvers. Finally, high-energy flights target a representative sequence for return-to-launch-site (RTLS) first-stage operations, including unpowered aerodynamically controlled descent and engine reignition prior to touchdown, as shown in Fig. 3. These final flights will also be used to validate the performance of the propellant management system via a dedicated sloshing-excitation maneuver.

All flights will be conducted with the same vehicle to demonstrate its reusability and evaluate the necessary effort for maintenance, repair, and overhaul (MRO) operations between flights. These incremental tests will therefore provide critical data to optimize both vehicle design and refurbishment processes, advancing the development of future reusable launch vehicles.

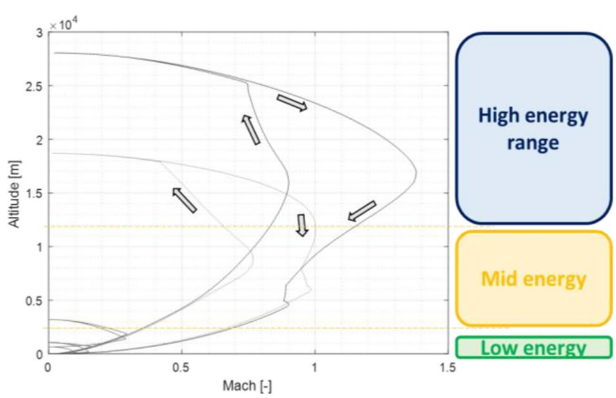

Fig. 2 Flight envelope of CALLISTO for the different flight classes during the incremental flight test campaign [5]

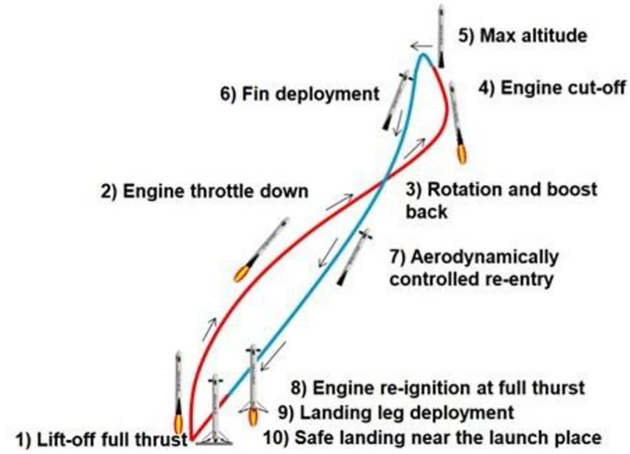

Fig. 3 Sketch of the flight profile with main events for the final demo mission of CALLISTO

2.3 Vehicle life cycle

The CALLISTO project adopts various model philosophies for its subsystems, tailored to the individual design maturity, resource availability, and risk acceptance [7]. The implementation and verification strategy primarily follows a prototype approach, which intends to verify the design on dedicated qualification models (QM), and to verify only correct workmanship on the flight models (FM) via acceptance tests. This covers environmental and functional verification on equipment, product, and system levels.

The initial focus lies on qualifying the vehicle modules as defined in Sect. 3.1, particularly the top block, which includes the structural model (SM) of the vehicle equipment bay (VEB) and the engineering qualification model (EQM) of the nose fairing module (NFM). Besides static and dynamic mechanical tests, this phase includes acoustic verification and antenna characterization tests. Following these tests, the top block SM supports integration activities for the bottom module in Japan, including the Hot-Firing Test Campaign at the Noshiro Test Center (NTC). In parallel, the top block flight model (FM) undergoes its integration and acceptance test campaign in Switzerland before final integration with the bottom module flight model in French Guiana. A combined end-to-end test phase verifies both the vehicle and the ground segment ahead of the first test flights.

Minimizing the turnaround time and effort between flights is crucial for demonstrating CALLISTO's reusability during the test and demo flight campaign. Therefore, it is necessary to define a detailed maintenance, repair, and overhaul (MRO) plan. In this plan, all MRO activities are categorized by duration and necessity, ranging from simple inspections or data analyses to more complex refurbishments, such as replacement of consumables or repair of thermal protection systems (TPS). These procedures will be verified during qualification campaigns to ensure rapid, efficient vehicle servicing between flights.

At the end of the vehicle's operational life, the post-flight analysis will provide critical data for the design of future vehicles. After the final test flight, the vehicle will be disassembled and its components returned to the respective project partners in Japan, Germany, and France.

2.4 Ground segment

The ground segment for the CALLISTO flight campaign is located at the Guiana Space Center (CSG) in Kourou, French Guiana. The chosen site, known as Zone Diamond, was originally used for the launch of the Diamond B rocket in 1970. Situated approximately 2 km from the former Ariane 5 launch site (ELA3), Zone Diamond is smaller than other launch areas dedicated to the Ariane and Vega programs, but is being adapted specifically to meet the needs of CALLISTO.

The launch site is currently undergoing significant refurbishment to support CALLISTO's vertical-takeoff vertical-landing (VTVL) operations. Key developments include the dismantling of the old mobile gantry tower as shown in Fig. 4, and the installation of new technical and ancillary infrastructure. This includes retrofitting of the vehicle preparation hall (VPH), as well as the preparation of the launch and landing zones, tailored to the vehicle's specific requirements [7].

The majority of the ground segment development is under CNES' responsibility, while the other project partners, JAXA and DLR, contribute ground support equipment (GSE) for vehicle subsystem operations. Notably, DLR is responsible for providing the differential global navigation satellite system (DGNSS) reference station. This system will generate a GNSS correction signal, transmitted to the CALLISTO vehicle during flight via a radio frequency (RF) link, enabling the onboard hybrid navigation system (HNS) to enhance its position, velocity, and attitude estimates.

Fig. 4 Dismantling of the former infrastructure at Diamant launch site in CSG, to prepare for the installation of CALLISTO's ground segment [8].

While the ground segment of CALLISTO is tailored to the conditions and requirements at CSG, the key reusability technologies and overarching operational concepts are intended to be transferable to future vehicles and, with site-specific adaptations, to operations from other European and Japanese spaceports.

3 Vehicle design and implementation

3.1 Mechanical architecture

The mechanical architecture of the CALLISTO vehicle consists of five modules, divided into two main blocks: top block and propulsion block.

The top block comprises the nose fairing module (NFM) and the vehicle equipment bay (VEB). These modules house many avionics components, such as the hybrid navigation system (HNS) and the onboard computer (OBC). Additionally, the foldable aerodynamic control surfaces (FCS/A) and reaction control thrusters (FCS/R) are integrated into the top block.

The propulsion block includes the LOX and LH2 tank modules, which form the core of the vehicle's propellant management system. These tanks are equipped with various feed and pressurization lines, as well as with external cable ducts providing necessary system connectivity. The bottom module, located at the aft of the vehicle, houses the RSR-2 rocket engine and the corresponding thrust vector control system (FCS/V), as well as further avionics equipment. The approach and landing system (ALS) is attached to the bottom module and includes four landing legs and a pneumatic deployment system.

An overview of CALLISTO's main components and load-carrying structures is provided in Fig. 5. DLR is responsible for the development of several critical components, including the NFM [9], VEB structure, LH2 tank, FCS/A, and the ALS [10].

Designing reusable load-carrying structures for CALLISTO is particularly challenging because they must withstand complex load conditions across multiple flight cycles [1]. Detailed studies have been conducted to select materials and optimize designs, ensuring that the structures meet performance requirements for all phases of the vehicle's life cycle. Special emphasis is placed on foldable and stowable components, which enable changes in the vehicle's external shape as needed for different flight phases.

Qualification tests are currently underway using flight-representative qualification models (QM) to verify the mechanical integrity of the structures. In particular, static

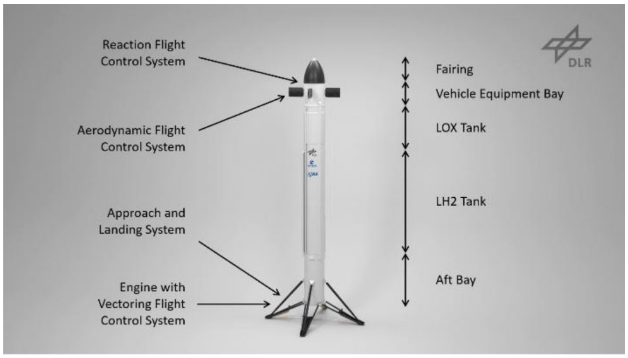

Fig. 5 Overview of CALLISTO's main components and modules

Fig. 6 Static test setup of the top block structural model

Fig. 7 CFD simulation of LH2 propellant sloshing inside the tank during low-gravity flight phases

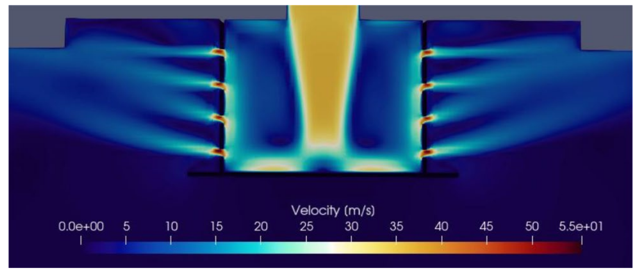

Fig. 8 CFD simulation illustrating the flow velocity on the LH2 tank diffusor

and dynamic load tests with the structural model (SM) of the top block are currently conducted in Bremen and Munich, as can be seen in Fig. 6. These tests replicate the stress and vibrations encountered during flight, ensuring stability against forces exerted by systems like the FCS/A. Upon successful completion of the qualification tests, flight models (FM) will be assembled and tested before the flight campaign.

3.2 Rocket propulsion system

The CALLISTO vehicle is powered by the Japanese RSR-2 engine, an optimized version of the original RSR engine developed for the RV-X vehicle. The RSR-2 engine runs on an expander bleed cycle driven by two turbo pumps feeding the cryogenic propellants: liquid oxygen (LOX) and liquid hydrogen (LH2). With deep-throttling capabilities down to 40% of maximum thrust, the engine enables precise throttle control required for vertical landing. The thrust vector control system (FCS/V) provides further pitch and yaw control of the engine thrust.

JAXA is responsible for developing the LOX tank and fluidic systems, while DLR has developed the LH2 tank, which is currently being manufactured by MT Aerospace. Pressurization of the LOX tank is achieved through gaseous helium (GHe) stored in the bottom module, whereas the LH2 tank is pressurized using gaseous hydrogen (GH2) during powered flight phases. In engine-off or idle phases, the LH2 tank is also pressurized by GHe.

One of the key challenges in managing cryogenic propellants during low-gravity flight phases is mitigating sloshing, which can lead to increased mixing, condensation, and ullage pressure drops. To address this, ring baffles have been designed to dampen propellant sloshing inside the LH2 tank, with their design optimized using isothermal 3D computational fluid dynamics (CFD) simulations as shown in Fig. 7.

To further enhance pressurization efficiency, the design of the LH2 tank diffusor has also been refined through CFD analysis as shown in Fig. 8, ensuring efficient gas distribution within the tank [11]. Besides that, a 1D thermodynamic model has been established to simulate the LH2 tank's operations during chill down, filling, pressurization, venting, and in-flight phases, validating the functional performance of the propellant management system [12, 13].

3.3 Flight control systems

The CALLISTO vehicle features three distinct flight control systems (FCS) that can be activated individually or in combination, depending on the flight phase and test flight scenario [14]. These systems are designed to ensure sufficient control during all flight phases, from ascent to landing.

The thrust vector control system (FCS/V), developed by JAXA, controls the gimballed RSR-2 main engine. It is primarily responsible for steering the vehicle during ascent, including the tilt-over maneuver, and during final approach and landing. This system provides critical control during powered flight phases.

The reaction control system (FCS/R), developed by CNES, comprises eight hydrogen peroxide thrusters mounted at the vehicle equipment bay (VEB). These thrusters are mainly used for roll control and for general attitude control during flight phases with low aerodynamic pressure.

The aerodynamic control system (FCS/A), developed by DLR, consists of four deployable aerodynamic fins. These control surfaces are employed primarily during atmospheric descent to stabilize and control the vehicle's attitude when the engine is switched off. The fins provide pitch, yaw, and roll control during unpowered flight.

Each aerodynamic control surface includes a fin structure, a deployment mechanism, a latch, lock, and release mechanism (LLRM), instrumentation, and the main electromechanical actuator with its controller and power electronics. The fins remain folded during ascent flight and are deployed during the transition to descent, while the aerodynamic pressure is relatively low. The deployment occurs in two stages: first, the deployment mechanism rotates the fin 90 degrees outward, and second, the main actuator aligns the fin by 90 degrees with the airflow [15]. Once deployed, each fin can be individually controlled for precise attitude adjustments. However, the key challenges in the FCS/A design relate not only to the deployability and functionality of the fins, but also to constraints regarding the installation space, mass, and energy budget, as well as the thermal environment [16].

After the completion of the critical design review, extensive tests were conducted to verify the structural and functional integrity of the system. A combined deployment test of the fin structure and actuator mechanism was performed in Stuttgart. Additionally, a vibration test campaign was conducted in Stuttgart and Bremen, simulating low-frequency sine and random environments. By measuring the accelerations at several locations as depicted in Fig. 9, these tests helped to determine the fin's dynamic response and the results will be used to characterize and update the fin's structural dynamic properties for further analyses such as dynamic stability studies [17].

Fig. 9 Instrumented fin structure used during the vibration test campaign (unfolded, excitation in flow direction)

3.4 Approach and landing system

The approach and landing system (ALS) ensures that the CALLISTO vehicle can land vertically and remain stable without external support. Its key functions include absorbing the vehicle's residual kinetic energy during touchdown, providing both dynamic and static stability, maintaining ground clearance, and minimizing load transmission to the rest of the vehicle. This way, the ALS facilitates a safe transition from flight to ground phase.

The ALS system consists of four foldable landing legs, which are locked against the vehicle's aftbay during ascent and descent flight. Just before touchdown, a pneumatic deployment subsystem activates the legs. Once fully extended, two latching mechanisms in the telescopic strut assemblies prevent retraction due to external forces. This way, the legs remain locked until post-landing operations. Additionally, the legs are equipped with an ablative thermal protection system (TPS) to withstand the harsh thermal environment during descent, which is caused by the engine plume.

The ALS design was solidified during the critical design review (CDR), which also finalized the main interface definitions to adjacent structures, such as the aftbay. Since then, simulations and subsystem tests focused on touchdown dynamics and deployment have validated its functionality. However, challenges remain in replicating flight conditions, particularly aerodynamic forces and engine plume interactions, which can only be tested in actual flight scenarios. As a result, the qualification of the full ALS system will be approached with a hybrid method, combining component-level ground tests and correlated system-level simulations.

Currently, the procurement of qualification models (QM) and partial flight models (FM) is ongoing, with initial components already delivered to DLR. Qualification and acceptance testing are underway, although procurement remains challenging due to the complexity of components, limited supplier availability, and long lead times.

Key tests during the qualification campaign include vibrational and thermal environment simulations on equipment level, though fully representative conditions on system level will only be achievable in flight. As such, the ALS pressure vessel shown in Fig. 10, which stores the working gas for the pneumatic deployment of the legs, has already successfully passed its vibration qualification test in the beginning of 2024. Also, for the ALS controller shown in Fig. 15, the electromagnetic compatibility (EMC) and climate chamber qualification tests are currently ongoing. The vibration test campaigns of the ALS controller and the landing legs, which entail random as well as sine sweep runs over its entire life cycle duration, are under preparation.

The ground tests of the ALS landing leg assembly will be complemented by simulations on a virtual shaker to verify deployment functionality and structural compatibility under integrated conditions with the aftbay, as these conditions cannot be tested in a laboratory setup. Compatibility of the ALS with the rest of the vehicle will then first be checked during the hot-firing test campaign at the Noshiro Test Center (NTC). Here, besides the mechanical fit check, the thermal, kinematic, and mechanical compatibility of ALS will be tested as a leg deployment test will be conducted while the engine is running.

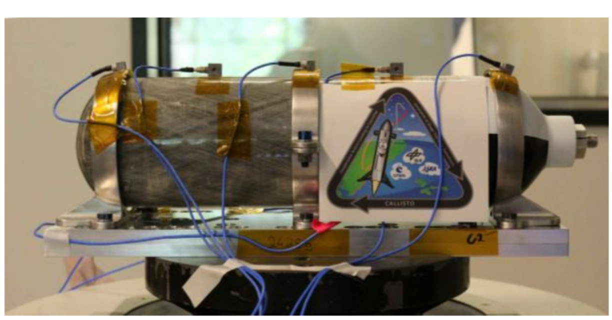

Fig. 10 ALS pressure vessel assembly mounted on the shaker for qualification tests

3.5 Guidance, navigation, and control system

The guidance, navigation, and control (GNC) system in CALLISTO has three primary objectives: to plan and command a feasible trajectory to the desired flight state (guidance), to estimate the vehicle's current state using sensor measurements (navigation), and to ensure that the vehicle follows the guidance commands while maintaining stability (control). These functions are essential for the successful operation of a reusable rocket, particularly for precision landing and maintaining stability throughout various flight phases.

As visualized in Fig. 11, the GNC system is divided into two main products: the onboard computer (OBC), which handles the guidance and control functionalities, including the mode vehicle manager (MVM), and the hybrid navigation system (HNS), which manages the navigation functions. Both hardware and software aspects are critical for these systems, with specific attention to algorithm development for accurate state estimation and control.

The OBC consists of a stackable architecture with two boards, one for processing and one for power supply, enclosed in a ruggedized housing shown in Fig. 12. This computer is responsible for executing both the guidance and control algorithms and for managing vehicle operations.

The guidance and control algorithms are developed in collaboration between DLR and JAXA, although this paper mainly focuses on the contributions made by DLR. These algorithms are tailored to the different phases of the demonstration flight, each with distinct requirements and challenges [4, 7, 18]. A key element of the system is the

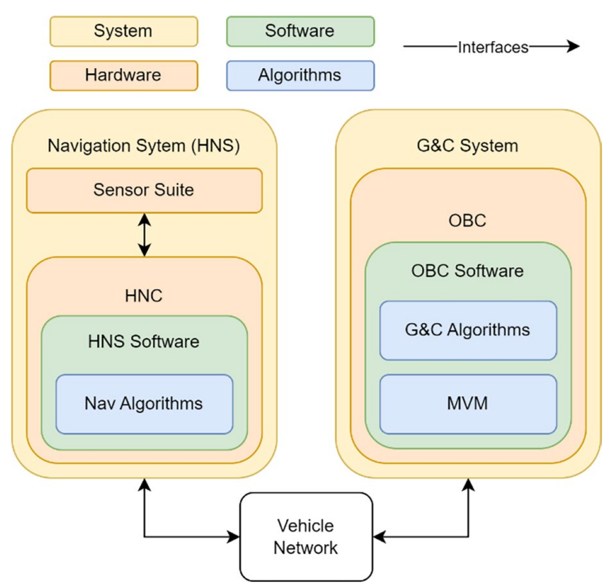

Fig. 11 Overview of the GNC system, which is composed of the HNS and the OBC, including flight software

Fig. 12 Engineering model of OBC

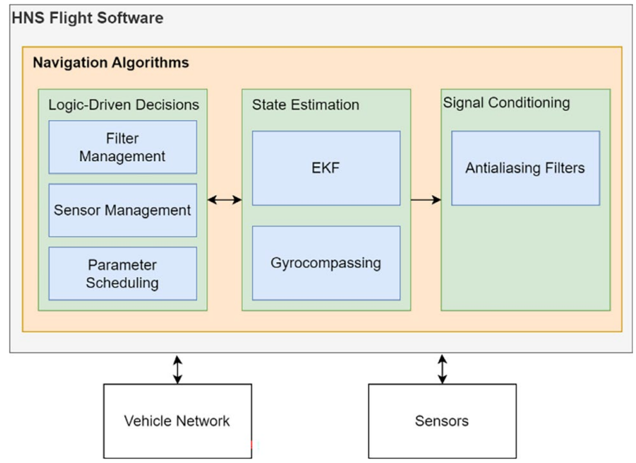

Fig. 14 Overview of the main components and interfaces of the HNS flight software

landing guidance algorithm, which allows for asynchronous trajectory updates in case of large discrepancies from the expected path. This algorithm merges pseudo-spectral methods [19, 20] with convex optimization, leading to the so-called sequential pseudospectral convex method that was successfully applied to 3-DoF aerodynamic descent guidance [21], 3-DoF powered descent [22] and more recently to 6-DoF powered descent applications [23].

The hybrid navigation system (HNS) fuses high-frequency inertial data from an inertial measurement unit (IMU) with lower-frequency data from a global navigation satellite system (GNSS) receiver. This combination provides accurate real-time state estimation by periodic correcting of drift errors. The HNS consists of the hybrid navigation computer, the GNSS receivers, and a tetra-axial IMU housed within the HNS box shown in Fig. 13. Additionally, a GNSS antenna is located in the nose of the vehicle, while a ground reference station is providing differential corrections (DGNSS) [4].

The HNS flight software handles the navigation algorithms, as well as the interfaces to the different sensors and network components, as visualized in Fig. 14. Here, a separation is made between implementation of logic-driven decisions, state estimation algorithms, and signal conditioning. An extended Kalman filter (EKF) is used to estimate the vehicle's state during flight, while a gyrocompassing algorithm is used to estimate the vehicle's attitude before launch.

Fig. 13 Structural model of HNS

The critical design reviews (CDR) for both the OBC and its algorithms, as well as for the HNS, are currently ongoing and expected to be completed by November 2024. Following these reviews, the next steps will include hardware-in-the-loop (HiL) testing, as well as continuation of the qualification campaigns. For the HNS, the focus will also be on integrating electronic components into a "flat" configuration, which will be functionally but not mechanically equivalent to the flight model.

3.6 Avionics system

The avionics system of the CALLISTO vehicle has two primary functions. First, it provides the infrastructure to control the vehicle's flight according to its mission profile. Second, it acquires and records flight data to ensure safe operations and vehicle re-validation before subsequent flights. To fulfill these functions, additional secondary functions include communication between avionics and equipment units, electrical power supply to all components, and the transmission of data from vehicle to ground segment, and vice versa.

Measurements are acquired via distributed sensors across all vehicle subsystems, which provide data for onboard control loops, for ground-based monitoring, and for post-flight analyses. The sensors' signals are sampled by different data acquisition units (DAU) and then distributed across the vehicle's Ethernet network.

DLR is responsible for four key avionic components: the onboard computer (OBC), the hybrid navigation system (HNS), the aerodynamic flight control system (FCS/A) controller, and the approach and landing system (ALS) controller [24]. While the former two are already discussed in Sect. 3.5, the latter two will be addressed below.

The FCS/A controller, developed in-house by DLR, provides the driver electronics for the main aerodynamic actuators and the fin unfolding actuators. To manage power consumption, a 48 V boost converter with large DC-link capacitors is used for short-term energy storage to reduce peak currents on the 28 V vehicle power bus. Communication between the controller and the vehicle is handled by an Ethernet gateway, which is responsible for mode management and control of the power electronics.

The ALS controller, also developed by DLR, integrates two functionally separated units into one housing: the deployment control unit (DCU) and the data acquisition central unit (DAC). The DCU handles control of the leg deployment system and provides operation-critical data to the OBC, while the DAC collects further sensor data for performance analysis and health monitoring. Additionally, four removable data acquisition landing gear units (DALs), one for each landing leg, will be installed for the first test flights [24].

Currently, all avionics systems are undergoing environmental qualification campaigns, including tests for electromagnetic compatibility (EMC), climatic conditions, and vibration environments. For example, the recently passed climate chamber test setup of the ALS controller is shown in Fig. 15.

3.7 Vehicle aerodynamics

The primary challenge in the aerodynamic analysis of CALLISTO is the creation of an extensive aerodynamic database that covers all flight configurations and conditions. Since typical trajectories include changes in the flight direction and possibly hovering phases, the aerodynamic flow direction can be arbitrary, so that aerodynamic coefficients need to be determined without any singularities. This database is crucial for the 6-DoF flight dynamics simulations, considering the vehicle's detailed shape, the complex mission profile, and the limited computational and experimental resources available. The aerodynamic performance significantly impacts the vehicle's overall mission success, necessitating a detailed and accurate estimation of aerodynamic coefficients. Classic engineering estimation methods alone cannot provide the required precision, which made it necessary to use a combination of computational fluid dynamics (CFD) models of varying complexity with wind tunnel tests (WTT) [25]. All results have been consolidated into the aerodynamic database (AEDB) and aerothermal database (ATDB) of the vehicle. Based on this combined approach, models on the aerodynamic uncertainties have also been derived, which are essential to ensure precision landings also under off-nominal conditions [26, 27].

During the initial conception phase, the overall aerodynamic shape of CALLISTO had to be defined and optimized. As the design progressed, additional tasks involved assessing the effects of various design details, including external protuberances such as cable ducts and fluid lines. Such influences can exemplarily be seen in Fig. 16, which illustrates the surface pressure distribution on the latest geometry version (1D). Based on these investigations, local aerodynamic optimizations have been implemented to reduce the negative effects of increased drag, as well as local mechanical and thermal loads [28].

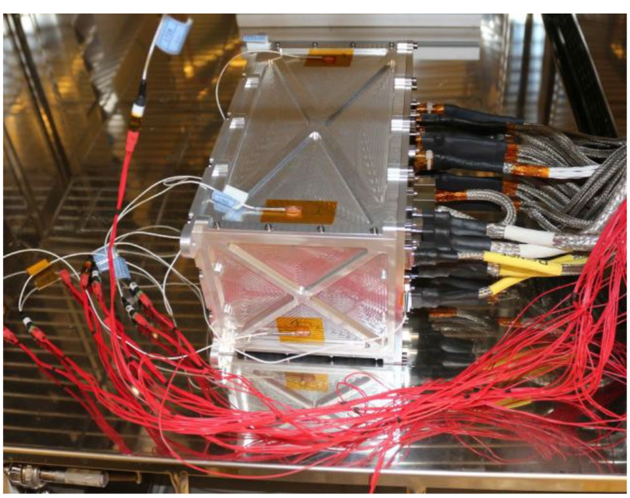

Fig. 15 ALS controller inside the climate chamber during qualification tests

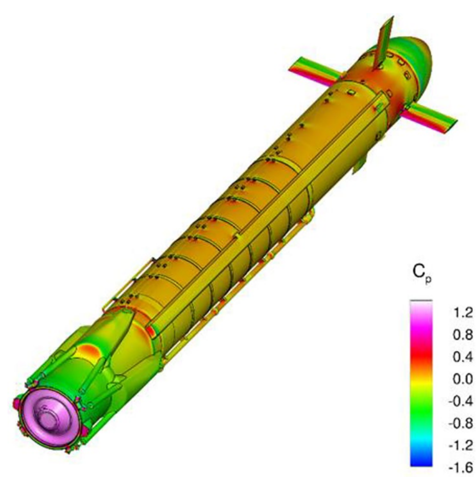

Fig. 16 Computed surface pressure distribution for the latest CALLISTO geometry (1D) during unpropelled flight ($M = 0.9$, AoA = 170 deg)

Ongoing aerodynamic investigations aim to validate and refine the aerodynamic databases. High-fidelity CFD methods are used to characterize both aerodynamics and aerothermodynamics to provide inputs for system-level databases, as well as product-level requirements. While earlier efforts focused on generating the database for aerodynamic and aerothermal loads using Reynolds averaged Navier–Stokes (RANS) simulations [29], the current work examines the uncertainties arising from geometric changes and different physical modeling approaches. Recent studies [30] have evaluated the impact of the design evolution from the 1C to the 1D geometry. These analyses of aerodynamic coefficients and flow fields showed minimal differences, indicating that the Phase C database remains valid. However, some local influences could be identified, such as for the landing leg geometry, which have been mainly caused by an increase in surface area.

Further research addresses the impact of turbulence modeling on the aerodynamic characteristics, particularly during powered descent flight. Previous studies [29] identified a significant influence of the turbulence model on engine plume length. To quantify this effect, a detached eddy simulation (DES) was conducted for a representative trajectory point, as can be seen in Fig. 17. Here, RANS results utilizing a Spalart–Allmaras turbulence model are compared with the DES results, showing temperature distributions in the flow center plane. The current and future work focuses on assessing the mean global coefficients, thermal loads, and the overall impact of turbulence modeling to identify the most suitable RANS turbulence closure.

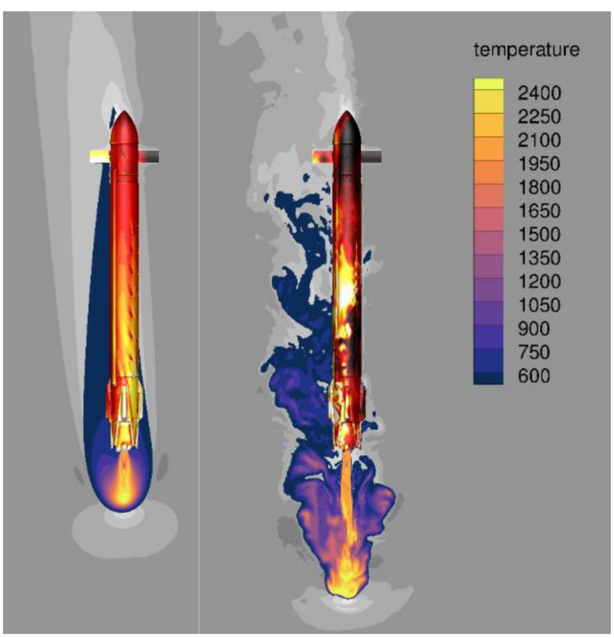

Fig. 17 Comparison of the flow field between RANS (Spalart–Allmaras) results (left) and instantaneous DES results (right), showing temperature distribution on the center plane ($M = 0.8$, AoA = 175 deg)

The ongoing aerodynamic work ensures that the databases accurately reflect the vehicle's behavior across all flight scenarios, contributing to mission success and vehicle design optimization.

3.8 Further subsystems

In addition to the systems detailed in previous sections, the CALLISTO vehicle integrates further subsystems that play a vital role in ensuring safe and reliable operations throughout its mission life cycle. Among these, the flight neutralization system (FNS) and the conditioning system are particularly noteworthy.

The flight neutralization system (FNS) is a safety-critical mechanism designed to terminate the mission in the event of a severe anomaly. In such scenarios, the FNS can safely destroy the vehicle to mitigate risks to both personnel and infrastructure. This system is integrated into the vehicle's core architecture, enabling immediate response in the case of a malfunction. Developed by CNES, the FNS leverages proven technology to ensure a robust response capability for CALLISTO's flight tests.

The conditioning system, also under CNES' responsibility, is designed to maintain optimal environmental conditions for vehicle components during ground phases. It flushes the vehicle compartments with gaseous nitrogen (GN2) to stabilize the internal environment, particularly to avoid the ingress of humidity or explosive atmospheres. This system ensures safe preparation for launch, protects sensitive equipment, and supports vehicle post-landing operations.

While not the primary focus of this paper, both the FNS and conditioning system are essential to the vehicle's overall design and safety strategy. Their development, testing, and integration have progressed in line with the other subsystems, contributing to CALLISTO's readiness for its upcoming flight campaign.

4 Status and progress toward the flight campaign

The CALLISTO project entered Phase D after completing the first part of the System Critical Design Review (CDR-S) in late 2023. This phase focuses on procuring qualification model components and some flight model hardware, particularly those with longer lead times. Finalization of the remaining product-level critical design reviews is currently ongoing and is expected to be completed by the end of 2024. This completion will facilitate the execution of the second and final part of the CDR-S, solidifying the project's progress toward the upcoming flight test campaign.

Significant progress was made in 2024, particularly in implementing key design aspects. For DLR, the qualification model of the nose fairing module (NFM) was successfully manufactured and passed its dynamic qualification tests. The vehicle equipment bay (VEB) structural model was also produced, with its structural test campaign starting in early September 2024. The aerodynamic flight control system (FCS/A) qualification models have been built, with functional tests already conducted, while the procurement of flight model components has also commenced. The raw cylinders and domes for the LH2 tank flight model have been manufactured, with further manufacturing steps currently under preparation. Regarding the approach and landing system (ALS), qualification model hardware has been procured and is currently being assembled. Several product-level qualification tests have already been performed, and part of the flight hardware has been ordered. The hardware for the onboard computer (OBC) and hybrid navigation system (HNS) for qualification purposes is ready or undergoing final assembly. These will be tested in conjunction with the VEB and at the avionics validation facility.

Both CNES and JAXA have achieved similar progress in their respective products and subsystems, maintaining a synchronized timeline across the project's partners. Upon completion of the product- and subsystem-centered AIV activities, the manufacturing of flight models will commence. The AIV activities for the top block, which includes all components above the tanks, will be performed in Switzerland and France under CNES' responsibility, with support by DLR. The propulsion block, consisting of the engine, aftbay, LH2 tank, and LOX tank, will be assembled at JAXA facilities in Japan, with assistance from DLR. This will be followed by hot-firing tests at the Noshiro Test Center on Japan's west coast.

Following the successful assembly and testing of both the top block and propulsion block, they will be transported to the launch site in Kourou, French Guiana, for final integration. This phase will include combined tests with the ground segment to ensure full system compatibility. The flight test campaign is planned to last approximately 9 months, marking the culmination of the extensive design, development, and integration efforts made by all partners involved in the CALLISTO project.

5 Conclusion

The CALLISTO project has made significant progress, successfully transitioning into Phase D after completing the System Critical Design Review (CDR-S) in late 2023. This milestone marks the beginning of the assembly, integration, and verification (AIV) phase, with extensive work underway across all subsystems, including the structural, propellant management, flight actuator, landing, GNC, avionics, and aerodynamic systems.

The upcoming AIV and hot-firing test campaigns are pivotal for validating the vehicle's design and performance before its transportation to the launch site in French Guiana. The flight test campaign aims to demonstrate key vertical-takeoff vertical-landing (VTVL) technologies and evaluate the vehicle's reusability, providing critical data to refine future maintenance, repair, and overhaul (MRO) processes.

The insights gained from CALLISTO will significantly inform the development of future reusable launch vehicles in Europe and Japan, while advancing key technologies to a higher technology readiness level. By focusing on cost-efficiency, rapid turnaround, and sustainability, the lessons learned from the project will help to de-risk and optimize the design of next-generation operational vehicles.

CALLISTO's success is a testament to the collaborative efforts of JAXA, CNES, and DLR, highlighting the importance of international cooperation in tackling the technical and operational challenges of reusability. This partnership sets a strong precedent for future joint initiatives aimed at advancing space technology.

In conclusion, the CALLISTO project represents a critical step toward the new era of reusable and cost-effective space launch systems, with implications that extend far beyond the current project, fostering innovation and competitiveness in the European and Japanese aerospace sectors.

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Author contributions S.K. took care of the overall structure and content of the manuscript, coordinated the work between the co-authors, and prepared chapters 1, 2.2, 3.8, and 5. L.E.B. and J.W. prepared chapter 3.3. E.D. prepared chapters 2.1 and 4. T.E., M.E., J.K., and B.R. prepared chapter 3.7. S.G.V. and J.R. prepared chapter 3.1. A.H. and J.R.G. prepared chapter 3.5. A.K. and L.O. prepared chapter 3.2. F.K. and A.S. prepared chapter 3.4. H.M. prepared chapters 2.3 and 2.4. M.P.R. prepared chapter 3.6. All authors reviewed and finalized the manuscript.

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Declarations

Conflict of interest The authors declare no competing interests.

References

1. Rickmers, P., Dumont, E., Krummen, S., Redondo Gutierrez, J.L., Bussler, L., Kottmeier, S., Wübbels, G., Martens, H., Woicke, S., Sagliano, M., Häseker, J., Witte, L., Sippel, M., Bauer, W., Peetz, H.-J.: The CALLISTO and ReFEx flight experiments at DLR - challenges and opportunities of a wholistic approach. Acta Astronaut. (2024). https://doi.org/10.1016/j.actaastro.2024.09.024
2. Wilken, J., Stappert, S.: Comparative analysis of European vertical landing reusable first stage concepts. CEAS Space J. (2024). https://doi.org/10.1007/s12567-024-00549-9
3. Dumont, E., Sagliano, M., Eichel, S., Markgraf, M., Glaser, T., Braun, B., Windelberg, J., Petkov, I., Schröder, S., Witte, L., Schneider, A., Panthen, B., Häseker, J. S., Opp, L., Krieger, A. T. E., Stief, M., Woicke, S., Martens, H., Krummen, S.: CALLISTO: Reusable rocket stage demonstrator: getting ready for implementation. In: 34th International Symposium on Space Technology and Science, Fukuoka, Japan (2023).
4. Dumont, E., Woicke, S., Sagliano, M., Krieger, A., Krummen, S., Callsen, S., Stief, M., Bergmann, K., Koch, A., Markgraf, M., Windelberg, J., Eichel, S., Klevanski, J., Ecker, T., Ertl, M., Reimann, B., Mierheim, O., Glaser, T., Heinrich, L.: CALLISTO Reusable rocket stage demonstrator: consolidating the design. IEEE Aerospace Conference (2024). https://doi.org/10.1109/AERO58975.2024.10521353
5. Dumont, E., Ishimoto, S., Illig, M., Sagliano, M., Solari, M., Ecker, T., Martens, H., Krummen, S., Desmariaux, J., Saito, Y., Ertl, M., Klevanski, J., Reimann, B., Woicke, S., Schwarz, R., Seelbinder, D., Markgraf, M., Riehmer, J., Braun, B., Aicher, M.: Callisto: towards reusability of a rocket stage: current status. J Evolving Space Activities **1**, 75 (2023). https://doi.org/10.57350/jesa.75. (**International Symposium on Space Technology and Science**)
6. Desmariaux, J., Lienart, T., Perbet, N., Ishimoto, S., Saito, Y., Adachi, H., Minami, Y., Witte, L., Schneider, A., Windelberg, J., Eichel, S.: Overview of CALLISTO Vehicle Development Status. In: 10th European Conference for Aeronautics and Aerospace Sciences, Lausanne, Switzerland (2023). https://doi.org/10.13009/EUCASS2023-998
7. Dumont, E., Illig, M., Ishimoto, S., Chavagnac, C., Saito, Y., Krummen, S., Eichel, S., Martens, H., Giagkozoglou Vincenzino, S., Häseker, J., Ecker, T., Klevanski, J., Krziwanie, F., Rotärmel, W., Schröder, S., Schneider, A., Grimm, C., Woicke, S., Sagliano, M., Schlotterer, M., Markgraf, M., Braun, B., Aicher, M., Ertl, M., Briese, L. E., Petkov, I., Riehmer, J., Reimann, B.: CALLISTO: A Prototype paving the Way for Reusable Launch Vehicles in Europe and Japan. In: International Astronautic Congress, Paris, France (2022). IAC-22-D2.6.1
8. Capcom Espace: Les Installations de Lancement Diamant. http://www.capcomespace.net/dossiers/espace_europeen/CSG/ELD/ELD.htm (Accessed 18 Sep 2024)
9. Eichel, S., Giagkozoglou Vincenzino, S., Markgraf, M.: Development of the fairing structure for CALLISTO. J Evolving Space Activities **2**, 167 (2024). https://doi.org/10.57350/jesa.167
10. Krziwanie, F., Rotärmel, W., Giagkozoglou Vincenzino, S., Schneider, A.: Development of the landing leg structure for CALLISTO. J Evolving Space Activities **2**, 168 (2024). https://doi.org/10.57350/jesa.168
11. Krieger, A., Opp, L., Stief, M., Dumont, E., Gerstmann, J.: Numerical Investigation of Cryogenic LH2 Tank Pressurization in Callisto. In: 34th ISTS Conference, Fukuoka, Japan (2023)
12. Opp, L., Krieger, A., Stief, M., Dumont, E., Gerstmann, J.: Hydraulic and Thermal 1D Modeling of the LH2-Tank within the CALLISTO Project Using EcosimPro/ESPSS. In: 34th ISTS Conference, Fukuoka, Japan (2023)
13. Opp, L., Scheufler, H., Stief, M., Dumont, E., Gerstmann, J.: Functional and thermal 1D modeling of a reusable LH2-tank using EcosimPro/ESPSS and comparison to CFD results. In: 8th Space Propulsion Conference, Estoril, Portugal (2022)
14. Sagliano, M., Tsukamoto, T., Macés-Hernández, J. A., Seelbinder, D., Ishimoto, S., Dumont, E.: Guidance and Control Strategy for the CALLISTO Flight Experiment. In: 8th European Conference for Aeronautics and Aerospace Sciences, Madrid, Spain (2019). https://doi.org/10.13009/EUCASS2019-284
15. Giagkozoglou Vincenzino, S., Eichel, S., Rotärmel, W., Krziwanie, F., Petkov, I., Dumont, E., Schneider, A., Schröder, S., Windelberg, J., Ecker, T., Ertl, M.: Development of reusable structures and mechanisms for CALLISTO. J Evolving Space Activities **1**, 36 (2023). https://doi.org/10.57350/jesa.36
16. Windelberg, J., Maier, O. H.: Design of Flight Control Actuators for Reusable Launch Vehicles. In: Deutscher Luft- und Raumfahrtkongress, Bremen, Germany (2021).
17. Briese, L. E., Kier, T. M., Petkov, I., Windelberg, J., Heinrich, L., Krummen, S.: Advanced Modeling and Dynamic Stability Analysis of the Aerodynamic Control Surfaces of CALLISTO. In: AIAA SciTech Forum, Orlando, USA (2023). https://doi.org/10.2514/6.2023-2405
18. Sagliano, M., Máces-Hernández, J.A., Farí, S., Heidecker, A., Schlotterer, M., Woicke, S., Seelbinder, D., Krummen, S., Dumont, E.: Unified-loop structured H-infinity control for aerodynamic steering of reusable rockets. J. Guid. Control. Dyn. (2023). https://doi.org/10.2514/1.g007077
19. Huneker, L., Sagliano, M., Arslantas, Y. E.: SPARTAN: an Improved global Pseudospectral Algorithm for High-Fidelity Entry-Descent-Landing Guidance Applications. In: 30th International Symposium on Space Technology and Sciences, Kobe, Japan (2015).
20. Sagliano, M.: Development of a Novel Algorithm for High Performance Reentry Guidance. In: PhD Thesis, University of Bremen, Bremen, Germany (2016). https://suche.suub.uni-bremen.de/peid=B85381682&
21. Sagliano, M., Heidecker, A., Farí, S., Máces-Hernández, J. A., Schlotterer, M., Woicke, S., Seelbinder, D., Dumont, E.: Onboard Guidance for Reusable Rockets: Aerodynamic Descent and Powered Landing. In: AIAA SciTech Forum (online), USA (2021). https://doi.org/10.2514/6.2021-0862
22. Sagliano, M., Heidecker, A., Farí, S., Máces-Hernández, J. A., Schlotterer, M., Woicke, S., Seelbinder, D., Dumont, E.: Powered

Atmospheric Landing Guidance for Reusable Rockets: the CALLISTO studies. In: AIAA SciTech Forum, Orlando, USA (2024). https://doi.org/10.2514/6.2024-1761
23. Sagliano, M., Seelbinder, D., Theil, S., Lu, P.: Six-degree-of-freedom rocket landing optimization via augmented convex-concave decomposition. J. Guid. Control. Dyn. (2024). https://doi.org/10.2514/1.g007570
24. Tatiossian, P., Cliquet Moreno, E., Perbet, N., Millet-Lacombe, L., Iizuka, N., Häseker, J.S., Schwartz, R., Grimm, C.: CALLISTO Avionics Overview: Architecture Principles, Product Development, Validation, Conditioning. In: 9th European Conference for Aeronautics and Space Sciences, Lille, France (2022). https://doi.org/10.13009/EUCASS2022-7311
25. Riehmer, J., Kapteijn, K., Klevanski, J., Reimann, B., Krummen, S., Gülhan, A., Dumont, E.: Wind Tunnel Experiments of the CALLISTO VTVL Launcher in the TMK and HST Wind Tunnels. In: 9th European Conference for Aeronautics and Aerospace, Lille, France (2022). https://doi.org/10.13009/EUCASS2022-4634
26. Krummen, S., Tummala, P., Wilken, J., Dumont, E., Ertl, M., Ecker, T., Riehmer, J., Klevanski, J.: Applying Bayesian Inference to Estimate Uncertainties in the Aerodynamic Database of CALLISTO. In: IEEE Aerospace Conference, Big Sky, Montana, USA (2023). https://doi.org/10.1109/AERO55745.2023.10115932
27. Krummen, S., Schraad, J.M., Ecker, T., Ertl, M., Reimann, B., Klevanski, J., Riehmer, J., Eichel, S., Sagliano, M., Briese, L.E., Dumont, E.: Bayesian Models for Uncertainty Estimation in Aerodynamic Databases of Reusable Launch Vehicles. In: AIAA SciTech Forum, Orlando, USA (2024). https://doi.org/10.2514/6.2024-0574
28. Klevanski, J., Reimann, B., Krummen, S., Ertl, M., Ecker, T., Riehmer, J., Dumont, E., Briese, L.E., Kier, T.: Further Progress in Aerodynamic Studies for CALLISTO - Reusable VTVL Launcher First Stage Demonstrator. In: 10th European Conference for Aeronautics and Aerospace, Lausanne, Switzerland (2023). https://doi.org/10.13009/EUCASS2023-510
29. Ecker, T., Ertl, M., Klevanski, J., Krummen, S., Dumont, E.: Aerothermal characterization of the CALLISTO vehicle during descent. CEAS Space J. (2024). https://doi.org/10.1007/s12567-024-00561-z
30. Ertl, M., Ecker, T.: Aerodynamic and aerothermal comparison between the CAL1C and CAL1D geometries for the CALLISTO vehicle. In: 10th European Conference for Aeronautics and Aerospace Sciences, Lausanne, Switzerland (2023). https://doi.org/10.13009/EUCASS2023-431
31. OpenAI: GPT-4 Technical Report (2023). https://cdn.openai.com/papers/gpt-4.pdf