



The LIFT Module: A Modular Fixation Platform for Biological Research on Sounding Rockets

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Abstract

Biological experiments under altered gravity conditions as encountered on sounding rockets often require automated in-flight chemical fixation under the challenging environmental and operational constraints, as accompanying any spaceflight mission. Enabling in-flight fixation while maintaining laboratory-equivalent cultivation conditions from ground handling to recovery poses significant challenges for reliability and reproducibility of experiment scenarios. A common flight-qualified architecture can address these constraints by enforcing controlled environmental and operational execution while decoupling sample-dependent fixation configurations through modular payload integration. This work describes a reusable, automated and standardized fixation payload platform designed to host interchangeable, pre-qualified chemical fixation payloads for biological experiments on a variety of platforms to achieve altered gravity. The module provides a standardized mechanical, thermal and electrical architecture for the integration and operation of experiments employing either adherent or suspension-based cells within a single flight-qualified unit, independent of the specific fixation configuration required. Hardware and operational performance were qualified within the German Aerospace Center's (DLR) Material-physikalische Experimente unter Schwerelosigkeit (MAPHEUS®) sounding rocket program. Laminar In-flight Fixation Technology (LIFT) was successfully flown across several missions and payload configurations, in-flight data demonstrate reliable execution of fixation procedures, stable thermal regulation, a pressure-stabilized internal environment and automated housekeeping data acquisition. The presented work establishes LIFT as a versatile, spaceflight-proven module to carry out a wide variety of cell culture experiments, allowing customizable in-flight fixation of samples as well as their monitoring within a common architecture.

Keywords Sounding rocket · Chemical fixation · Gravitational biology · bio-experimental payload · Automated fixation

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Introduction

Current and future human spaceflight missions, including Lunar and Mars exploration, require mitigation of risks to human health and wellbeing. Experience from missions aboard the International Space Station (ISS) shows that exposure to microgravity induces pronounced physiological changes and cognitive decline in astronauts, including loss of bone density, muscle atrophy and cardiovascular deconditioning (Gabel et al. 2022; Khune 2024; Shibata et al. 2023).

Understanding these gravity-dependent processes is essential for safeguarding human health during future exploration missions (Patel et al. 2020; Bosutti et al. 2025). Controlled and reproducible experiments on model systems such as cell cultures, spheroids and organoids under altered

gravity conditions provide a fundamental approach to decipher the underlying mechanisms in a reproducible manner (Grimm et al. 2022; Striebel et al. 2023; Schulz et al. 2022). Whereas hypergravity can be generated using ground-based centrifuges, high quality microgravity conditions require flight platforms such as sounding rockets or orbital platforms (Penley et al. 2002; Kirchhartz et al. 2018; von Kampen et al. 2006; Ferranti et al. 2021).

Cellular and tissue models are widely used to investigate altered gravity-induced changes, for example in cell structure and function (Baran et al. 2022; Strauch et al. 2019; Wu et al. 2022). Such research requires specialized hardware to adapt standard laboratory procedures to the technical and operational constraints of the respective experiment platform (Feles, Keßler, et al. 2025).

The effects observed on cultured cells in spaceflight are often subtle and time-dependent. A simple, reliable and well-established approach to assess such time-resolved changes is chemical fixation of samples. Fixation preserves the structural and molecular integrity of the samples for subsequent post-flight histological, proteomic or transcriptomic analyses (Fox et al. 1985; Huang et al. 2015; Humbel et al. 2019).

Chemical fixation compromises a broad range of preservation strategies that differ in both their biochemical mechanisms and technical implementation. Depending on the scientific objective, fixation may employ aldehyde-based crosslinking agents such as paraformaldehyde, precipitation-based fixatives, or preservation solutions such as RNAlater. Likewise, fixation concepts can vary with respect to sample geometry, fluid handling and actuator technologies. As a result, fixation hardware is typically customized to suit the specific sample type and experimental requirements. The LIFT module presented here does not dictate the fixation concept itself, but enables the actuation and operation of interchangeable fixation payloads employing different fixation strategies.

In dynamically changing environments such as sounding rocket trajectories, exclusively carrying out a post-flight analysis is insufficient, as many biological responses occur on time scales shorter than the ascent, microgravity and re-entry phases. Delayed fixation after landing may thus introduce post-flight artifacts that alter molecular and structural readouts and thereby obscure the in-flight state.

Enabling robust in-flight fixation on suborbital platforms presents substantial engineering challenges under flight conditions (Park et al. 2020). Sounding rockets subject payloads to high mechanical loads, strong thermal gradients and strict operational constraints related to access of hardware holding samples, power and safety requirements. At the same time, biological samples must be maintained under controlled environmental conditions throughout all mission phases. This combination requires dedicated hardware solutions to ensure reliable operation during countdown, flight and post-landing

recovery, while maintaining controlled environmental conditions and executing automated fixation sequences.

Existing platforms to carry out biological research under altered gravity conditions such as spaceflight only partially address these requirements. On the ISS, available hardware typically operates under mission timelines characterized by extended pre-flight integration phases and long dwell times (up to days or weeks), which can impose stress on sensitive samples (Hudson et al. 2001). In contrast, sounding rocket missions offer short countdowns of just a few hours, allowing biological samples to remain under optimal laboratory conditions until shortly before lift-off (LO), thereby supporting well-defined and controlled sample preparation.

A DLR-developed predecessor module (CellFix) for automated chemical fixation in the MAPHEUS framework (Stamminger et al. 2009) was restricted to a single adherent-cell implementation within a smaller payload volume. These constraints limited sample throughput, experimental flexibility, platform reusability and scientific scalability, despite the successful proof of automated in-flight fixation on MAPHEUS-7 and -8 (Liemersdorf et al. 2020).

Accordingly, the newly developed LIFT module extends this concept toward a scalable and reusable platform architecture, providing increased flexibility for different sample types and experimental configurations while eliminating the need to develop a dedicated module for each new scientific application.

In this work, we introduce the LIFT module, a reusable, automated and spaceflight-qualified core platform designed to host interchangeable chemical fixation payloads for both adherent and suspension-based sample configurations on sounding rockets and other gravity research platforms. By implementing a standardized mechanical, thermal and electrical architecture, LIFT decouples mission-specific payload requirements from the core architecture, thus ensuring rapid adaptation to diverse biological sample configurations without redesign of the core system.

Within the operational and qualification constraints of sounding rocket missions, combining a reusable flight-qualified core with pre-validated payloads constitutes a system architecture to support diverse scientific requirements across different cell and tissue models. This configuration ensures controlled environmental conditions (temperature-controlled and pressure-stabilized), reliable housekeeping data acquisition and synchronization of fixation operations with the mission timeline.

Using deployment within the MAPHEUS sounding rocket program as a reference, we derive the mission and system requirements and describe the mechanical, thermal, electrical and control architecture of the module. Additionally, we use ground-based qualification tests demonstrating compliance with the relevant constraints for suborbital missions.

The LIFT module has successfully flown on three MAPHEUS missions – MAPHEUS-13 (05/2023), MAPHEUS-14 (02/2024) and MAPHEUS-16 (11/2025) – hosting multiple fixation payloads for both adherent cells and cells in suspension. While detailed qualification and verification of the individual payloads will be presented elsewhere, we here report the module's in-flight performance. Across all flight campaigns, the LIFT module maintained stable thermal and environmental conditions, demonstrating its compatibility with representative fixation payloads for different biological sample types.

In summary, these results establish the LIFT module as a flight-proven and reusable platform for sounding rocket missions, corresponding to Technology Readiness Level (TRL) 7 and providing a reliable framework for automated, time-resolved chemical fixation payloads in altered gravity experiments.

System Requirements

Rocket Vehicle and Operational Mission Constraints

The LIFT module has been developed as a reusable platform to enable biological research under altered gravity conditions, with a focus on sounding rocket operations. The functionality of LIFT was verified within the framework of the DLR MAPHEUS sounding rocket program. MAPHEUS is engineered to provide researchers with uninterrupted high-quality microgravity research time (residual acceleration levels of 10^{-4} – 10^{-6} g) of approximately 6–7 min depending on the vehicle configuration, thereby defining the available time window for gravity-dependent sample exposure and actuation.

The vehicle employs a two-stage solid booster configuration with a modular payload section located in the upper portion of the rocket. The total flight duration is approximately 10 min, during which the payload ascends to an apogee altitude of about 250–300 km before returning to Earth under parachute. During ascent and re-entry, the payload is subjected to elevated mechanical loads, including broadband vibration levels in the order of 10–15 g_{RMS} and superimposed shock events associated with stage separation and parachute deployment. Here, g_{RMS} represents the root mean square acceleration integrated across the relevant frequency range. The corresponding power spectral density depends on the mission-specific booster configuration, whose technical details are subject to confidentiality and thus cannot be disclosed here. The descent rate at impact is approximately 8 m s⁻¹.

Within the program, RADAX 17" rocket compartments (Weydert 1968) are used as the standardized structure for all experimental hardware (Fig. 1). This standardization facilitates a flexible mission design, as available experiment modules can be combined into varying payload combinations

for each launch. Accordingly, the LIFT system is designed to be fully compatible with the RADAX form factor and its mechanical interfaces.

Prior to its flight, the payload stack is assembled on site on the launch facility and subsequently mated with the boosters in the launch tower. Individual experiments may either be integrated into the rocket before payload stack transfer to the launch tower or be designed for removal from the RADAX compartments. Integration of removable experiments is typically conducted during countdown and may take place either several hours before launch (early-access) or down to approximately 1–2 h before launch (late-access). Late-access capability is critical for experiments involving sensitive samples, as it enables integration shortly before launch while maintaining environmental control and preserving sample integrity.

Experiment control authority is constrained by the Service Module, which prohibits electrical switching during defined radio-silence phases of the countdown to prevent electromagnetic interference. These constraints directly impact payload power management, control logic and actuation strategies. Therefore, the Service Module retains power-control authority over all experiments and can deactivate them as required.

In addition to vehicle- and mission-imposed constraints, sounding rocket campaigns may be subject to challenging environmental and operational conditions. European campaigns are typically conducted from ESRANGE (Kiruna, Sweden) or Andøya Space Center (Norway), where ambient temperatures regularly reach -30 °C and substantial wind loads can occur during transport and countdown (Westerlund 2018; Thrane 2018). Consequently, launch delays, aborted launch attempts and delayed payload recovery operations are common, increasing the demand for reliable, reusable hardware with straightforward assembly procedures. Although the ESRANGE Skylark launch tower serves as the nominal launch site for MAPHEUS and provides a temperature-controlled environment of approximately 20 °C during pre-launch operations, transport and handling remain subject to external environmental conditions.

For the LIFT module, these environmental effects are partially mitigated during pre-launch transfer from laboratory facilities to the launch tower through the use of a custom transport incubator. This system provides uninterrupted power and a controlled thermal environment. Together with the LIFT internal thermal control, it ensures stable handling of sensitive biological samples during transport operations (Feles, Holbeck, et al. 2025).

LIFT Module: Scope and Requirements

At the system level, the LIFT module functions as a reusable core platform, providing electrical power supply,

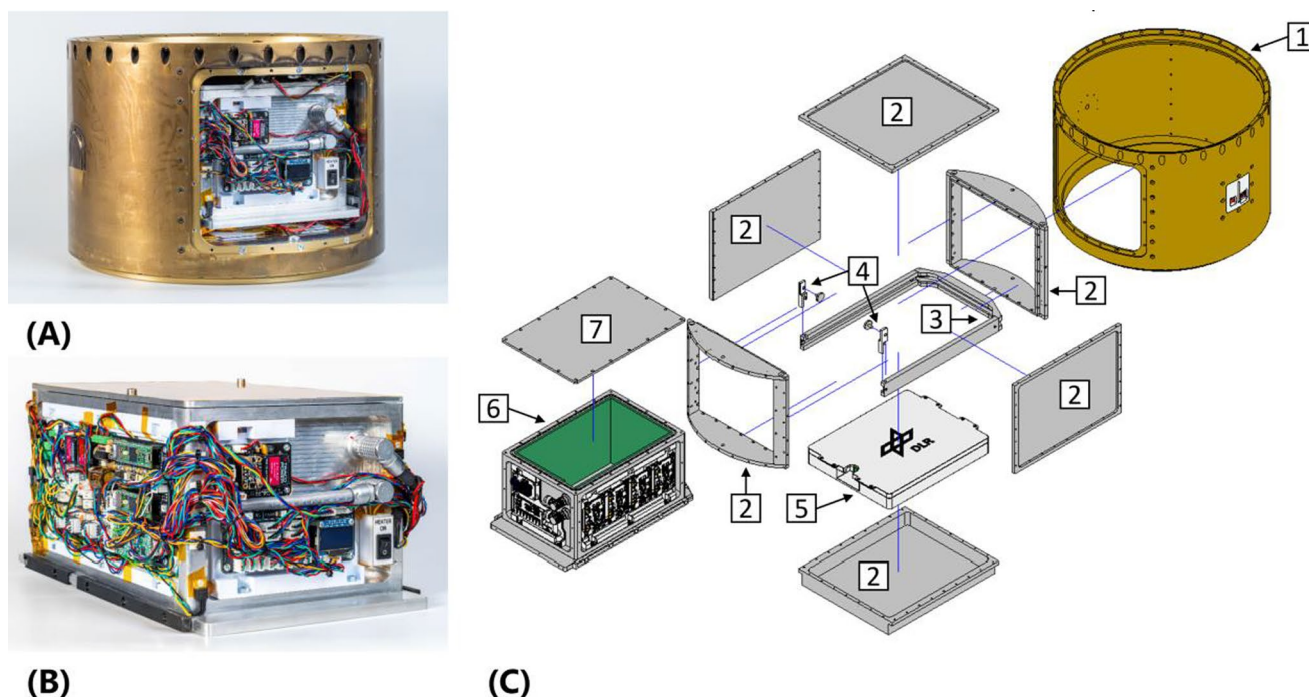


Fig. 1 Overview of the LIFT module mechanical setup. (A) LIFT module in its full integration setup within the RADAX compartment (without lid); (B) late-access unit (standalone); (C) exploded view of the architecture: (C-1) RADAX compartment with umbilical interface,

(C-2) metal inner housing with bottom compartment for the battery pack (C-5), (C-3, C-4) guide rail system with lock mechanism, (C-6, C-7) late-access unit

environmental control and housekeeping data acquisition for interchangeable biological fixation payloads. Across all supported configurations, biological samples are cultivated in nutrient-enriched culture media and require chemical fixation at mission-defined time points, typically associated with the hyper- and microgravity phases of the flight. Fixation procedures are executed autonomously during flight, synchronized with the mission timeline. While experiment-specific setups vary, the LIFT module provides standardized interfaces to enable payload operation. Multiple payload variants for different biological model systems have been developed and were successfully flown (an overview of representative implementations is provided in Sect. 3.5), enabling adaptation to specific mission requirements. Established procedures are defined for each implementation and are coordinated with scientific users to ensure alignment with experimental requirements.

The effects of altered gravity on cellular samples are typically minor compared to other environmental factors, such as temperature fluctuations, pressure or atmospheric deviations. To isolate gravity-induced biological effects from environmental stress-related artifacts, culture conditions are required to remain laboratory-equivalent throughout all mission phases until fixation procedures are initiated, including ground-based handling and transport. Accordingly, the samples must be accommodated within a controlled environment that shields them from external influences such as vacuum-induced pressure drops during ascent.

Based on the mission scenario and operational constraints, described in Sect. 2.1, system-level design requirements were derived to ensure structural integrity, operational robustness and safe handling of sensitive biological samples.

Prior to fixation actuation, the module is required to sustain laboratory-equivalent storage conditions for biological samples by maintaining internal pressure stability within ± 50 hPa and a mission-defined target temperature, typically corresponding to physiological culture conditions ($37\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$), independent of ambient environmental variations. Fluctuations around the target setpoint are required to be minimized to avoid compromising sample viability and triggering thermal stress responses (Casado et al. 2014; Nguyen et al. 2020).

Consequently, maximizing the duration of sample cultivation under well-controlled laboratory conditions is essential and requires late-access capability. Once the late-access unit is closed and transferred to the launch infrastructure, oxygen availability and other culture conditions become inherently constrained, making minimization of pre-launch residence time inside the flight unit a key operational objective.

The late-access concept directly imposes additional system requirements on the LIFT module. During pre-integration operations, a late-access unit must operate independently outside the RADAX compartment. To fulfill this requirement the LIFT core is implemented as a self-contained, late-access pressure vessel that houses the biological samples

within the fixation payload. It performs all payload operations autonomously, including fixation execution and on-board data handling. The vessel integrates all electrical subsystems, thermal control and on-board data storage, requiring only an attached battery pack or external ground support power equipment to ensure uninterrupted operation during ground handling, flight and recovery.

The system is required to withstand the mechanical loads associated with sounding rocket missions, including vacuum induced pressure drops, launch and re-entry vibrations and shock events in accordance with MAPHEUS acceptance levels, while supporting late-access integration and autonomous standalone operation outside the RADAX compartment.

To support payload operations, the module provides modular electrical interfaces for fixation actuation hardware, enables automated fixation sequences synchronized with the flight profile and incorporates sensors to record relevant environmental parameters for post-flight analysis. Continuous power availability and on-board data storage independent of telemetry are ensured.

System Design and Architecture

Mechanical Integration

The LIFT RADAX compartment incorporates a metal inner housing that shields the late-access unit from environmental influences like ingress of particulate matter and plasma during ascent and re-entry. In addition, the inner housing provides mechanical shielding by physically separating the module harness from the rocket harness.

The inner housing includes a bottom compartment accommodating the battery pack and lateral guide rails that define the insertion path and final position of the late-access unit, which is secured to the guide rails by a two-stage retention mechanism. It consists of primary locking clamps and secondary knurled-screw fasteners. This arrangement ensures mechanical fixation under launch and re-entry dynamics, while allowing fast and reproducible installation during late-access operations.

The late-access unit is implemented as a pressure vessel with a minimum wall thickness of 3 mm. Pressure integrity is ensured by O-ring seals integrated at the top and bottom interfaces. The bottom interface is permanently closed by a 10 mm thick carrier plate, which also serves as the primary mechanical interface to the rail system and as the mounting plane for all internal experiment hardware. Payload hardware is inserted from the top and the unit is sealed with a 5 mm thick lid prior to its integration into the launch vehicle.

The vessel geometry maximizes usable payload volume within the metal housing, while the wall thickness was selected to accommodate external electronics while

maintaining sufficient structural margin for vacuum-related pressure differentials. Structural integrity and sealing performance are addressed by mechanical and vibration testing at system level prior to each flight application.

The pressure vessel provides an envelope of $267 \times 167 \times 154 \text{ mm}^3$ (6.86 L) for interchangeable fixation hardware, surrounded by an internal closed-cell foam insulation layer that reduces heat losses to the surrounding structure. After accounting for insulation and structural interfaces, the effective payload volume available for biological samples and associated experiment hardware is approximately 5.81 L.

Thermal Management

As stated above, environmental control is essential for biological sample integrity. Temperature fluctuations impose high stress on cellular systems - thus thermal stability is a key factor for experiment validity. The thermal management system is designed to maintain a mission-defined setpoint temperature throughout all operational phases. The concept relies on temperature preconditioning and thermal retention rather than active warm-up, reflecting MAPHEUS operational constraints.

Prior to integration, biological samples are cultivated in cell culture incubators at the environmental conditions (typically 37 °C, 5% CO₂ and >95% humidity), while the late-access unit is prewarmed using a custom transport incubator (Feles, Holbeck, et al. 2025). Following sample loading, the integrated unit remains thermally conditioned and is powered by its battery. Consequently, the thermal control system is primarily required to compensate for residual heat losses, prioritizing low thermal conductance and thermal inertia to minimize heater power demand. Heat losses are reduced through thermal insulation in the late-access unit, implemented as a 6 mm thick closed-cell Armaflex Ultima (Armacell, Germany) foam layer ($\lambda \leq 0.040 \text{ W m}^{-1} \text{ K}^{-1}$).

Theoretical heat transfer coefficients were calculated for the insulated pressure vessel, accounting for the dominant conductive and convective transfer pathways, yielding values of $GL=0.055 \text{ W K}^{-1}$ for the short sides, $GL=0.078 \text{ W K}^{-1}$ for the long sides, $GL=0.087 \text{ W K}^{-1}$ for the lid and $GL=0.096 \text{ W K}^{-1}$ for the carrier plate. Radiative heat transfer was not included, as it was expected to have only a minor influence on the steady-state thermal balance. Based on these estimates, maintaining a target temperature of 37 °C requires approximately 13 W at an ambient temperature of 0 °C and about 6 W at 20 °C, representative of ESRANGE Skylark launch tower conditions. Although simplified, these steady-state estimates indicate a substantial thermal control margin relative to the available heating capacity (approximately 120 W in the present configuration). This margin

is reserved for off-nominal conditions and transient disturbances, rather than continuous operation.

Analog Heating System

Due to launch-site safety regulations, payload access in the launch tower is restricted to defined radio-silence windows. Uninterrupted active thermal control is nevertheless provided by an analog heating system qualified for continuous operation under electromagnetic interference (EMI) constraints, remaining operational throughout all mission phases and independent of other payload electronics to ensure continuous sample thermal conditioning. The setup is comprised of four heating channels, each rated at up to 30 W, with heating elements mounted inside the late-access unit in close proximity to the biological sample housings.

Each channel is powered directly from the battery and regulated by an independent analog control circuit. Temperature setpoints are adjustable to allow mission- and configuration-specific calibration.

For post-fixation and recovery phases, the system provides a secondary temperature mode (“frostguard”), typically set to approximately 4 °C. This mode is selected via a latching switch and enables a controlled transition from the pre-fixation temperature to reduced-temperature storage. Upon activation, heater output initially drops to zero, allowing passive cooling before stabilizing at the lower setpoint. The frostguard mode stabilizes fixed samples, prevents freezing and preserves sample integrity for subsequent analyses. Further, heater power demand is reduced, thereby extending battery-supported operation during potentially delayed recovery scenarios and exposure to low ambient temperatures.

Electrical Power System

Table 1 provides an overview of the electrical power lines implemented within the LIFT module and summarizes their main architectural features. A complete overview of the electrical and power system architecture is presented in Fig. 2.

Battery System

Power is provided to the LIFT system by a custom lithium iron phosphate (LiFePO₄) battery configured as 10 cells in

series with two parallel strings (10S2P) architecture, delivering a total energy capacity of 142.5 Wh (measured after three flight campaigns) at a maximal voltage of 36 VDC and an end-of-discharge voltage of approximately 24 VDC. LiFePO₄ was selected for its high thermal stability, low susceptibility to thermal runaway, stable voltage profile over discharge and mechanical robustness under vibration, making it well suited for sounding rocket and space applications (Li et al. 2024; Ma et al. 2025).

In absence of a sufficient central onboard power supply from the launch vehicle, the battery serves as the sole power source for all payload operations. During ground operations and countdown, the battery is charged using ground support equipment (GSE), a programmable DC power supply (DP811(A), 200 W, Rigol, China). Charging is executed via XT60 power connectors at the RADAX umbilical interface. Maintaining full battery charge until shortly before launch ensures a sufficient energy margin for extended module operations in the event of delayed payload recovery.

At lift-off, the GSE cabling is passively disconnected by the vehicle launch. A self-locking shutter mechanism subsequently closes the umbilical interface under launch acceleration, providing a defined separation from the external harness and protecting the battery charging connectors from electrical interference, unintended contact and environmental exposure, including thermal loads during re-entry and recovery.

The nominal pre-fixation payload power demand is approximately 20 W. During frostguard operation, the steady-state power demand is estimated at approximately 3 W. Based on these operating conditions, the available battery capacity corresponds to a nominal operating time of approximately 42 h. Hence, the battery system is conservatively sized to provide a substantial margin beyond the nominal mission duration. This is supported by own flight experience from the MAPHEUS-16 campaign, in which payload retrieval took place approximately 52 h after landing due to adverse weather conditions (substantial wind loads, continuous snowfall and ambient temperatures well beyond -7 °C), while the battery remained operational.

Power Conversion

The electrical bus layout of the LIFT module supports external enable/disable control by the Service Module to comply with operational safety requirements. Power distribution is organized around the unregulated battery, from which all payload subsystems are supplied through conversion and control stages.

At system level, the MAPHEUS Service Module retains external authority through a dedicated power-on control line that enables or disables the primary DC-DC converters. Disabling these converters removes power from all

Table 1 Power line overview within the LIFT module

Component	Specification
Battery capacity	142.5 Wh, max. 36 VDC
Heating power	Up to four channels, with max. 30 W each
Regulated outputs	24 VDC, 12 VDC, 5 VDC, 3.3 VDC
Maximum currents	3.2 A (24 VDC), 6.3 A (12 VDC), 2 A (5 VDC), 3 A (3.3 VDC).

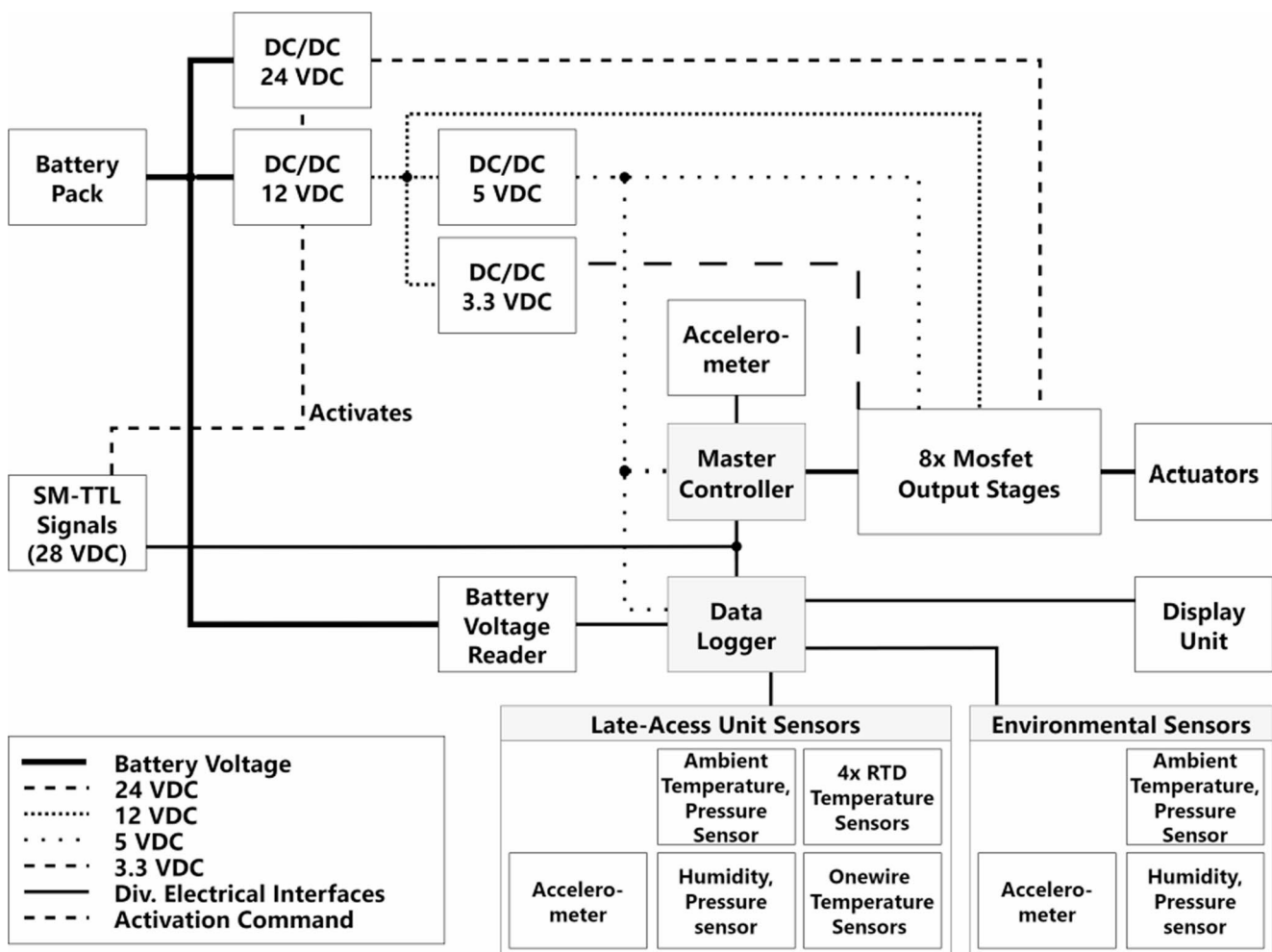


Fig. 2 Overview of the LIFT electronic system architecture. A LiFePO₄ battery pack supplies max. 36 VDC to a central power-conversion stage, generating fused 24 VDC, 12 VDC, 5 VDC and 3.3 VDC supply rails. A master microcontroller orchestrates experiment control via eight redundant load-switch channels, individually assignable to interchangeable actuators at different voltage levels. Experiment timing

is synchronized with mission timeline using trigger signals from the Service Module. A redundant fallback for the triggers is provided by mission phase detection, employing an on-board acceleration sensor. A data-logger microcontroller, functionally decoupled from the control logic, passively records sensor and housekeeping data

downstream electronics, placing the payload in a defined safe state. The analog heaters run independently of this governing authority.

Two primary DC-DC converters supply all experiment-related loads, including actuator-driven fixation hardware (e.g., pumps, valves and motors), as well as downstream power conversion stages. A 24 VDC converter (TEP 75-2415WI, TRACO Power, Switzerland) provides up to 3.2 A, while a 12 VDC converter (TEP 75-2412WI, TRACO Power, Switzerland) supplies up to 6.3 A.

The secondary conversion stage derives lower voltage levels from the 12 VDC output. A 5 VDC converter (THN 10-2411WIR, TRACO Power, Switzerland) provides up to 2 A. In addition, a 3.3 VDC converter (THN 10-2410WIR, TRACO Power, Switzerland) provides up to 3 A. All converters operate over an input range of 9–36 VDC. Both secondary

converters are implemented with direct interfaces to the master controller, data-logger microcontroller and associated loads.

All connections between conversion stages incorporate protection to safeguard critical components. These measures mitigate risks of switching spikes, connector bounce or disturbances induced by vibration and shock events, thereby enhancing the overall electrical safety.

Payload Control

Dual-Microcontroller Setup

To support uninterrupted payload operations in parallel with continuous sensor data recording, the module employs two independent Teensy 4.1 microcontrollers (PJRC, USA) to decouple control logic from data logging. This

dual-controller architecture isolates control functions from data acquisition tasks. Both controllers are supplied from the regulated 5 VDC rail.

The primary microcontroller acts as the master controller and central processing unit of the module. It governs all experiment events with respect to operational control and fixation actuation in accordance with the mission timeline.

Complementing this control functionality, the secondary microcontroller serves as a dedicated data logger. It operates as a passive data-acquisition system, continuously collecting and storing measurements from the distributed sensor array integrated inside and outside of the payload. This provides a complete record of environmental and operational conditions throughout the mission and supplies the context required for post-flight analysis of the biological samples.

Three discrete Transistor-Transistor Logic (TTL) trigger signals are provided by the Service Module to both microcontrollers and employed to initiate payload operations according to the mission timeline. These include a lift-off signal at launch and two independently schedulable experiment triggers. The two programmable triggers, designated “Start of Experiment” (SOE) and “Start of Data Storage” (SODS), can be freely scheduled along the mission timeline to support experiment-specific requirements. While SOE is typically associated with the onset of microgravity, SODS is employed for various functions across different payloads. Within the LIFT module, the signals are used during pre-flight ground operations and in-flight to synchronize experiment execution with the mission phases.

Master Controller and Actuator Outputs

The master controller uses these signals to execute the experiment’s operational logic, managing payload activities and ensuring fixation actuation according to the mission timeline. As a fail-safe mechanism, the LIFT module employs an onboard acceleration sensor to detect lift-off and identify the onset of microgravity, thereby establishing an internal reference timeline. If the Service Module TTL signals are not received within a predefined tolerance window relative to onboard detection, the master controller autonomously initiates the corresponding operational sequences. This fail-safe mechanism ensures fixation actuation even in the absence of external triggers, thereby preserving the scientific validity of the samples. The origin of fixation initiation, whether Service Module-triggered or fail-safe, is recorded in the module data stream.

The interchangeable fixation configurations employ a range of actuators, including membrane and peristaltic pumps, valves, gear motors and DC motors. For actuator control, the master controller drives eight low-side N-channel power trench MOSFET output stages, each implemented redundantly and diode-protected for inductive-load suppression.

The redundant output-stage architecture increases fault tolerance by allowing individual actuator channels to be

electrically isolated in the event of failure, without compromising remaining fixation functions, thereby reducing single points of failure in the control path.

The supply rail for each channel can be selected from the available DC-DC converter outputs, allowing loads to be operated from 24 VDC, 12 VDC, 5 VDC or 3.3 VDC as required, maximizing the flexibility for different fixation setups. Three control channels employ TO-220 MOSFETs (FDP5800, ON Semiconductor, USA) mounted to the vessel structure to dissipate waste heat from higher-current actuator switching, while the remaining five channels use SOT-223 FDT86102LZ devices (ON Semiconductor, USA) on the main board for lower-power loads. The high-power channels are derated to approximately 5 A continuous (8–10 A peak), resulting in maximum conduction losses of approximately 0.6 W. The lower-power channels support currents of up to approximately 2 A continuous (3–4 A peak), maintaining conduction losses below 0.3 W and providing a sufficient thermal margin relative to the 2.2 W package limit.

Sensor Data Acquisition and Storage

The data logger microcontroller records sensor data (list provided in Table 2) redundantly to its native storage, a socket equipped with a removable microSD card and to a soldered SD-chip storage device. Write operations are conducted in parallel to both media. This soldered storage improves

Table 2 Overview of sensors implemented in the LIFT module

Sensor	Measured Parameters	Interface(s)	Notes
ADXL345 accelerometer	3-axis acceleration	I ² C (late-access unit), SPI (environment)	acceleration profile monitoring, redundant implementation
HDC3022 temperature/humidity sensor	ambient temperature, relative humidity	I ² C (late-access unit), SPI (environment)	temperature profile monitoring
BMP280 pressure/temperature sensor	ambient pressure, ambient temperature	SPI (late-access unit) [until MP-14]	temperature profile and ambient pressure monitoring
BMP390 pressure/temperature sensor	ambient pressure, ambient temperature	I ² C (late-access unit) [from MP-14 on], SPI (environment) [from MP-16 on]	temperature profile and ambient pressure monitoring
PT100/0 RTD temperature sensors (4 units)	sample temperature	SPI via MAX31865 front-end	4 × sensors submerged in sample storage medium
OneWire temperature sensors (optional)	ambient temperature	OneWire	optional sensors inside late-access unit

robustness against vibration and lateral accelerations and mitigates the risk of contact-related data loss. The recorded data provides the environmental and operational context required for post-flight analysis of biological samples, including temperature and acceleration profiles and fixation timing.

To mitigate the risk of power-loss induced file corruption, the system implements a shutdown-detection and buffering scheme. The data logger monitors its supply voltage via a galvanically isolated circuit and suspends write operations upon detection of an impending power cut to protect existing files. To bridge the short interval between power-loss detection and shutdown, a 16 VDC, 4.7 mF capacitor provides approximately 260 ms of backup energy, allowing completion of ongoing file-write operations, thereby preventing data loss and File Allocation Table (FAT) corruption.

Biological Payload Integration

Chemical Fixation

Chemical fixation instantaneously preserves the state of a biological sample at a defined time point, maintaining its structural and molecular integrity for subsequent analyses. In practice, fixation is performed by introducing a chemical fixative into the sample, rapidly stabilizing cellular structures and halting ongoing physiological processes. Commonly used chemical fixatives include aldehyde-based solutions such as paraformaldehyde (PFA) and salt-based preservation solutions such as RNAlater, which differ primarily in their physical properties (e.g., viscosity, mixing rates and behavior) and downstream analytical compatibility. In altered gravity experiments, fixation must be performed autonomously in-flight to preserve gravity-dependent biological states. Here, the discrimination between hypergravity phases during ascent and re-entry and the microgravity phase is of utmost importance to ensure experiment validity and significance.

The selection of chemical fixatives for the use within the LIFT module is driven exclusively by scientific objectives. From an engineering perspective, differences in fixative properties may require corresponding adaptations of the fixation hardware, particularly with respect to material compatibility, fluid routing dimensioning (e.g., tubing) and sealing concepts to withstand aggressive chemicals.

Interchangeable Fixation Hardware

The LIFT module was designed as a reusable platform to support different biological sample types through interchangeable fixation payloads, while providing each configuration with identical mechanical, electrical and thermal

interfaces. To date, two principal fixation concepts have been implemented and successfully demonstrated in flight:

- (I) Integrated fixation reactors (IFR) for adherent cell cultures on microscope slides.
- (II) Fixation containments for samples in suspension (e.g., organoids).

Both concepts employ custom sample carriers which are mechanically compatible with the late-access unit envelope and interface set and can be exchanged without any modification of the core platform. These implementations represent flight-proven examples and do not represent an exhaustive set of fixation setups. Detailed qualification and verification of these payload configurations will be presented in separate manuscripts.

As an example of an adherent fixation configuration, integrated fixation reactors (Fig. 3) accommodate microscope slides and enable controlled introduction of fixative via a pump-valve system, displacing excess culture medium into a designated waste reservoir. This arrangement enables controlled fixation actuation while preventing backflow or cross-contamination.

In a suspension-based sample configuration, the module can be equipped with sealed fixation chambers (Fig. 3) which enable a controlled separation of culture medium and fixative. Using gear-motor-driven actuators that remove a separator foil between the two fluid phases, mixing of both liquid phases is initiated. For pre-launch operations, this configuration can optionally incorporate a stepper-motor-driven linear guiding system operating between limit switches to provide gentle, periodic mixing of the medium within the sample carriers. This approach is intended to limit the formation of local concentration gradients, particularly with respect to oxygen and nutrient availability prior to fixation and to promote uniform pre-flight conditions across all samples.

Using these sample carriers, the LIFT module enabled successful in-flight fixations of 64 microscope slides in adherent configuration within MAPHEUS-13, 128 slides within MAPHEUS-14 and 20 suspension-based samples within MAPHEUS-16.

Fixation Timing

The overall fixation timeline comprises the trigger timing precision provided by the LIFT module and the duration of the biological fixation process. Fixation commands are received from the SM through TTL signals with a LIFT internal backup trigger in the event that the scheduled signal is not received, see Sect. 3.4.3. Following receipt of the trigger, the corresponding electrical control chain (trigger

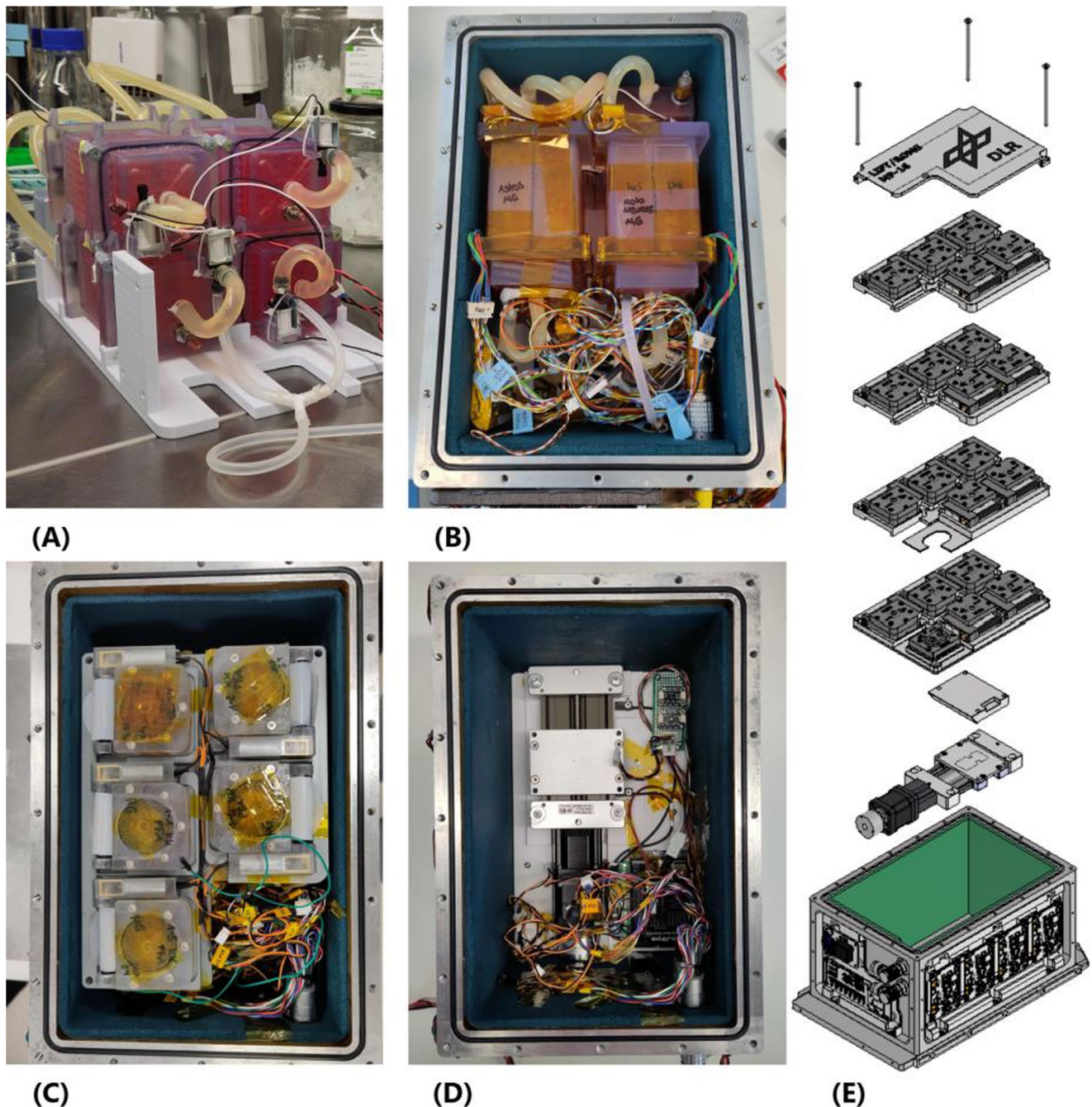


Fig. 3 Overview of representative biological payload accommodation configurations supported by the LIFT module: **(A)** integrated fixation reactors (IFR) for adherent cell cultures on microscope slides; **(B)** IFR-based fixation configuration flown during the MAPHEUS-14 mission; **(C)** optional linear guiding system used for pre-launch mixing of sus-

pension samples; **(D)** suspension fixation configuration employing a separator foil, flown during the MAPHEUS-16 mission; **(E)** exploded view of the suspension sample payload on the linear guiding system for MAPHEUS-16

processing, microcontroller execution and actuator activation) operates on sub-millisecond to millisecond timescales and therefore contributes negligibly to the overall fixation timing.

In previously implemented IFR payloads, the fixative transport, sample exposure and the biochemical fixation reaction was enabled by an active pump-driven flow,

facilitating simultaneous delivery and mixing across all samples. The corresponding fluidic transport required approximately 30 s. By comparison, suspension-sample concepts achieved fixative delivery within approximately 5–6 s. Mixing occurred passively and was therefore dependent on vehicle motion induced fluid dynamics.

To isolate biological responses associated with a defined gravity phase while maximizing the available exposure time, fixation is typically initiated before the end of the respective phase. The required lead time accounts for fixative transport and mixing, together with a timing margin for a sufficient biochemical fixation reaction under the target gravity condition. Therefore, the exact trigger time is defined on a per mission basis and implemented in the SM timeline exclusively driven by scientific objectives and fixation hardware implementation. An exemplary mission and fixation timeline is shown in Fig. 4.

Ground Qualification Tests

Ground qualification testing of the LIFT module is performed prior to each flight application. Both vibration and thermal qualification are configuration-specific and depend on the implemented hardware configuration and fluid distribution. For thermal qualification, the thermal mass and mission-specific target temperature are additional determining factors. As a representative example, this section presents the qualification campaign conducted in preparation for the MAPHEUS-16 mission.

Mechanical Qualification

Mechanical environmental testing is conducted in a flight-representative payload configuration at the Airbus Defence

and Space GmbH Environmental Test Laboratory in Ottobrunn, Germany. The tests are executed in accordance with the MORABA Vibration Specifications v1.1 (2016), derived from the NASA Sounding Rockets User Handbook (Burth et al. 2023), defining the acceptance-level within the MAPHEUS program.

The mechanical qualification comprises initial sine resonance sweep, followed by random vibration testing and a subsequent sine sweep to assess potential shifts in resonance frequencies and response amplitudes. The sine resonance sweep is performed over a frequency range of 5–2000 Hz at an acceleration level of 0.25 g. The random vibration profile is applied between 20 and 20,000 Hz with an overall level of 7.6 g_{RMS} along the X and Y axes and 10 g_{RMS} along the Z axis, each applied for a duration of 20 s.

Acceleration response data for the LIFT module were obtained from a sensor mounted on its surrounding RADAX compartment, representing an indirect measurement location (Fig. 5). Given that the LIFT module was located within the first meter above the motor adapter in all three flight missions, the applied shaker input and measured responses are considered representative of the mechanical excitation at the module interface during flights. While this approach does not provide a direct measurement of the local interface response between the late-access unit and its rail system, it enables the assessment of mechanical integrity under representative qualification loads.

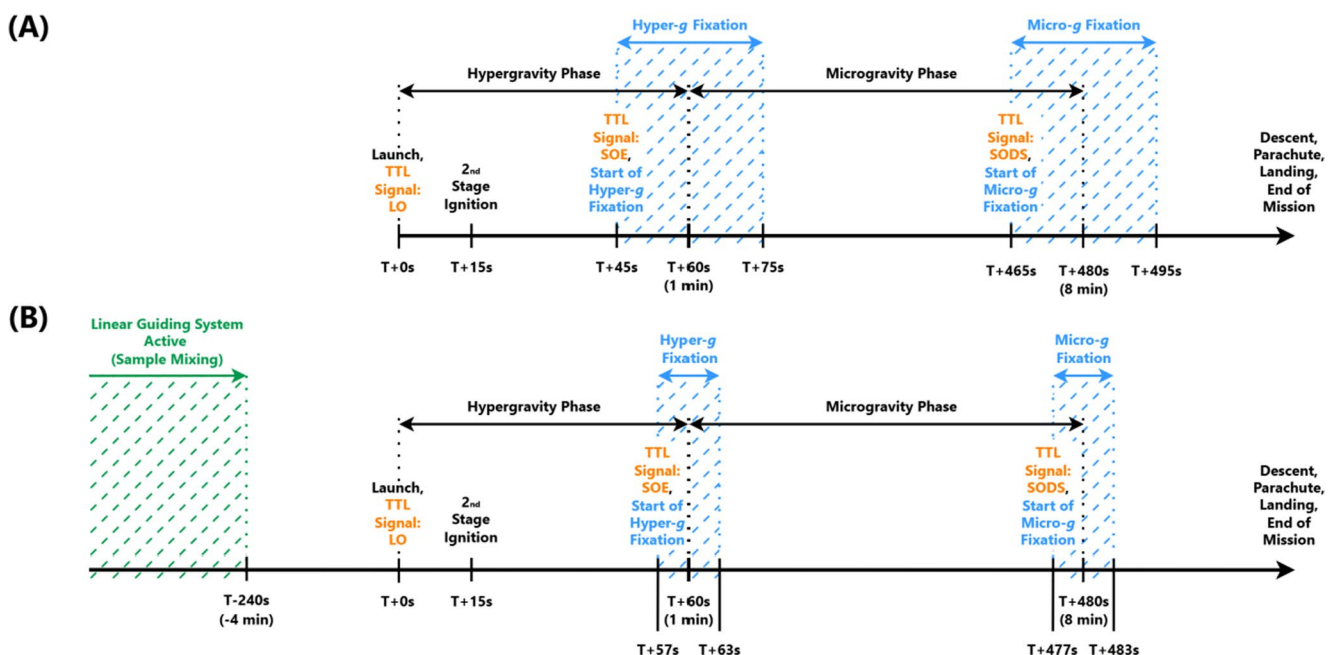
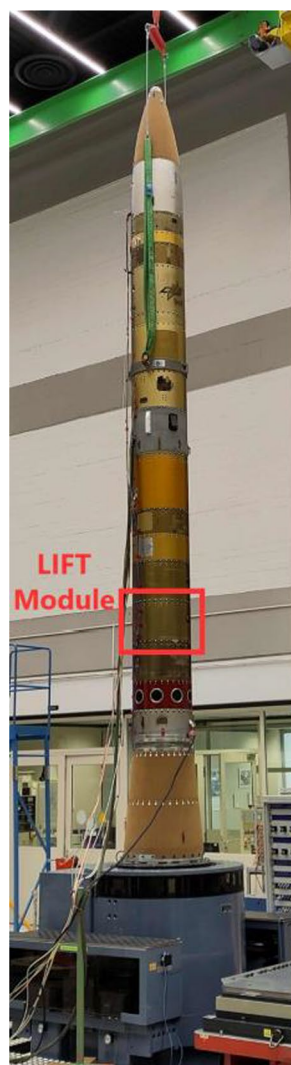


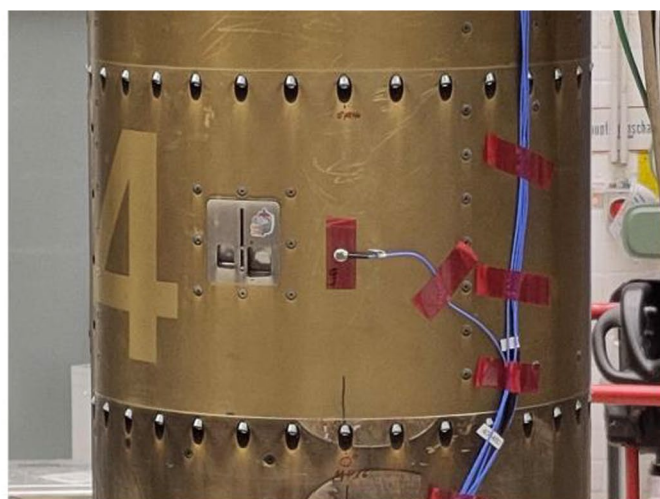
Fig. 4 An exemplary mission timeline for representative fixation hardware configurations. (A) shows the timeline for an adherent sample payload with a duration of approximately 30 s for fixative fluid transport. (B) shows an exemplary setup implementing fixation containment for samples in suspension with a duration of approximately

5–6 s for fixative fluid handling. The setup incorporates the optional linear guiding system for sample mixing pre-launch, given in green. The overall timeline is given in black, with SM fixation commands indicated in orange and the fixation actuation phases given in blue

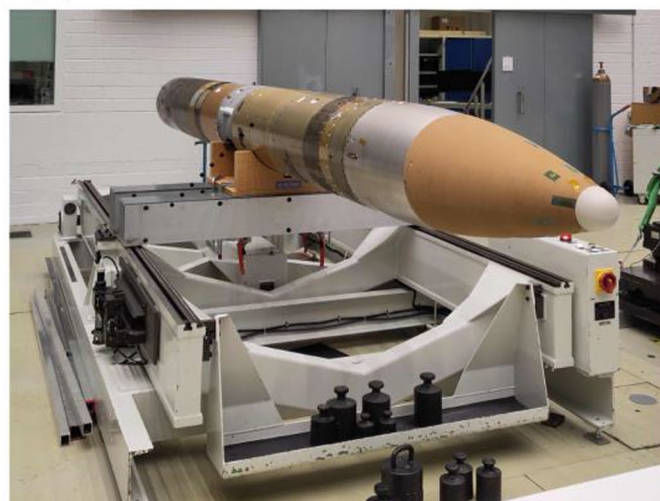
Fig. 5 Mechanical environmental qualification of the MAPHEUS-16 payload: **(A)** Fully integrated payload mounted on the shaker system in the Z-axis configuration, with the LIFT module indicated; **(B)** Close-up view of the LIFT module within the payload assembly, showing the indirect acceleration sensor placement at the outer RADAX shell; the umbilical interface with integrated shutter mechanism is visible adjacent to the sensor; **(C)** Payload in re-entry configuration, without motor adapter, on the balancing table



(A)



(B)



(C)

Following acceptance-level random vibration exposure, the post-test sine resonance sweep was evaluated against the pre-test sweep to check for changes in the dominant resonance peaks of the integrated payload assembly along all three Cartesian axes. Dominant peaks were defined as the highest-amplitude resonance peaks in the measured acceleration response spectra per excitation/response axis, as documented in the post-test vibration qualification report issued by Airbus Defence and Space GmbH (Ottobrunn, Germany).

Across all excitation directions, no new resonance features were identified and the overall response characteristics remained similar regarding pre- and post-test sweeps. Dominant resonance frequencies reported for pre- and post-random sweeps differed only slightly, typically by less than 4%, with one isolated cross-axis deviation of approximately 9%; no systematic frequency drift indicative of structural degradation was observed.

Variations in response amplitudes were observed between pre- and post-test sweeps, predominantly in cross-axis channels. Given the indirect measurement location on the payload stack and sensitivity to stack-level coupling and boundary conditions, amplitude variations cannot be unambiguously attributed to the late-access unit and were therefore not used as a module-level degradation criterion.

Post-test inspections revealed no loosened fasteners or visible structural alterations and functional verification tests conducted pre- and post-vibration testing confirmed nominal operation of all electrical and mechanical subsystems. Taken together, the observed resonance frequency stability, the absence of new dynamic features and the unchanged post-test functionality provide no evidence of mechanical degradation under acceptance-level launch vibration loads.

Although the dynamic response of the late-access unit could only be assessed indirectly, consistent outcomes across multiple shaker runs and three qualification campaigns with different

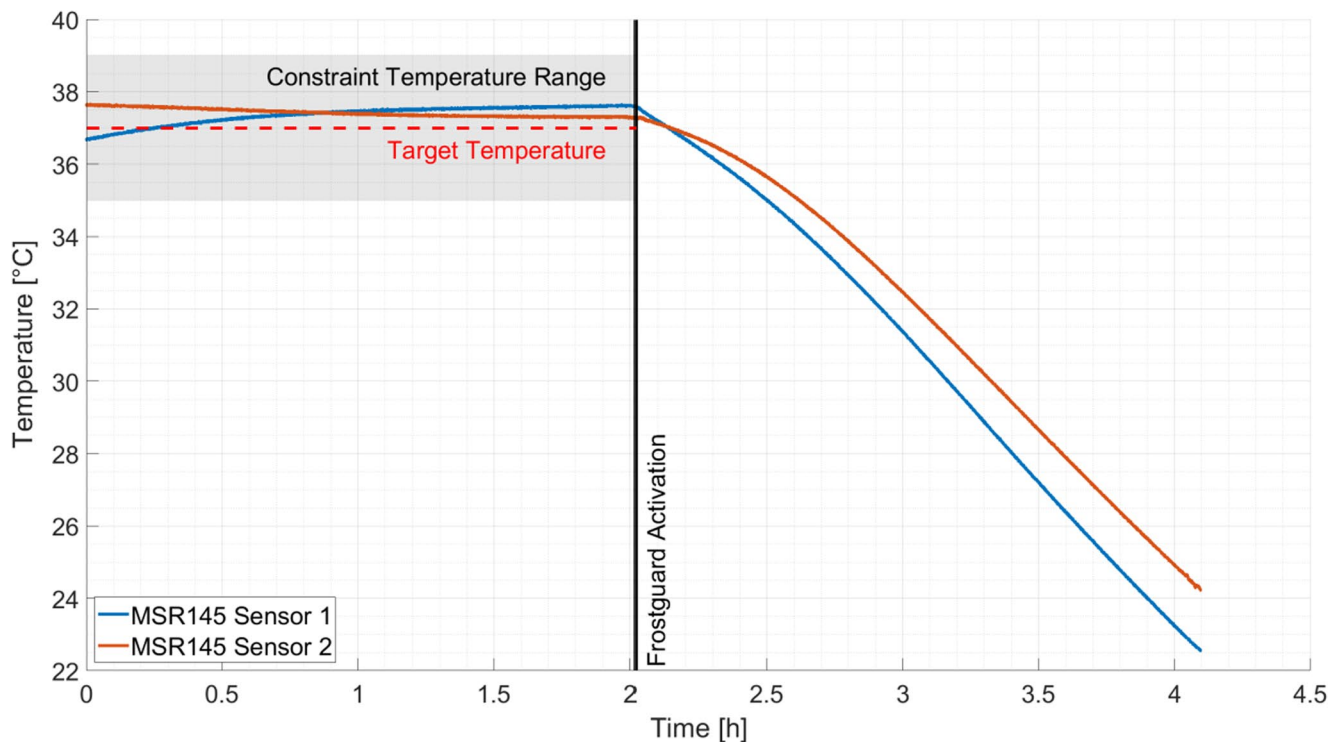


Fig. 6 Temperature profile of the LIFT module in suspension configuration during thermal qualification in advance of the MAPHEUS-16 campaign (mission-specific target temperature 37 °C). Procedures were conducted according to countdown operations. The test was started at room-temperature (21 °C) to simulate late-access handling,

remaining countdown dwell time and launch. Subsequently, the frostguard mode was activated and the module was exposed to an ambient temperature of -7 °C for an additional 2 h to simulate post-flight recovery conditions. The temperature profile starts with the simulated late-access integration phase

payload configurations demonstrate compliance with the defined load requirements (Sect. 2.2) and confirm the suitability of the LIFT module for sounding rocket flight applications.

Thermal Qualification

The qualification test was conducted for the suspension sample configuration with a mission-specific temperature setpoint of 37 °C under representative thermal boundary conditions and in accordance with countdown timelines. Heater calibration was carried out prior to testing.

The late-access unit was powered by a laboratory power supply rather than its onboard battery pack, as the objective was to exclusively validate temperature control performance rather than system endurance. Reference temperature measurements were conducted using a MSR145WD data logger (MSR Electronics GmbH, Switzerland). Two of its external factory-calibrated temperature probes (factory calibrated at 37 °C) were inserted into the suspension sample containers and immersed in the liquid to quantify the sample temperature during the qualification sequence.

Late-access unit assembly and integration of the suspension sample containers were carried out on the laboratory workbench at room temperature (21 °C) with intermediate

storage in the transport incubator, replicating the procedures during countdown. After completing the late-access procedure in its entirety, the integrated unit was held at room temperature for two hours. This phase represents the period after integration into the rocket, including nominal pre-launch dwell time, potential countdown delays and the flight phase. The laboratory temperature is representative of the ESRANGE Skylark launch tower ambient temperatures.

Finally, the module was placed outdoors at an ambient temperature of -7 °C for a duration of two hours and the frostguard mode was activated. This phase simulated post-flight environmental exposure and recovery conditions until experiment completion and sample stabilization.

Figure 6 displays the reference temperature measurements obtained from the two probes immersed in the sample medium, starting with simulated late-access integration and covering the subsequent standalone operation during countdown dwell times. Throughout this sequence, the measured temperatures remained well within the required temperature limits as specified in Sect. 2.2. The mean temperatures measured by the external MSR145WD probes were $T_1 = 37.36$ °C ($\sigma = 0.25$ °C) and $T_2 = 37.41$ °C ($\sigma = 0.11$ °C).

To estimate a worst-case passive cooling scenario and assess the potential onset of sample freezing during adverse

recovery conditions, the temperature decay was approximated using linear fits, yielding an average cooling rate of $7.2\text{ }^{\circ}\text{C h}^{-1}$ under the applied environmental conditions. Linear extrapolation indicates that freezing conditions would be reached after approximately 5 h, if no frostguard were activated. In addition, to provide a more realistic approximation, a first-order exponential decay model was evaluated under identical boundary conditions. The estimation yielded the following expression, with t given in hours:

$$T(t) = 44\text{ K} e^{-\left(\frac{\ln(44) - \ln(29.6)}{2}\right)t} + 266.15\text{ K}$$

Based on this model, freezing conditions are predicted after approximately 9.3 h. In both cases, sufficient thermal inertia and margin are provided relative to optimal post-flight recovery durations of approximately 2–3 h. This assessment is further supported by the reduced freezing point of the chemically fixed samples in medium-fixative solution mixtures. Depending on the fixative agent used, freezing-point depression ranges from approximately $-2\text{ }^{\circ}\text{C}$ to $-10\text{ }^{\circ}\text{C}$.

Based on the thermal qualification results, sample freezing is not expected during countdown operations, even in the event of extended post-flight recovery beyond nominal timelines, as supported by MAPHEUS-16 flight data and presented in Sect. 3.3.1.

In-Flight Verification

This section presents in-flight data acquired during the first three sounding rocket missions employing the LIFT module. We assess the module's capability to provide a controlled sample environment during ground-based operations and in-flight conditions, independent of mission-specific environmental conditions, according to the specifications of Sect. 2.2.

Launch and Mission Scenarios

The LIFT module was flown on three sounding rocket missions (MAPHEUS-13, -14 and -16) under distinct environmental and integration conditions. While all missions were conducted from ESRANGE Space Center, variations in launch infrastructure, season and payload configuration resulted in differing constraints.

The module was employed in two missions using adherent-cell fixation payloads (MAPHEUS-13 and -14) and once with a payload for suspension-based samples (MAPHEUS-16). The latter additionally incorporated a linear guiding system for pre-launch sample agitation to improve culture stability prior to fixation. Biological outcome analyses are reported elsewhere. Within each mission, distinct sample sets were designated for fixation after the

hypergravity launch phase and after the subsequent microgravity phase. The campaigns were conducted in different seasons and mean ambient temperatures: MAPHEUS-13 (May 2023, approximately $10\text{ }^{\circ}\text{C}$), MAPHEUS-14 (February 2024, approximately $-8\text{ }^{\circ}\text{C}$) and MAPHEUS-16 (November 2025, approximately $-8\text{ }^{\circ}\text{C}$).

For MAPHEUS-14 and MAPHEUS-16, payload integration and launch were performed from the Skylark launch tower. As a result, the payload was largely decoupled from ambient environmental conditions prior to lift-off. In contrast, MAPHEUS-13 was launched from the MAN 2 mobile launcher, where the rocket remained exposed to ambient conditions on the launch rail up about 30 min prior to launch.

Pressure Development

Internal pressure within the late-access unit was recorded across all three flight missions. The MAPHEUS-13 configuration employed a BME280 pressure sensor (Bosch, Germany; min. 300 hPa), while subsequent missions used a BMP390 sensor (Bosch, Germany; min. 300 hPa).

Figure 7 compares the pressure evolution relative to lift-off. Panel (A) shows the relative vessel pressure for all missions, while panel (B) presents the ambient pressure within the RADAX inner housing for MAPHEUS-16, the only mission equipped with an external pressure sensor. As the sensor operated outside its specified range, the ambient data were interpreted qualitatively as a time indicator for the vacuum-induced ambient pressure drop.

In comparison to the ambient vacuum pressure at peak apogee, the vessel pressure exhibits only a small absolute reduction. This behavior is likely attributable to elastic deformation of the pressure vessel walls under low-pressure conditions and launch acceleration loads.

For MAPHEUS-13, the maximum internal pressure reduction attributed to effective leakage was approximately 16 hPa, corresponding to about 1.6% of standard atmospheric pressure. For MAPHEUS-14 and MAPHEUS-16, smaller reductions were observed, with MAPHEUS-14 exhibiting a relative reduction of approximately 13 hPa (1.3%) and MAPHEUS-16 of approximately 8.4 hPa (0.84%). In all cases, the internal pressure remained well within the required $\pm 50\text{ hPa}$ range, demonstrating successful decoupling of the internal biological environment from the ambient conditions.

The pressure increase observed following the interval associated with the yo-yo de-spin interval is primarily attributed to continuous operation of the heating system, which induces a thermodynamically driven pressure rise rather than the de-spin event itself.

Transient pressure reductions are observed in the internal pressure profiles of MAPHEUS-13 and MAPHEUS-14,

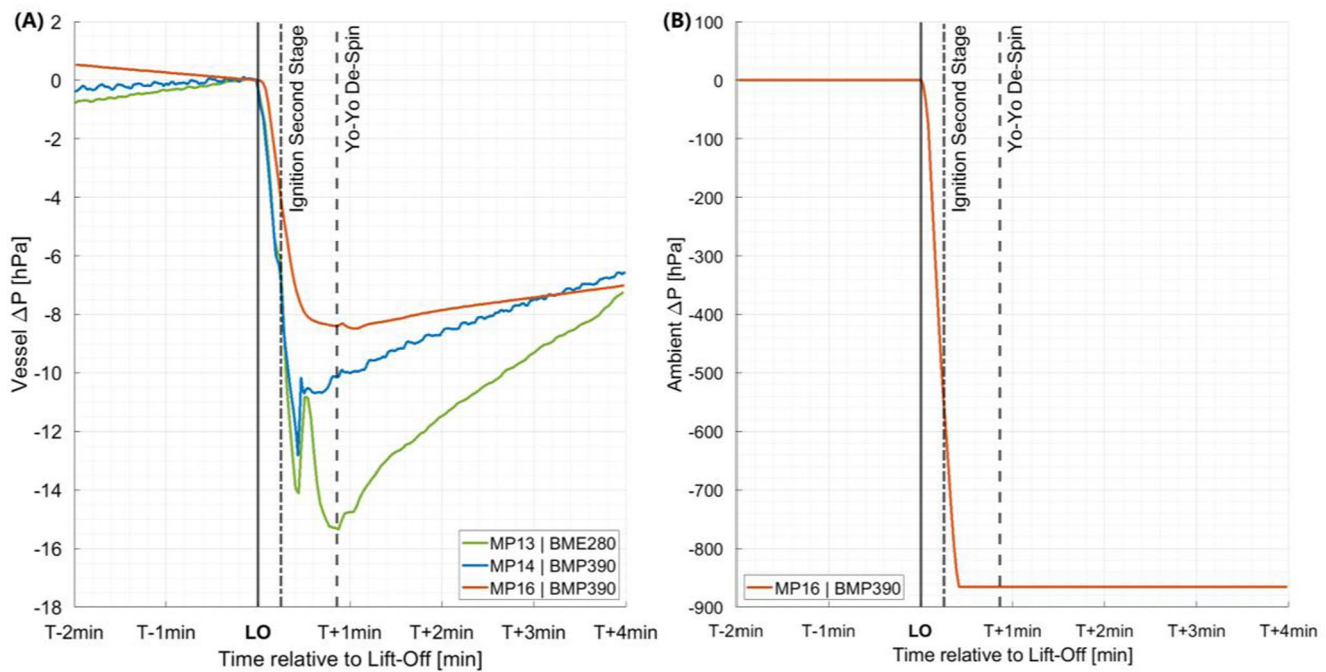


Fig. 7 Late-access unit and ambient pressure evolution measured during three LIFT module flight missions. **(A)** internal pressure inside the late-access unit relative to lift-off, remaining close to pre-launch conditions with only small transient reductions; **(B)** ambient pressure

temporally coincident with payload separation from the boosters. These features are not observed in the MAPHEUS-16 data. Their transient character, together with the absence of any sustained pressure offset, suggests that they originate from short-duration dynamic loading events during second booster stage separation, such as shock loads, or rapid acceleration changes, causing temporary elastic deformation of the late-access unit rather than leakage.

Differences between missions are consistent with variations in second-stage propulsion systems. MAPHEUS-13 and MAPHEUS-14 employed a military-grade solid booster as the upper stage, whereas MAPHEUS-16 used the RED KITE solid rocket motor designed to reduce vibrational loads transmitted to the payload (Scheuerpflug et al. 2025). The reduced transient pressure response is therefore attributed to mission-specific dynamics rather than an intrinsic limitation of the LIFT module design.

Biological Sample Temperature

In-flight sample temperature profiles were evaluated to verify that the LIFT module maintains the mission-specific setpoint for fixation of the biological samples following hyper- and microgravity exposure, independent of sample type and fixation configurations.

To illustrate this capability, temperature data from MAPHEUS-14 and MAPHEUS-16 are compared: two

measured within the RADAX inner housing during MAPHEUS-16; values below the sensor's specified range are shown as a qualitative timing indicator of the pressure decrease toward vacuum rather than as absolute pressure; Vertical markers indicate key flight events

representative flight missions with similar launch and ambient conditions. The MAPHEUS-14 mission employed the LIFT module as an adherent-cell fixation platform using integrated fixation reactors (Fig. 3), whereas MAPHEUS-16 utilized the module for fixation of biological samples in suspension. These configurations represent distinct thermal loads, sample distributions and heating implementations within the same flight-qualified LIFT platform, enabling a comparative assessment of thermal performance across configurations.

In the MAPHEUS-14 configuration, temperature control was implemented using individually heated IFRs, each equipped with a heating pad and a PT100 resistance temperature detector (RTD) governed by the analog heater circuits and set to 36.5 °C. In contrast, the MAPHEUS-16 configuration employed an updated analog architecture with improved stability, using a customized common heating pad covering all biological sample carriers and a PT1000 RTD-based control architecture to maintain a setpoint of 37.0 °C.

Figure 8 displays the in-flight temperature profiles of representative hyper- and microgravity fixation samples for both missions. In both configurations, sample temperatures remained well within the specified tolerance band around the mission-defined setpoint (Sect. 2.2), with observed deviations limited to approximately ± 0.5 °C, corresponding to about 25% of the constraint temperature range.

The MAPHEUS-14 configuration exhibits more pronounced temperature fluctuations about the setpoint,

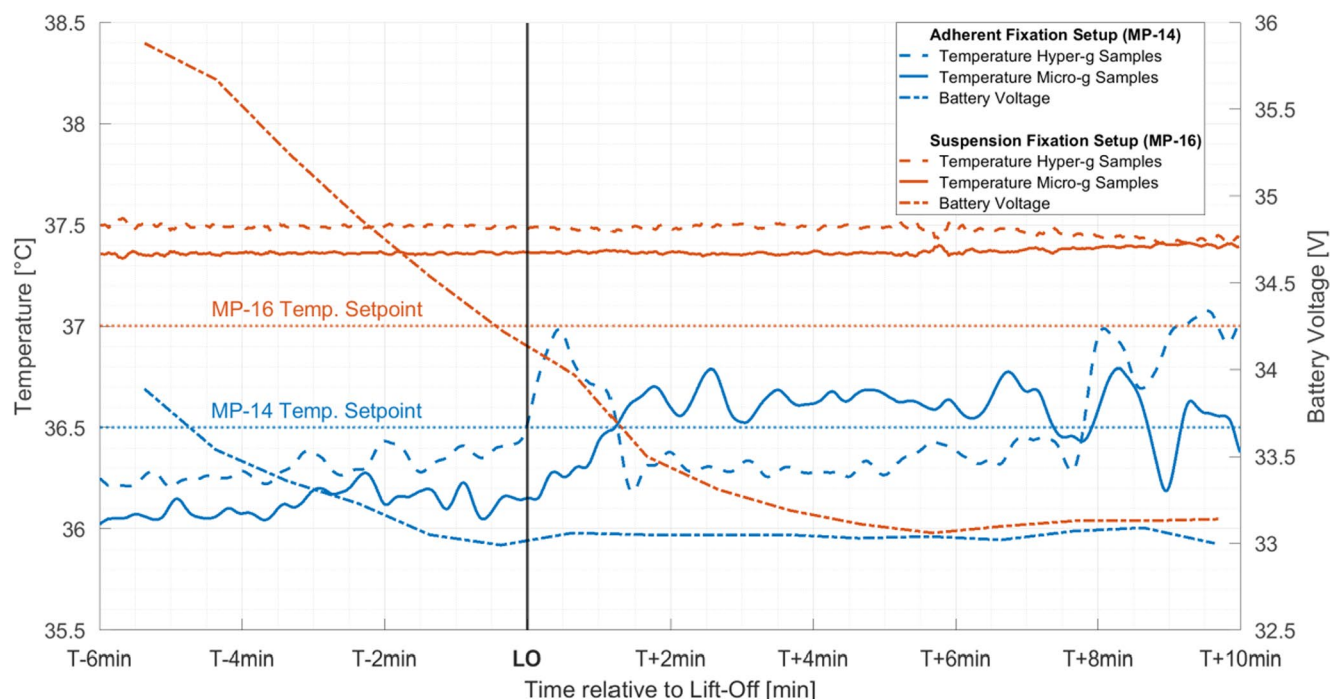


Fig. 8 In-flight temperature profiles of biological samples during the MAPHEUS-14 (adherent sample payload) and MAPHEUS-16 (suspension sample payload) missions, shown relative to lift-off. Sample temperatures for hyper- and microgravity fixation are plotted on the left axis, while the corresponding battery voltage is shown on the right

whereas the revised thermal control architecture implemented within the same LIFT platform for MAPHEUS-16 provides noticeably improved stability. The differences are attributed to the heater circuit design and sensing architecture rather than to variations in mission operations or count-down procedures.

For MAPHEUS-14, the battery could not be fully charged prior to launch due to operational constraints during count-down, resulting in a pre-launch voltage of approximately 34 VDC compared to 36 VDC for MAPHEUS-16. This condition did not affect thermal control performance or experiment execution, but reduced the available post-flight energy margin. As payload recovery took place within approximately three hours after landing, no operational limitations resulted.

In-Flight Performance Summary

The in-flight data acquired during three sounding rocket missions demonstrate that the LIFT module meets all functional and environmental requirements for the protection and fixation of biological samples under flight conditions as defined in Sect. 2.2. Across all missions, the late-access unit effectively isolated the samples from ambient vacuum conditions, with measured internal pressure variations remaining well within the specified ± 50 hPa target range.

axis to contextualize the thermal control performance with respect to the available power state. In both configurations, sample temperatures remained well within the specified ± 2 °C requirement, with reduced fluctuations observed for the MAPHEUS-16 configuration

The maximum internal pressure reduction observed across all flight missions was 16 hPa.

Temperature data from representative fixation configurations confirmed stable in-flight thermal control. Independent of sample type and payload configuration, biological samples were maintained well within the ± 2 °C requirement, with observed deviations limited to approximately ± 0.5 °C. The modular thermal architecture enables configuration-specific adaptation while maintaining standardized platform operation. Iterative refinement of the thermal control architecture resulted in improved temperature stability in later missions.

All fixation actuations were executed successfully across all flight campaigns, demonstrating reliable operation of the LIFT platform with multiple interchangeable fixation payloads. Detailed findings will be presented in the associated scientific payload publications.

Discussion and Outlook

The LIFT module enables exposure of biological samples to altered gravity conditions within an environmentally controlled platform, while supporting time-critical chemical fixation synchronized with the flight phase. By combining late-access capability, automated operation and support for interchangeable fixation payloads, the platform enables

biological experiments across different sample types and mission scenarios under well-defined and repeatable boundary conditions suited for, but not limited to, sounding rockets.

In addition to its fixation capability, the platform provides a continuous acquisition of environmental and operational data, including temperature, pressure and acceleration. This is achieved through an onboard sensor suite and data processing pipeline that form part of the platform's core architecture and remain independent of the selected experiment-specific fixation hardware. This configuration-invariant data acquisition improves traceability of experimental conditions and supports reproducibility and cross-mission comparability.

Successful deployment within three MAPHEUS sounding rocket flights demonstrated reliable execution of all mission-critical functions under representative spaceflight conditions. All requirements were fulfilled as specified. Time-synchronized fixation sequences were executed successfully, while stable thermal conditions were maintained independent of flight dynamics, supporting the sensitive samples from laboratory preparation, through the flight sequence to recovery. Power supply integrity, trigger-based experiment execution and automated data acquisition were successfully demonstrated across all campaigns.

A key strength of the LIFT module lies in its modular architecture. A single flight-qualified core system was successfully operated with multiple interchangeable biological fixation payloads, without modification of the underlying platform design. This modularity enables efficient reuse of flight-qualified hardware and established operational procedures while supporting a wide range of biological experimental objectives. Different biological applications require different fixation chemistries, actuator concepts and fluidic architectures, each exhibiting distinct biochemical reaction kinetics and technical requirements. Rather than defining a single fixation approach, LIFT was designed to accommodate and enable interchangeable fixation payloads. Detailed descriptions and validation of these payloads are therefore beyond the scope of this platform paper and will be presented in dedicated application-specific publications.

Despite present work focusing on sounding rocket applications, the underlying platform concept is not restricted to this mission class. A modified implementation based on the LIFT architecture has already proven successful during parabolic flight campaigns, showcasing the versatility of the modular fixation concept under various altered gravity profiles. Due to the distinct operational constraints, flight timeline and hardware adjustments needed for a parabolic flight, these advancements are not within the scope of this manuscript. A dedicated publication detailing the modified platform architecture, mission execution and experimental validation will be reported separately.

Despite its demonstrated performance, the current implementation of the LIFT module exhibits several limitations

that are important to acknowledge. The usable payload volume is inherently limited by the pressure-vessel architecture required for late-access integration and environmental isolation, limiting subsystem expansion.

In addition, trigger-based fixation relies on signals provided by the MAPHEUS Service Module. Although redundant fallback mechanisms based on onboard acceleration sensing are implemented, fixation timing remains partially dependent on external signal quality.

Thermal control relies exclusively on active heating and passive cooling - no active cooling capability is implemented. Consequently, the post-fixation cooling rate is limited and depends on ambient recovery conditions. While sufficient for the evaluated mission scenarios, this architecture constrains post-fixation thermal dynamics.

From an operational perspective, the analog heating system introduces additional complexity. The system requires a channel-wise calibration using adjustable resistors, a rather time-consuming process that requires careful tuning. While this approach enables uninterrupted thermal control essential for biological sample integrity, it limits flexibility and ease of reconfiguration.

To address these limitations, a hybrid thermal control architecture can be envisioned, in which the analog heating system usage is restricted to transport, late-access and frost-guard operation phases which require uninterrupted heating under radio-silence safety constraints. During powered pre-flight and flight phases, a digitally controlled PID-based system should be employed to provide improved temperature stability. Such an approach could be implemented within the existing system architecture by allocating a dedicated actuator output, thereby preserving safety compliance while simplifying calibration and improving in-flight temperature control performance.

The integration of an active cooling capability represents an additional potential extension. However, this would introduce trade-offs in terms of increased power demand and a reduced scientifically usable payload envelope. Given the finite energy capacity of the onboard battery pack, active cooling could constrain power availability for other payload functions, including heating and actuation. Accordingly, implementation of active cooling would require a dedicated power-budget and system-level trade off analysis to assess its impact on overall platform performance.

Conclusion

This work presents LIFT as a modular platform enabling automated in-flight chemical fixation for biological experiments under altered gravity, validated across multiple sounding rocket missions. Consistent performance under varying

launch conditions and payload configurations demonstrates the operational maturity of the system. Its modular design enables the integration of interchangeable fixation hardware without requiring modification to the flight-qualified core. This supports reproducible and quantitatively monitored experiments across diverse sample types and mission scenarios.

By reliably maintaining stable thermal regulation and a pressure-stabilized environment throughout all mission phases, while executing synchronized fixation sequences according to the mission timeline, LIFT is demonstrated as a reusable and spaceflight-proven platform for autonomous biological fixation experiments on sounding rockets and other microgravity platforms.

Abbreviations

DC-DC	Direct current-direct current converter
DLR	German aerospace center
EMI	Electromagnetic interference
ESD	Electrostatic discharge
FAT	File allocation table
GSE	Ground support equipment
IFR	Integrated fixation reactor
ISS	International space station
LIFT	Laminar in-flight fixation technology
LO	Lift-off
MAPHEUS	Materialphysikalische experimente unter schwerelosigkeit
MAPHEUS, MP;	Proportional integral derivative
PID	controller
RADAX	Rocket experiment compartment standard
RMS	Root mean square
RTD	Resistance temperature detector
SM	Service module
SOE	Start of experiment
SODS	Start of data storage
TTL	Transistor-transistor logic
TRL	Technology readiness level

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Data Availability The raw data supporting the findings of this study and are available from the corresponding author upon reasonable request.

Declarations

Ethics in publishing Not applicable.

Competing interests The authors declare no conflicts of interest.

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