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ATEMO

Aerospace Technologies for Earth Monitoring and Observation

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Declaration to the Reader

This doctoral thesis is presented as a collection of published, accepted, and submitted scientific articles (“paper collection”), in accordance with the regulations of the PhD Course in Sciences, Technologies and Measurements for Space at the University of Padova.

The main body of the thesis consists of the following scientific articles:

- Paper I: Launch of an innovative air pollutant sampler up to 27,000 metres using a stratospheric balloon – published in *Aerotecnica Missili & Spazio*, 2023 [1].
- Paper II: Development and Preliminary Testing of the ATEMIO Multi-Purpose Sensing Platform – published in *Aerotecnica Missili & Spazio*, 2024 [2].
- Paper III: In Flight Characterization of a Balloon-Payload Dynamic through a Sensorised Sounding Balloon's Chain – accepted with minor revision by *Aerospace Science and Technology*, 2025.
- Paper IV: Characterisation of the Flight Chain for Sounding Balloon Missions – presented at IEEE 12th MetroAeroSpace, 2025 [3].
- Paper V: The J2050 student PocketQube for space debris investigation and optical observation technology development, 2025 [4].

For each article, the candidate’s specific contribution is clearly declared at the beginning of the relevant chapter. Each included paper maintains its own reference list, and the introductory and concluding sections share a single and consolidated bibliography.

Introductory, discussion and concluding sections have been exclusively developed to provide a coherent scientific and editorial framework for reading the collected papers as a unitary research work.

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Abstract

In a context of rapid climate change and growing demand for high-resolution environmental data, this thesis—structured as a collection of scientific papers—advances the development and validation of modular aerospace technologies for Earth observation. Defined as the ATEMO (Aerospace Technologies for Earth Monitoring and Observation) project, the research explores the design, experimental validation, and practical deployment of versatile sensing platforms for use on drones, stratospheric, and tethered balloons.

This body of work addresses several scientific and engineering challenges, such as enabling multi-purpose, high-resolution data acquisition for applications ranging from vegetation health monitoring to light pollution analysis. The ATEMO platform, based on a scalable and accessible architecture, integrates commercial sensors and cameras to provide a cost-efficient solution that complements traditional satellite and ground-based observation methods. Its flexibility and modularity allow for rapid adaptation to diverse operational scenarios, ensuring robust performance during experimental campaigns across varied environments.

A distinctive focus of the research lies in the comprehensive analysis of flight dynamics, with particular attention to the oscillatory behaviors, the balloon-payload relative movements and the stability constraints affecting lighter-than-air systems. Through a combination of analytical modeling, laboratory testing, and flight experiments, the thesis provides new insights into pendular, torsional, and longitudinal modes that can impact the accuracy of remote measurements. The detailed study of the balloon flight chain, including its dynamic characterization and the interplay between mechanical structure and environmental forces, provides a methodological solution for future mission planning and platform optimization.

Furthermore, the research extends to the critical assessment of miniaturized technologies and emerging approaches for cost-effective Earth observation. Participation in international collaborations and complementary projects—such as the E-FORESTER MSCA staff exchange European project, the “Light Pollution Source Detection” project in Chile, The Italian PRIN (Project of Relevant National Interest) named “Rewatering” and the RedPill pocketcube of the J2050 team—demonstrates the potential of scalable, low-cost instruments to broaden access to environmental data and support sustainable monitoring strategies.

By advancing methodologies for the integration and cross-validation of aerial, in-situ, and satellite data, the thesis delivers practical solutions for comprehensive environmental assessment and supports calibration/validation protocols necessary for operational reliability. The collective outcomes underline the importance of modularity, dynamic understanding, and technological accessibility in shaping next-generation environmental monitoring, with impacts spanning precision agriculture, urban studies, and global sustainability initiatives.

Declaration to the Reader.....	II
Abstract.....	IV
List of abbreviations and acronyms	VII
1. Introduction.....	1
1.1. General Framework	1
1.2. State of the Art	3
1.2.1. Earth observation technologies	3
1.2.2. Flight dynamics and System Characterization.....	5
1.2.3. Gaps and Research Motivation	6
1.3. Thesis Objectives and Structure.....	7
2. Paper I: Air Pollution Payload	9
Launch of an innovative air pollutant sampler up to 27,000 meters using a stratospheric balloon.....	10
3. Paper II: First ATEMOS payload	26
Development and Preliminary Testing of the ATEMOS Multi-Purpose Sensing Platform ...	27
4. Paper III: ATEMOS Flight Dynamics Assessment	43
In Flight Characterization of a Balloon-Payload Dynamic through a Sensorised Sounding Balloon's Chain	44
5. Paper IV: Flight Chain Characterization.....	62
Characterisation of the Flight Chain for Sounding Balloon Missions.....	63
6. Paper V: Miniaturization Application	76
The J2050 student PocketQube for space debris investigation and optical observation technology development	77
8. General Discussion and Synthesis	93
8.1. Key Findings and their Implications.....	93
8.2. Limitations and Challenges.....	94
8.3. Integrative Applications and Interdisciplinary Impact.....	95
8.4. Future Directions	96
9. Conclusions.....	97
9.1. Main Conclusions	97
9.2. Outlook	98
9.3. Final Remarks	98
Acknowledgments.....	100
References.....	102

List of abbreviations and acronyms

AREO	Attitude Reconstruction and Earth Observation
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ATEMO	Aerospace Technologies for Earth Monitoring and Observation
BEXUS	Balloon EXperiments for University Students
cal/val	Calibration and validation
CLEAR	Compact LEDs and Attitude Reconstruction
CLOUD	CLassifying Orbital Undetectable Debris
COTS	Commercial Off-The-Shelf
CRYSTALS	ChRomatic Yielding, and Smart Technologies for Anti-Light Shielding
DLR	Deutsches Zentrum für Luft- und Raumfahrt
E-FORESTER	Effective FOrEst Research Electronic System Terrain Exploration Rover
EDX	Energy Dispersive X-ray Analysis
ENDVI	Enhance Normalized Difference Vegetation Index
EO	Earth Observation
EPS	Electrical Power System
ESA	European Space Agency
ESEM	Environmental Scanning Electron Microscopy
FTIR	Fourier-transform infrared spectroscopy
GCMS	Gas Chromatography–Mass Spectrometry
GEO	Geostationary Earth Orbit
GNDVI	Green Normalized Difference Vegetation Index
GPS	Global Positioning System
GS	Ground Station
IMU	Inertial Measurement Unit
ISRO	Indian Space Research Organization
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
MAIT	Manufacturing Assembly Integration and Testing
mgmt	management
MINLU	Instrumental Suite for Monitoring Light Pollution from UAVs
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
O-ZONE	Stratospheric Payload for Air Pollution Assessment
OBC	On Board Computer
PCB	Printed Circuit Board
PDTs	Payload Data Transfer
PRIN	Project of Relevant National Interest
PVDF	Polyvinylidene fluoride
PWM	Pulse Width Modulation
REWATERING	REassessing crop WATER Requirements in the face of global warming
SNSA	Swedish National Space Agency
SQM-L	Sky Quality Meter type L
TD	Thermal Desorption
TinyGS	Tiny Ground Station Network
UAV	Unmanned Aerial vehicle
VI	Vegetation Indices

1. Introduction

The monitoring of Earth's environment through advanced aerospace technologies has become increasingly vital in addressing the intertwined challenges of climate change, sustainable resource management, and the rapid evolution of urban and agricultural landscapes. The growing demand for accurate, spatially and temporally resolved environmental data has driven the development of flexible, innovative, and accessible observation systems capable of supporting informed decision-making from scientific research to operational practice. In this context, the ATEMO project (Aerospace Technologies for Earth Monitoring and Observation) was established to design, validate, and implement a new generation of modular sensing platforms deployable on drones and stratospheric balloons.

This thesis originates from the significant experimental milestone marked by the launch and in-flight validation of an innovative pollutant's sampler using a stratospheric balloon—an endeavor that bridged pre-doctoral research with the more advanced investigations carried out during the PhD. The lessons learned from this initial campaign provided not only operational proof-of-concept for the modular architecture but also highlighted the technical and methodological challenges that would shape the scientific objectives of the following years. These challenges included payload reliability under dynamic flight conditions, the integration of commercial off-the-shelf sensors, and the necessity to harmonize calibration, data acquisition, and trajectory reconstruction protocols.

Building upon the experience gained with the previous investigations, the research evolved to address more complex requirements, such as multi-sensor integration, flight dynamics analysis, and cross-platform data fusion. The work presented here, structured as a collection of peer-reviewed scientific papers, retraces this progression: from the foundational achievements of the early balloon campaign, through the iterative engineering of the ATEMO platform, to the broader application of innovative and cost-effective technologies for environmental monitoring. In doing so, the thesis offers an integrated perspective on the technical, methodological, and application-driven advances that define the ATEMO framework and its contribution to contemporary Earth observation.

1.1. General Framework

Over the last decade, the landscape of Earth observation has undergone a rapid and profound transformation, driven by pressing societal challenges such as climate change, sustainable resource management, and rapid urbanization. While satellite platforms continue to play a fundamental role in planetary-scale monitoring, their intrinsic limitations—such as high operational cost, inflexible revisit times, and constraints in spatial and spectral resolution—have stimulated the search for accessible, agile, and high-resolution alternatives. In response, a new generation of complementary approaches—including unmanned aerial vehicles (UAVs), tethered and free-flying stratospheric balloons, and modular sensor payloads—has emerged, reshaping the possibilities for environmental data acquisition and exploitation.

Within this dynamic scenario, the ATEMO (Aerospace Technologies for Earth Monitoring and Observation) project establishes itself as a forward-looking initiative aimed at creating versatile solutions to bridge the gap between traditional satellite observation and localized, mission-oriented monitoring. The core philosophy of ATEMO centers on the design and deployment of a modular, scalable payload system, able to collect robust, high-quality environmental data across an array of operational settings and platforms. This adaptability allows the same architecture to be effectively deployed on UAVs, tethered balloons, or stratospheric balloons, making it possible to conduct targeted campaigns for a wide range of scientific objectives—from assessing vegetation health and mapping light pollution to broader applications in precision agriculture and ecosystem monitoring.

A fundamental tenet of the ATEMO project is its focus on modularity and scalability. Each subsystem—whether dedicated to data acquisition, power management, or communications—can be independently updated or reconfigured, supporting both rapid experimental prototyping and extended, routine operations. This architectural flexibility encourages technological evolution and ensures the long-term sustainability of the platform, accommodating new sensors, cameras, or communication protocols as requirements and scientific priorities shift.

In addition, ATEMO deliberately embraces the integration of commercial off-the-shelf (COTS) components to maximize both accessibility and reproducibility. The decision to utilize standard digital cameras with customized optical filters, widespread inertial measurement units (IMUs), GPS receivers, and other commercially available hardware demonstrates that high-quality scientific instrumentation can be achieved at a fraction of the traditional cost. Strict calibration and data harmonization protocols are employed to guarantee the reliability, consistency, and comparability of the data collected across campaigns, platforms, and hardware generations.

Central to the effectiveness of environmental data acquisition is the comprehensive analysis of dynamic system behavior during aerial operations, particularly for balloon-based and tethered missions. The project addresses critical challenges associated with flight and attitude dynamics—such as pendular, torsional, and longitudinal oscillations—using a combined approach of analytical modeling, laboratory-based vibration characterization, and in-flight experimentation with distributed IMUs. This rigorous treatment not only safeguards the scientific quality of the collected data but also delivers actionable insights into mission planning, payload stability, and trajectory optimization, even under highly variable atmospheric conditions.

Beyond the purely technological dimension, the development and deployment of ATEMO have fostered broad interdisciplinary collaboration. Technologies and methodologies originally developed within ATEMO have been successfully transferred to large-scale research initiatives, such as the European Union E-FORESTER project, confirming their adaptability and scalability in diverse research and operational contexts.

In summary, the ATEMO project offers a pragmatic, accessible, and scientifically robust pathway for addressing the evolving needs of contemporary Earth observation. By bringing together modularity, affordability, and rigorous dynamic system analysis, ATEMO demonstrates how next-generation environmental monitoring platforms can be both

scientifically advanced and operationally attainable—laying the groundwork for sustainable and impactful innovation in the coming years.

1.2. State of the Art

The field of Earth observation has undergone a significant transformation in recent years, propelled by both technological advancements and the ever-growing need for timely, accurate, and actionable environmental data. Traditional approaches, which rely heavily on spaceborne platforms, have delivered unprecedented global coverage and historical continuity in environmental monitoring. However, these systems are inevitably subject to certain constraints: high operational costs [5], [6], fixed revisit intervals, and limitations in spatial, spectral, and temporal resolution that can hinder their suitability for localized and dynamic applications.

In response, a new ecosystem of complementary observation technologies has emerged. The proliferation of unmanned aerial vehicles (UAVs) [7], together with the resurgence of high-altitude and stratospheric balloons equipped with modular payloads [8], has broadened the operational flexibility and scope of environmental monitoring. These platforms, leveraging rapid advancements in miniaturized sensors and onboard data processing, make it possible to collect high-resolution, mission-driven data [9] that supplements satellite records and bridges critical gaps in both temporal and spatial coverage.

This expansion of observational capabilities has fundamentally changed the landscape of Earth observation, enabling cross-platform integration [10], real-time data acquisition, and adaptive mission planning [11]. At the same time, it has introduced new scientific and technical challenges—ranging from the calibration and interoperability [12] of heterogeneous systems to the dynamic effects imposed by flight conditions on measurement quality.

Against this backdrop, the research presented in this thesis is positioned at the intersection of these developments. By critically evaluating the current state of technologies, methodologies, and open questions in the field, the following sections provide the necessary context to understand the rationale, challenges, and innovation embedded in the ATEMO project and related scientific contributions.

1.2.1. Earth observation technologies

Earth observation technologies have evolved rapidly over the past decades, transforming how researchers, governmental agencies, and industry address challenges related to climate, environmental monitoring, resource management, and urban development. Today's technological landscape is characterized by a growing synergy between spaceborne, airborne, and in-situ platforms—each contributing unique capabilities and overcoming specific limitations inherent to the others.

Satellite-Based Platforms

Satellites represent the historic backbone of Earth observation, providing unparalleled spatial coverage and temporal continuity. Modern satellite missions, such as those in the European Copernicus program (Sentinel series) [13], NASA's Earth Science missions [14], and commercial constellations like PlanetScope [15], supply multi- and hyperspectral imagery,

radar data, and thermal observations [16]. These data support applications ranging from climate change assessment and disaster response to agricultural management and urban planning [17], [18], [19].

Despite their strengths, satellites are subject to operational constraints [20], [21]. Limitations in revisit frequency—especially for high-resolution payloads—mean that transient or small-scale phenomena can be missed [22], [23]. Cloud cover and atmospheric interference may further restrict data usability [24], particularly for optical sensors [25]. Additionally, while commercial satellites now achieve sub-meter resolution, many open-access datasets operate at coarser scales, which can hinder precise monitoring of localized events [26], [27], [28].

Airborne Platforms and UAVs

The proliferation of unmanned aerial vehicles (UAVs), as well as instrumented aircraft, has revolutionized environmental monitoring by introducing flexible, high-resolution data collection at affordable costs [29]. UAVs can be rapidly deployed, flown at low altitudes, and programmed for site-specific missions—providing detailed observations for everything from crop health [30] and water resources [31] to urban heat mapping [32], [33].

Advancements in sensor miniaturization and onboard processing enable UAVs to carry sophisticated cameras (including multispectral, hyperspectral, and thermal) [34], LiDAR systems [35], and air analyzers [36]. This suite of tools supports applications that demand fine spatial detail, repeatability, and custom data products—which satellites alone often cannot provide. Airborne campaigns are also critical for calibration and validation (cal/val) [37] of satellite-derived products, strengthening the reliability of multisource data integration [38].

Stratospheric and Tethered Balloons

Tethered and stratospheric balloons offer an intermediate solution between satellites and low-flying UAVs [39], [40]. They enable the deployment of heavy and complex payloads, high-end cameras, and scientific instruments into near-space conditions, often for extended durations and at a fraction of the cost of traditional satellite missions [41]. Balloons are particularly valued for atmospheric chemistry measurements [42], technology demonstration [43], and targeted Earth observation in regions or timeframes not accessible by other means [44], [45], [46], [47].

Tethered balloons are similarly important for targeted, long-duration monitoring at fixed locations or low-to-moderate altitudes, combining the persistence of ground-based systems with the vertical reach of aerial platforms [48].

Modularity and System Integration

A key trend in the field is the increasing modularity and interoperability of observation technologies [49], [50]. Platforms such as ATEMU [40] exemplify this approach: payloads are designed around commercial off-the-shelf (COTS) components—including digital cameras with custom optical filters, inertial measurement units (IMUs), GPS, and environmental sensors—allowing rapid reconfiguration to meet diverse mission requirements. This modular design philosophy enhances cost-effectiveness, scalability, and the rapid adoption of new scientific capabilities as technology advances [51], [52], [53].

Furthermore, modern observation systems are engineered for seamless integration between data streams—merging satellite imagery, aerial surveys, ground sensors, and ancillary datasets to deliver comprehensive, multi-layered environmental intelligence [54]. This cross-platform synthesis is essential to maximize data value, ensure calibration consistency, and address the complex, multi-scale dynamics of environmental processes.

Future Perspectives

Earth observation technologies will continue to progress toward greater accessibility, autonomy, and precision, driven by ongoing developments in sensor technology, artificial intelligence, edge computing, and collaborative networks. The democratization of data—emphasized by open-access satellite programs and the affordability of UAVs and balloon systems—will foster innovation across disciplines, facilitating timely and actionable insight into the world’s most pressing environmental challenges [55], [56], [57], [58], [59]. The European Union’s commitment to open access policies [60] and full, free data policies exemplified by Copernicus [61], [62] further supports this democratization trend.

1.2.2. Flight dynamics and System Characterization

Understanding the flight dynamics and system characterization of aerial platforms—especially those involving stratospheric and tethered balloons—is vital for reliable, high-quality environmental monitoring and data acquisition. The dynamic environment experienced during ascent, float, and descent presents a range of mechanical and operational challenges that directly affect payload stability, data integrity, and mission success.

The Challenge of High-Altitude Flight Dynamics

Balloon-based platforms, while offering access to near-space altitudes at relatively low cost, are inherently subject to complex dynamic behaviors. The balloon-payload chain acts as a coupled mechanical system influenced by aerodynamic forces, wind shear, thermal gradients, and the intrinsic properties of the flight chain itself [63]. These factors induce a spectrum of oscillatory modes, primarily [47], [64], [65]:

- **Pendular Oscillations:** Large amplitude swinging motions due to wind gusts, buoyancy changes, or launch dynamics, affecting the pointing accuracy of sensors and cameras.
- **Longitudinal Vibrations:** Extension and contraction along the chain axis, which can influence the structural integrity and the performance of sensitive equipment.
- **Torsional Movements:** Rotational motions around the main axis, especially critical for instruments that require stable orientation, such as inertial measurement units and imaging payloads.

These dynamics not only impact the accuracy of in-flight measurements but also influence the safety and recoverability of payloads.

Analytical and Experimental Approaches

Modern research integrates analytical modeling with rigorous experimental characterization to map the behavior of the balloon-payload system. Analytical models employ a combination of spring-mass-damper systems, eigenmode analysis, and numerical simulations to predict

oscillatory frequencies, damping ratios, and amplitude responses under nominal and disturbed conditions. These models guide the design of the flight chain, informing material selection, geometric configuration, and the placement of vibration isolation elements.

With the theoretical work, laboratory and field experiments the workflow appears a complete procedure. Campaigns replicate the multi-modal dynamics of the flight chain by inducing controlled pendular, torsional, and longitudinal excitations, with sensors such as accelerometers and rate gyros logging responses at multiple points. Flight controllers (e.g., Pixhawk units) are often installed at both the balloon and payload interfaces to characterize differential behavior and enable high-fidelity reconstructions of motion. Field campaigns, including actual balloon launches [66], [67], provide invaluable data for model validation, revealing environmental interactions that may not be fully captured in laboratory settings.

Impact on Payload and Data Quality

The results from recent campaigns [2][45] underscore the necessity of thorough dynamic analysis. Pendular motions can cause systematic misalignment in imaging data or degrade the accuracy of atmospheric samples, while excessive vibrations risk damaging electronics. Torsional oscillations, in particular, are difficult to model precisely but can be detected and mitigated through careful design and real-time data analysis.

Robust synchronization and calibration protocols are essential to ensure that sensor data—especially from distributed IMUs and cameras—remain consistent and scientifically useful throughout the mission. Synchronization enables post-processing corrections and supports the reconstruction of payload attitude, further improving the integrity of the data collected.

Toward Optimized System Design and Operations

The integration of analytical, experimental, and operational insights can lead to improved mission planning, greater reliability, and the establishment of best practices in the community. Design choices—such as modularity in the flight chain, strategic placement of mass, and redundancy in data collection—now reflect a sophisticated understanding of flight dynamics. These advances have facilitated the repeatable deployment of balloon-borne systems for Earth observation, atmospheric science, and technology validation, ensuring that the benefits of high-altitude platforms are realized without compromising data quality or mission safety.

The work presented in this thesis builds upon this foundation, employing comprehensive dynamic characterization to support the design and implementation of advanced modular payloads, and contributing new experimental data and insights that inform the next generation of high-altitude environmental monitoring systems.

1.2.3. Gaps and Research Motivation

Despite rapid technological advancement in Earth observation and a growing ecosystem of platforms—including satellites, UAVs, and balloon-based systems—numerous scientific and operational gaps persist that constrain the reliability, resolution, and practical impact of environmental monitoring.

A primary limitation remains the comprehensive dynamic characterization of aerial platforms, particularly for balloon-borne missions. While analytical models and simulation tools provide valuable predictions of system behavior, there is a persistent lack of high-fidelity, experimentally validated data capturing the full spectrum of oscillatory phenomena encountered during real flights. Pendular, longitudinal, and torsional modes often behave differently under laboratory conditions compared to the complex and variable environment of the stratosphere, where wind shear, temperature gradients, and turbulence are prevalent. This insufficient understanding directly affects payload stability, data quality, and the accuracy of attitude determination during critical phases of ascent and float.

Closely related is the challenge of integrating and cross-validating heterogeneous data streams. Combining in-situ sensor measurements with aerial and satellite observations requires rigorous calibration protocols and robust data fusion strategies, especially as new sensor types and collection methods are adopted at scale. Variations in sensor characteristics, data formats, and acquisition protocols can lead to inconsistencies and limit the scientific utility of multi-platform campaigns unless systematic harmonization strategies are employed.

Moreover, the optimization of flight planning and trajectory control for both UAVs and balloon payloads remain an open area of research. Atmospheric uncertainties—such as wind fields, turbulence, and thermal gradients—can cause significant deviation from planned trajectories and mission profiles. Adaptive modeling and real-time control solutions are needed to enhance mission reliability, position accuracy, and data repeatability in the face of these uncertainties.

Cost, scalability, and accessibility represent additional hurdles, particularly for research groups and institutions with limited resources. Achieving robust, high-quality data acquisition at a manageable cost necessitates the adoption of modular, reconfigurable architectures, the employment of commercial off-the-shelf components, and the development of user-friendly, maintainable software and workflows.

The ATEMO project is explicitly designed to address these challenges. By integrating innovative modular payload design, systematic dynamic modeling, laboratory and field experimental validation, and comprehensive calibration and harmonization protocols, the research sets out to enhance the fidelity, reliability, and operational flexibility of multi-platform environmental monitoring. This systematic approach not only aims to close current scientific and technical gaps but also to establish a replicable model for accessible and scalable Earth observation, enabling the broader research community to address emerging environmental and societal needs with greater confidence and efficacy.

1.3. Thesis Objectives and Structure

The research presented in this thesis is driven by the need to enable more accessible, reliable, and high-resolution environmental monitoring by leveraging modular aerospace platforms and advanced multi-sensor integration. This need was first brought into sharp focus by the O-ZONE mission, a stratospheric pollutant collection experiment that represented not only a technological proof of concept but, above all, a compelling proof of the urgent necessity for new, more agile monitoring technologies. The operational, technical, and calibration challenges

encountered during O-ZONE, together with its demonstration of the capabilities of modular payload design, crystallized the scientific and engineering gaps that would shape the subsequent direction of the research.

The development of ATEM0 is conceptually and methodologically rooted in a continuum of pioneering activities undertaken by the Flight Mechanics research group at the University of Padova, including the MINLU project—which advanced modular sensor suites and explored airborne light pollution mapping—alongside the dynamic and attitude modeling efforts exemplified by AREO, and trajectory optimization studies such as AVERLA [68]. Each of these initiatives identified real-world limitations in existing approaches, underscored the necessity for improved system adaptability and data quality, and seeded technological and methodological innovations that would directly inform and accelerate the objectives of this doctoral work. The interplay of these experiences established a robust foundation, not only for the physical integration of modular hardware on multiple platforms, but also for a more comprehensive and resilient approach to calibration, data fusion, and mission planning.

Consequently, the overarching goals of the thesis are oriented toward addressing four core challenges: the design and validation of robust, multi-purpose, and modular payload systems deployable across drones and balloon-borne missions; a systematic experimental and analytical investigation of the flight dynamics and mechanical behavior of these platforms, with particular attention to pendular, longitudinal, and torsional oscillations that impact measurement reliability; the creation and refinement of rigorous protocols for integrating, calibrating, and cross-validating multi-source data—including in-situ, aerial, and satellite datasets; and, finally, the demonstration of transferability and scalability of methodologies and hardware, through collaborative initiatives such as E-FORESTER and field implementations in the “Rewatering” PRIN, to support both targeted campaigns and broader, cost-effective Earth observation efforts.

Structurally, the thesis follows the progression of these scientific challenges and their corresponding solutions, employing a “paper collection” model to highlight major peer-reviewed contributions. The work starts with the O-ZONE campaign as an operational and conceptual benchmark, before advancing through the engineering and experimental testing of the ATEM0 payload; it then delves into the comprehensive study of flight chain dynamics and proceeds to assess the integration and application of miniaturized, highly adaptable sensing technologies in real and simulated environments.

Each chapter is constructed to reflect not only the evolution of the research but also the growing maturity of modular aerospace environmental sensing as a field, systematically addressing the intersecting themes of hardware design, dynamic system analysis, quantitative calibration, and cross-platform data exploitation. In so doing, the thesis provides a cohesive and rigorous framework that both retraces and advances the frontier of deployable, scalable, and scientifically credible environmental monitoring.

This structure ensures your research trajectory, and the role of foundational and parallel projects are fully and seamlessly embedded in the narrative, matching the expectations of an international, academic readership.

2. Paper I: Air Pollution Payload

Role in the research project: *Team Manager*

Paper Contribution: *Drafting of introductory and connecting parts between chapters, main revision, corresponding Author.*

The following chapter presents the first core scientific paper on which this thesis is built, documenting the conception, engineering, and stratospheric deployment of a modular platform for the collection of atmospheric pollutants—known as the “O-ZONE” experiment. This work stands at the intersection of prior group experience and methodological innovation and marks the crucial transition from preliminary concept development to real-world implementation of airborne environmental monitoring technologies.

The O-ZONE campaign represented both a technological proof-of-concept and a compelling demonstration of the practical necessity for robust, adaptable, and accessible modular platforms capable of conducting demanding scientific missions in the stratosphere. The lessons learned during this mission—especially regarding sensor integration, calibration routines, and in-flight dynamics—identified critical challenges and design requirements that would guide the subsequent evolution of the ATEMPO project.

It is important to highlight that, while the stratospheric balloon launch and data collection activities were conducted prior to the official start of the doctoral program, the entire data analysis, the completion of the scientific work, and the structuring of the results for publication were carried out after the PhD had commenced. This ensured that the intellectual effort, methodological rigor, and scientific framing of the study directly contributed to the objectives and broader research themes of the doctoral thesis.

Furthermore, the O-ZONE experiment was deeply embedded within a continuum of research activities in the group, drawing on insights from parallel projects such as MINLU, AREO, and AVERLA. These collective experiences not only illuminated the innovation and remaining gaps within existing approaches, but also motivated the pursuit of scalable, reconfigurable, and methodologically sound solutions for environmental monitoring.

The present chapter provides the broader scientific and historical rationale for the O-ZONE campaign, illustrating how the work’s findings and methodological advances laid the operational and conceptual groundwork for the advanced engineering, dynamic analysis, and multi-platform integration addressed in the subsequent chapters of this thesis. As such, this contribution is pivotal—not only in its demonstration of technological feasibility, but in defining the trajectory and research philosophy that underpin the entire doctoral project.

Launch of an innovative air pollutant sampler up to 27,000 meters using a stratospheric balloon

Federico Toson, Mauro Pulice, Marco Furiato, Matilde Pavan, Simone Sandon, Dumitrita Sandu, Giovanni Righi [1]

Abstract

Air pollution, besides being one of the leading causes of death worldwide, remains one of the most controversial topics in environmental monitoring. The current state of the art refers to remote satellite analysis and static ground-level technologies. The O-ZONE project has set itself the objective of bridging this technological gap using dynamic in situ analysis using compact, inexpensive and reusable samplers that can be integrated onboard stratospheric balloons and drones. The prototype, therefore, consists of a pneumatic system, a set of filters and a sampling bag. Thanks to this architecture, it is possible to sample atmospheric air at different altitudes. After the flight, the samples collected are analysed using chromatographic techniques to provide a picture of the various air layers. On 30 September 2021, the fully autonomous payload successfully flew in Kiruna (Swedish Lapland) aboard BEXUS 30, the stratospheric balloon made available by the promoters of the “hands-on” project of the same name, SNSA (Swedish National Space Agency), DLR (Deutsches Zentrum für Luftund Raumfahrt) and ESA (European Space Agency). In this paper, the technical specifications of the device are described, with a focus on the sampling system; we then highlight the results obtained by the filters that, at different altitudes, collected stratospheric pollutants such as VOCs and, in the first layers of the atmosphere, PM. In conclusion, an interpretation of the results is provided to better understand the possible future uses of the prototype.

Keywords Atmospheric pollution analysis, Innovative air sampler, VOCs sampling in the stratosphere, PM research at different altitudes

1 Introduction

Air pollution, besides being one of the leading causes of death worldwide, remains one of the most controversial topics in environmental monitoring. The causes of climate change are primarily attributable to anthropogenic activities, such as industry, agriculture, intensive livestock farming, transport and an increasing difficulty in disposing of greenhouse gases because of deforestation, which has worsened ecosystems with a consequent deterioration in air quality [1]. Humans, like many other animal species, are also at risk due to the rapid temperature change but mostly because the decreasing quality of the air they breathe may lead to respiratory complications followed, in many cases, by death. The presence of fine dust, harmful combustion products, such as VOCs (Volatile Organic Compounds), CO₂ and methane (CH₄) and other greenhouse gases, disrupts the atmospheric composition, increasing global temperature. Moreover, the excessive presence of CFCs (ChloroFluoroCarbons) causes the depletion of the thin layer of Ozone (O₃) protection against the sun’s UV rays [2, 3].

It is therefore essential to not only define methods of intervention to take care of the situation but also to optimise environmental monitoring processes by refining the technologies available. This willingness to find alternative and more refined monitoring strategies influences the

process that regulates the emission of air pollutants and tightens the penalties for those whose environmental damage is considerable, as stated in the Montreal agreement [4].

In recent years, different research groups and companies have studied air quality, provided new innovative solutions and made full use of the various technologies available. A very important example is provided by the information giant Google, which has recently integrated the possibility of displaying the atmospheric status from its map localization app Google Maps.

In this context, the O-ZONE project was born; some students of the Aerospace Engineering course at the University of Padova at the beginning of 2019 engaged in the design and development of alternative sampling systems [5]. Currently, measurements of atmospheric pollutants are mainly carried out by satellite (ESA's Sentinel Mission [6]) and by ground using static samplers. The study of the atmosphere in situ employing systems that can estimate the atmospheric composition at different altitudes and identify pollutants to understand how they can interact and then spread over time remains an open field.

With the support of Professors Alessandro Francesconi and Roberta Bertani, the students then applied to participate, with their experiment, in the BEXUS project of SNSA, DLR and ESA [7]. The acceptance of O-ZONE then led the team to launch on 30 September 2021, at the Esrange base in Kiruna, the prototype for the first test collecting atmospheric data [8]. It is highlighted that the data collected is of high scientific interest following the COVID-19 pandemic that altered atmospheric composition in 2020 and 2021 [9]. The coronavirus also allowed the O-ZONE team to improve the initial prototype making the launch, delayed due to the pandemic, obtain better results.

This paper briefly describes the design of O-ZONE, the flight aboard the BEXUS 30 balloon, the data collected and the conclusions based on the interpretation of these data.

2 O-ZONE Payload

O-ZONE is an atmospheric air sampler designed to operate at different altitudes and collect various pollutants, especially VOCs (Volatile Organic Compounds) and, below 5000 m, PM (Particulate Matter). The samples collected by the payload are then analysed on the ground to reduce the costs associated with in situ analysis. The device underwent two design phases, with the first design being revised to enable higher reliability and facilitate reuse.

The O-ZONE experiment can be divided into three main subsystems: pneumatic, chemical sampling and control [8]. There are three sampling components: the VOC filter, the PM filter and the collection bag. In the current configuration, there is only one PM filter, as a single control sampling is carried out within an altitude of 5 km, whilst there are four VOC filters to allow sampling at various altitudes.

The 3 systems are closely arranged in different compartments and are housed in an aluminium frame made of BOSCH profiles, as can be seen in Fig. 1. The box is shielded on each side by multi-layer panels of polystyrene and aluminium (with a structural and protective function), with an additional aluminium foil on the outside to reflect the sun's rays.

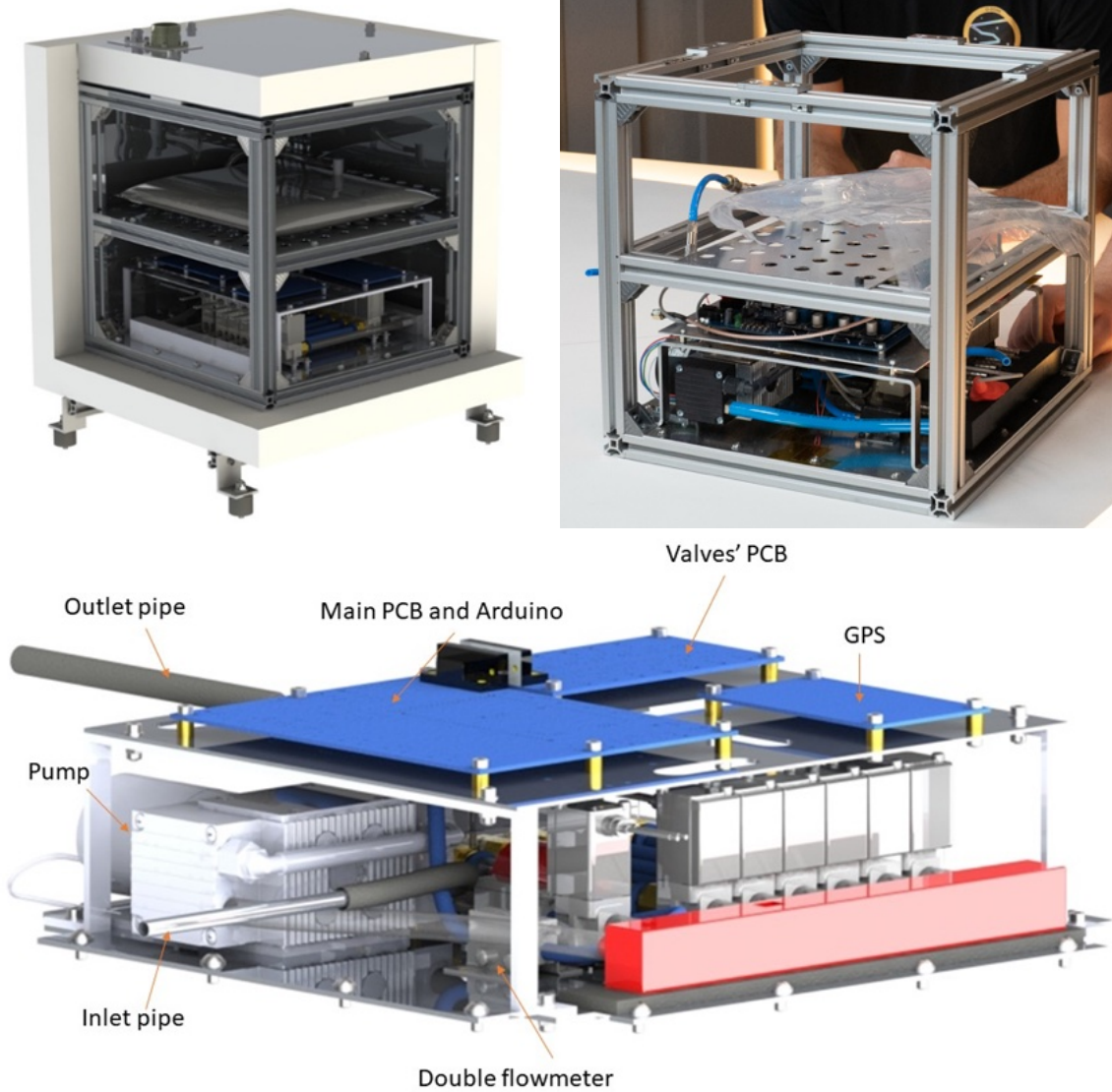


Figure 1: Setup of the O-ZONE experiment; top left full view, right a photo of the system without insulation, bottom zoom on the pneumatic and electronic subsystems.



Figure 2: Main components of the pneumatic subsystem; starting from the left, N85.3 KPDCB pump by KNF, VDW20QAP valve and PFMV5 flowmeters both from SMC. (Photo credits to KNF and SMC)

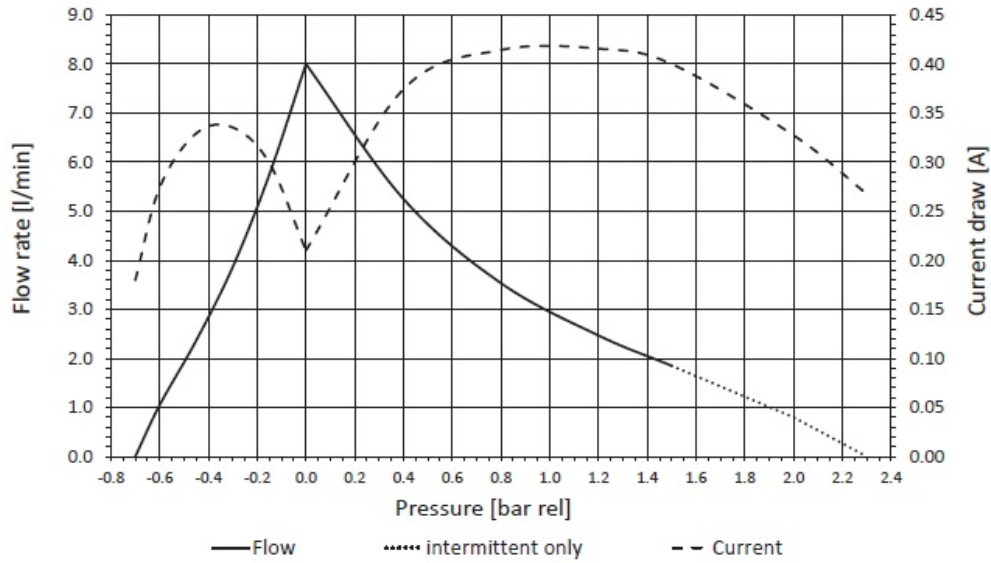


Figure 3: Pump performance in relation to pressure from KNF data sheet

O-ZONE is fixed to the gondola employing rubber bumpers, which prevent current flows and dampen vibrations and eventual shocks (such as the one that occurs during a controlled fall). The design of the pneumatic system starts with the pump, the real heart of the experiment, which allows the suction of the external air. This four-wire pump is a KNF (model N85.3 KPDCB in Fig. 2) [10], a diaphragm pump that was chosen mainly because of the low contamination rate of the air collected; any other type of pump could have distorted the analyses by contaminating the air with oil or other lubricating products.

Another reason for choosing this pump is the head that is typical of this type of pump, which is designed for vacuum (Fig. 3). The air flows through the pump, located upstream of the pneumatic system, to reach the first manifold which has, as can be seen in Figs. 4, 7 possible outlets, one for each of the filters (4 VOC and 1 PM), one for the sampling bag and one for the route used to clean the pneumatic system. Each way is regulated by a pair of solenoid valves (SMC model VDW20QAP) [11], which guarantees an additional safety net as if the system should fail to respond, they stay sealed, preventing the samples from getting contaminated. After passing through the various ducts, these re-join in a second manifold that ends with the outlet pipe. Before exiting, the air passes through two flow metres, both same model (PFMV5 from SMC) but with different scales [12]. This way it is possible to obtain accurate measurements for both the airflow rates needed during the flight, which is necessary to meet the sampling requirements of the filters and to keep the flow rate constant compensating for the effects caused by the variations in pressure. The pump is controlled by the Arduino which reads the flow rate data. The pipes have an internal diameter of 6 mm except for those between the pairs of valves which have an internal diameter of 8 mm to allow the housing of the VOC filters. The particulate filter holder and collectors were designed by the team and 3D printed in plastic to reduce weight and better fit into the limited space.

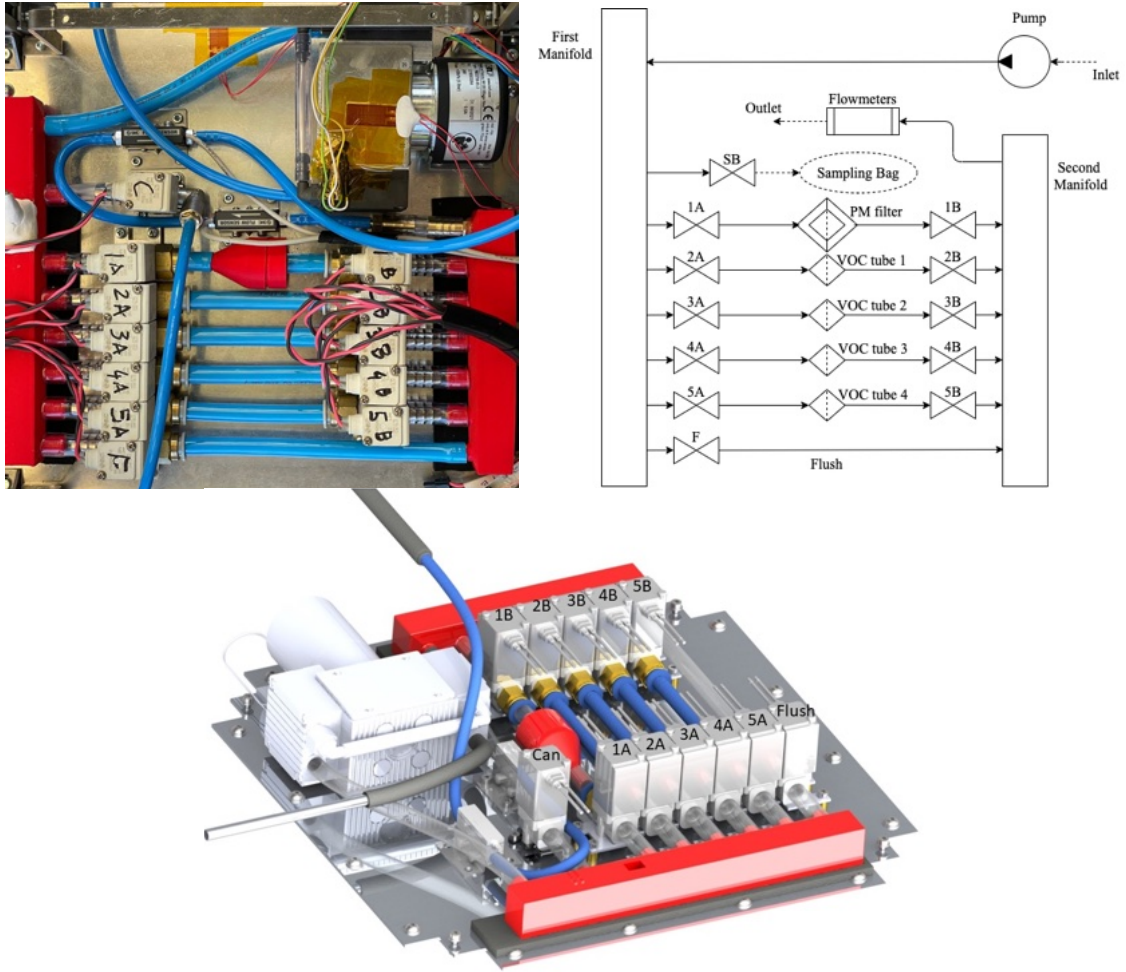


Figure 4: Overview of the pneumatic subsystem; top picture and diagram, bottom CAD reproduction.

The high number of joints and systems involved may cause pressure losses, so various tests have been carried out in a vacuum chamber at various pressures. This way, knowing the output flow rate and the external pressure, it is possible to trace the flow rate injected into the system just before the filters.

The sampling system, as mentioned before, consists of filters and the sampling bag (Fig. 5). The sampling bag is located on the top shelf of the device and has a maximum capacity of 3 L. To ensure that the sampling bag is empty before the flight, the pipe connecting it to the valve at the exit of the manifold is fitted with an at-joint ending in a non-return valve, creating a vacuum and ensuring that no air from the wrong altitude contaminates the sample. Desorption tubes were used for VOCs and quartz filters for PM. The choice of filters aims to involve a broad spectrum of combustion products but also takes into account their reusability, which makes O-ZONE a sustainable experiment from all points of view. The proposed experimental configuration may vary depending on the gondola and the analytes being researched.

Regarding the control system, O-ZONE is powered by a voltage of 28.8 Volts and an average current of 1.3 Ampere, which was provided, for the flight in Kiruna, by an external battery

pack. Also, the antenna and its Ethernet connexion with the experiment are possible, thanks to the gondola's bus. Although the experiment could operate autonomously, this redundancy proved useful in the test phase to allow a real-time verification of housekeeping and device operation. The onboard computer is an Arduino Due, with an Ethernet shield, connected to the PCB designed by the team (Fig. 6). It switches on and off the pump and the valves, and in the meantime receiving the data from the GPS and the temperature and pressure sensors.

This way, O-ZONE is completely autonomous and, by interpreting altitude data, manages the correct order of the filters at various atmospheric layers. An additional duty of the control system is to check that the thermal ranges of the various components are respected. In fact, in addition to the passive thermal control system, which consists of the polystyrene box described above, O-ZONE is equipped with an active system composed of two heaters, housed on the base plate, which increase the temperature of the experiment when necessary.

After the assembly phase, the team began the testing phase. Considering that the minimum pressure reached by the device would be around 10^{-2} bar and the minimum temperature would be -70 °C (at an altitude of 30 km [13]), it was appropriate to test O-ZONE in a thermo-vacuum chamber. However, the cleanliness of the experiment only met the characteristics of the vacuum chamber and not the thermo-vacuum of the available facility (CISAS “G. Colombo”, the space centre of the University of Padova). To implement the thermal test as well, the following approach was therefore taken: a conductive metal interface, known as a “cold plate”, was attached to the experiment's fastenings (Fig. 7), this simulated the gondola which, during flight, would be the only conductive element in contact with the inner frame of O-ZONE (Fig. 8). This plate was placed in direct contact with dry ice and, although this releases CO₂, the chamber was kept between 10 and 15 mbar. This set-up allowed an extensive test of the experiment under realistic conditions that were confirmed after the mission.

The described device flew onboard the BEXUS 30 after the complete verification of the mentioned requirements. All the operational phases of the flight are described in the next chapter.



Figure 5: Elements of the sampling system; starting from the left PM filter, desorption tubes (Photo by RESTEK) and sampling bag (Photo by RESTEK).

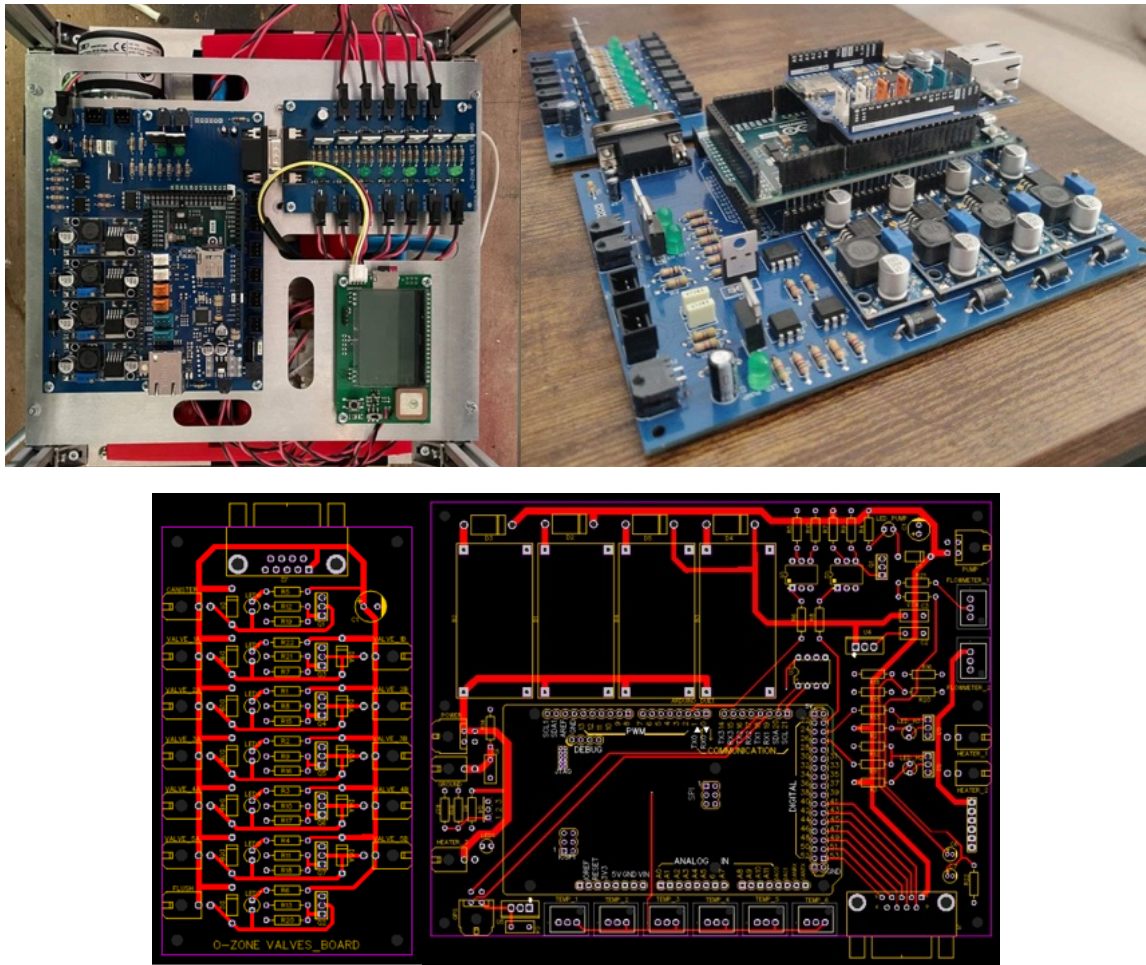


Figure 6: Top two shots of the PCBs, bottom the design schematics.

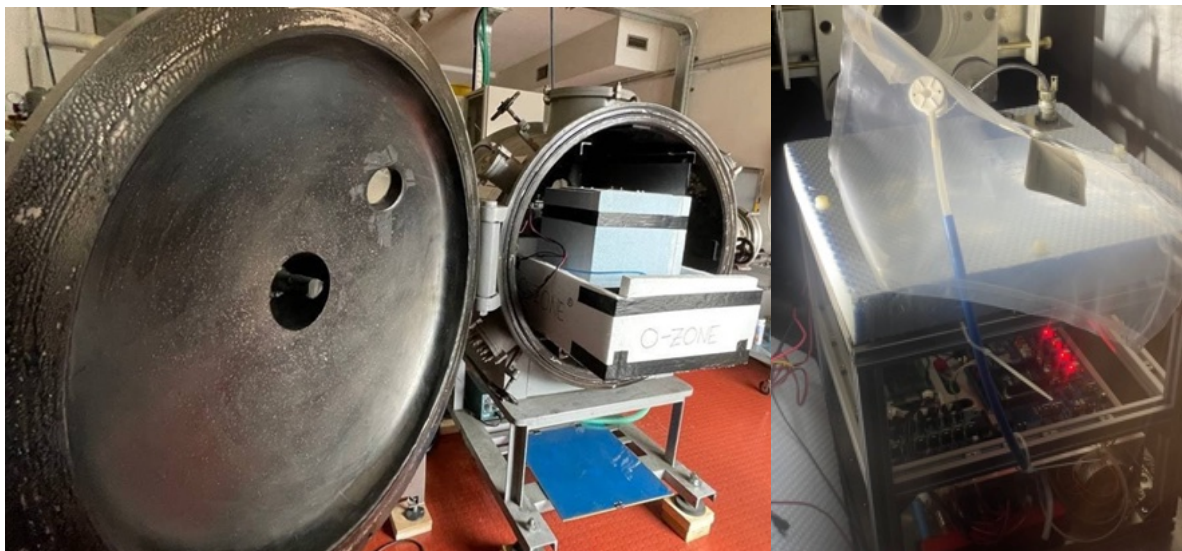


Figure 7: Thermo-vacuum test in CISAS G. Colombo centre facilities.

3 *Flight on BEXUS 30*

The flight aboard the BEXUS 30 gondola (Fig. 8) took place at the SSC (Sweden Space Corporation) base in Kiruna, called Esrange. As per the BEXUS project of SNSA, DLR and ESA [8], many experiments are on board the gondola. In our case, they were all experiments related to chemical and biological research, which was positive in many aspects, amongst them the comparison of data. At 06:54 local time on 30 September 2021, O-ZONE, together with the other devices, began its flight aboard the gondola weighing approximately 120 kg in total. The ascent phase, which lasted approximately 2 h, marked the end of the filter-sampling phase and the start of the sampling bag phase. The bag was completely inflated a few minutes after reaching the maximum altitude of 27.3 km; the floating phase lasted approximately 3 h and the experiment was kept in stand-by with controlled temperature, as shown in Fig. 9, to preserve the samples and avoid damage to the electronic subsystem.

During the first 5 km, the airflow was directed into the PM filter, and its rate was around 3 l/min as per the filter's requirement. Subsequently, the air was conveyed towards the VOC filters. The first VOC filter sampled the air between 5 and 9.5 km, the second between 9.5 and 14 km, the third between 14 and 18.5 km, the fourth and last filter between 18.5 and 23 km. Finally, during the floating phase, the air was conveyed into the sampling bag which was filled with approximately 1 L of air after 30 min of intake. The filters just described have quite strict flow rate requirements to carry out a correct sampling and therefore the pump was regulated by PWM to guarantee a flow rate of about 0.05 L/min. In the table below (Table 1), a summary of all the phases can be seen, with the durations, altitudes, temperatures and flow measurements taken.

Once the floating phase was over, the gondola began its controlled fall, landing in Finland at 11:33 local time after 5 h of total flight time. Recovery took place in the following 24 h and the collected samples were taken to the laboratory for analysis.

In the next chapter, the sample analysis methodologies and related results are described.

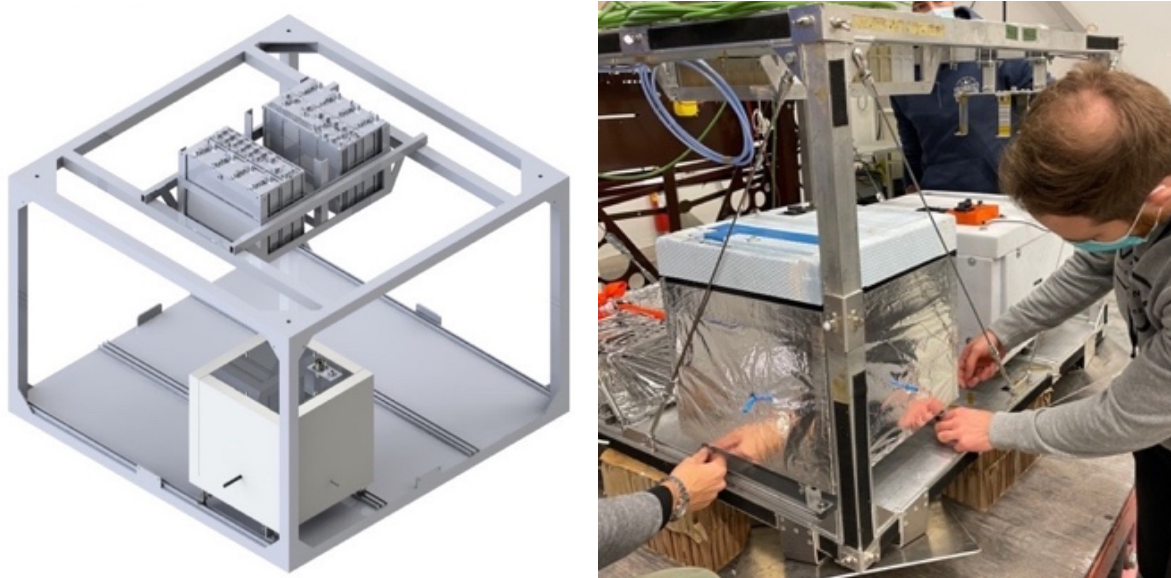
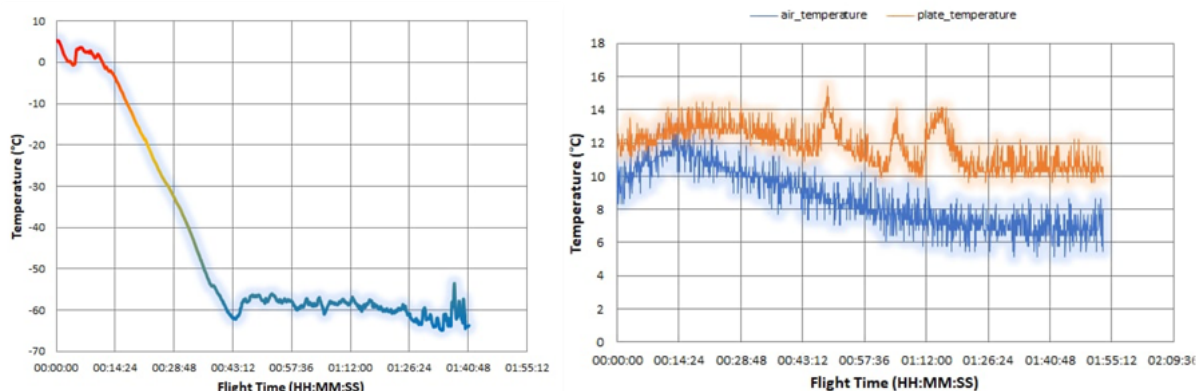


Figure 8: Location of the O-ZONE experiment on the SSC gondola.

Table 1: O-ZONE flight data

Phase	Start time [hh:mm:ss]	End time [hh:mm:ss]	Altitude range [m]	External pressure [mbar]	*Average internal Flow rate [l/min]	Inside temperature [°C]	External temperature [°C]
<i>Cleaning tube</i>	06:55:00	06:58:00	500	962,4	variable	12,0	4,0
<i>PM tube</i>	06:58:00	07:13:00	5000	546,2	2,933	12,5	-14,8
<i>Cleaning tube</i>	07:13:35	07:15:30	5500	511,1	variable	13,0	-18,5
<i>First VOC tube</i>	07:15:30	07:29:50	9500	289,1	0,049	13,5	-49,0
<i>Cleaning tube</i>	07:30:00	07:31:00	10000	267,6	variable	12,2	-53,3
<i>Second VOC tube</i>	07:31:30	07:46:30	14000	141,9	0,048	13,0	-56,2
<i>Cleaning tube</i>	07:47:20	07:48:13	14500	131,1	variable	13,2	-57,9
<i>Third VOC tube</i>	07:48:23	08:03:23	18500	69,4	0,048	13,0	-58,6
<i>Cleaning tube</i>	08:03:54	08:05:23	19000	64,1	variable	11,0	-57,6
<i>Fourth VOC tube</i>	08:05:23	08:20:23	24100	28,4	0,048	9,9	-60,8
<i>Cleaning tube</i>	08:21:10	08:22:10	25000	24,5	variable	9,9	-63,0
<i>Sampling bag</i>	08:22:18	08:52:18	27000	17,7	0,029	10,0	-61,0

* The cleaning phase was used not only to clean the tubes between each phase, but also to set the correct flow rate.

**Figure 9:** Temperature data during the flight; on the left the external temperature, on the right the internal ones.

4 Data Analysis

The flight aboard the BEXUS 30 gondola enabled to collect data at different altitudes, namely 4.5, 9, 13.5, 18, 22.5 and 25 km. Volatile organic compounds (VOC), chlorofluorocarbons (CFC) and particulate matter (PM) were collected and analysed.

Volatile organic compounds (VOC) and chlorofluorocarbons (CFC) were collected using a constant flowrate of 0.05 L/min, which was stated within the performance requirements. The sampling was performed using four Tenax TA/ Graphitized Carbon Black/Carboxen 1000 stainless steel TD tubes. After the experiment, the latter taken out, sealed and afterwards placed in an isothermal box at 4 °C for 4 days. This temperature was chosen to prevent potential migration of chemicals to more retentive sorbent. Indeed, this may lead to incorrect concentrations of the analytes. Samples were analysed by SGS Italia S. p. A. in compliance with the method of analysis NIOSH 2549. VOCs were also sampled with a sampling bag made

by polyvinylidene fluoride (PVDF), volume of 3 L. The sampled materials were analysed by SGS Italia S.p.A. employing the methods EPA 3C 2017 and EPA TO 15 1999.

Particulate matter (PM) was collected with PM homemade filter system made by two filters, both placed in the same slot of the device. The first was a Whatman® QM-A quartz filter that trapped the PM via inertial impact. This microfiber filter was made by a disc of microporous quartz (SiO₂) and it had an average pore size of 2.2 µm. The second filter was a microporous polycarbonate filter, which was a membrane composed by high-quality polycarbonate film with a sharply defined pore size of 0.8 µm diameter.

The characterization techniques employed were standard analyses for these air pollutants. The methods used were Fourier-transform infrared spectroscopy (FTIR), environmental scanning electron microscopy (ESEM) and chromatography–mass spectrometry (GC–MS). The VOCs and CFCs were collected at different altitudes during the flight. Instead, the atmospheric PM sampling was carried out in the first part of the ascending phase, so at low altitudes. If the measurements were performed over a longer period, they would provide more data and information on concentrations. The values reported herein are the result of preliminary tests which were carried out to verify the performance of the device before and after the launch campaign.

The experimental conditions at which the VOCs samplings were performed in Kiruna are reported in Table 2, whilst those for PM are shown in Table 3.

The most significant concentrations of VOCs collected during the lunch campaign in Kiruna are reported in Tables 4 and 5.

Table 2: conditions under which sampling, through VOC filters and sampling bag, was carried out during the launch campaign.

	VOC 1	VOC 2	VOC 3	VOC 4	Sampling bag
Time [s]	855	855	855	855	1780
Litres [L]	0.7075	0.7225	0.7225	0.7225	0.8820
Temperature [°C]	10.58	9.38	8.16	7.29	6.89
Humidity [%]	1.6	0.4	0.4	0.4	0.4
Initial pressure [mbar]	513.39	270.3	132.56	62.88	26.86
Final pressure [mbar]	290.85	144.32	68.57	29.98	17.54

Table 3: Conditions under which sampling, through PM filters, was carried out during the launch campaign.

Time [s]	890
Litres [L]	43.5
Temperature [°C]	10.78357542
Humidity [%]	13.45586592
Initial pressure [mbar]	876.67
Final pressure [mbar]	560.27

Table 4: Results of the chemical analyses conducted on VOC filters.

Sampled Volume [m³]		2.97x10 ⁻⁴	1.59x10 ⁻⁴	7.8x10 ⁻⁵	3.6x10 ⁻⁵
Flow Rate [L/min]		0.05	0.05	0.05	0.05
Compound	Method	Value VOC1 [µg/m³]	Value VOC2 [µg/m³]	Value VOC3 [µg/m³]	Value VOC4 [µg/m³]
2-Methylpentane	NIOSH 2549 1996	67.34	283.02	<256.41	<555.56
3-Ethylpentane	NIOSH 2549 1996	114.48	345.91	<256.41	<555.56
Benzene	NIOSH 2549 1996	181.82	245.28	512.82	2500.00
Cyclohexane	NIOSH 2549 1996	101.01	<125.79	<256.41	<555.56
n-Dodecane	NIOSH 2549 1996	215.49	301.89	371.79	1333.33
ethyl benzene	NIOSH 2549 1996	144.78	213.84	<256.41	<555.56
meta+para Xylene	NIOSH 2549 1996	205.39	295.60	<256.41	1166.67
1-Butanol	NIOSH 2549 1996	2962.96	4088.05	<256.41	4611.11
Orto-xylene	NIOSH 2549 1996	148.15	207.55	<256.41	<555.56
Styrene	NIOSH 2549 1996	309.76	440.25	<256.41	944.44
Toluene	NIOSH 2549 1996	185.19	232.70	<256.41	972.22

Table 5: Results of the chemical analyses conducted on a sample of air (sampling bag).

Compound	Method	Value [µg/m³]	Compound	Method	Value [µg/m³]
1,2,3-Trimethylbenzene	EPA TO 15 1999	0.46	Cyclohexane	EPA TO 15 1999	15.3
1,2,4-Trimethylbenzene	EPA TO 15 1999	1.80	Dichlorodifluoromethane	EPA TO 15 1999	3.09
1,2,5-Trimethylbenzene	EPA TO 15 1999	0.51	Chloromethane	EPA TO 15 1999	1.80
4-Ethyltoluene	EPA TO 15 1999	0.50	Carbon disulfide	EPA TO 15 1999	2.53
2-Propanol	EPA TO 15 1999	920	Dichloromethane	EPA TO 15 1999	3.38
Acetone	EPA TO 15 1999	77	Ethanol	EPA TO 15 1999	510
Acrylonitrile	EPA TO 15 1999	2.53	Ethyl benzene	EPA TO 15 1999	2.14
Acrolein	EPA TO 15 1999	2.83	Hydrocarbon C5-C12	EPA TO 15 1999	124
Trichlorofluoromethane	EPA TO 15 1999	1.51	Styrene	EPA TO 15 1999	5.1
Methyl acetate	EPA TO 15 1999	2.28	Naphthalene	EPA TO 15 1999	1.28

The PM filters were qualitatively investigated by ESEM (Fig. 10). Although no analytes of any kind could be observed on the first Quartz disc, the polycarbonate filter collected few both organic and inorganic particles with dimensions ranging from 5 to 10 µm. It was possible to identify the composition of those particles using EDX analysis (Fig. 11). In Fig. 10, the lighter and brighter spots stand for the inorganic components (mainly Silicon, Calcium and aluminium) whilst the transparent particle represents an organic compound. From a chemical point of view, the prototype proved to be operating [14, 15]. The chemical analyses revealed the presence of many compounds belonging to the class of chlorofluorocarbons, aliphatic and aromatic hydrocarbons and other VOCs.

The system was able, at all assigned altitudes, to sample all the analytes of interest (VOCs, CFCs and PM) but also to provide a complete picture of the compounds present in the air with concentrations in the order of µg/m³. The data are here reported (Tables 4 and 5) without any error because so far, they are not enough to either validate the method or to estimate the sampling error [14]. The experiment should be repeated other times to verify the reliability and integrity of this promising and low-cost sampling tool.

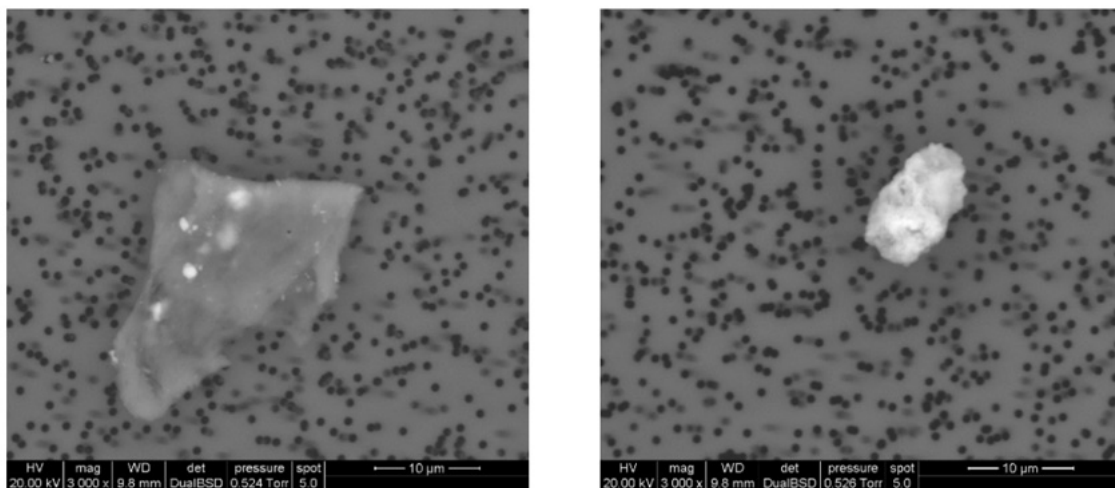


Figure 10: ESEM image of polycarbonate filter, on left an organic particle is displayed while an inorganic particle is shown on the right.

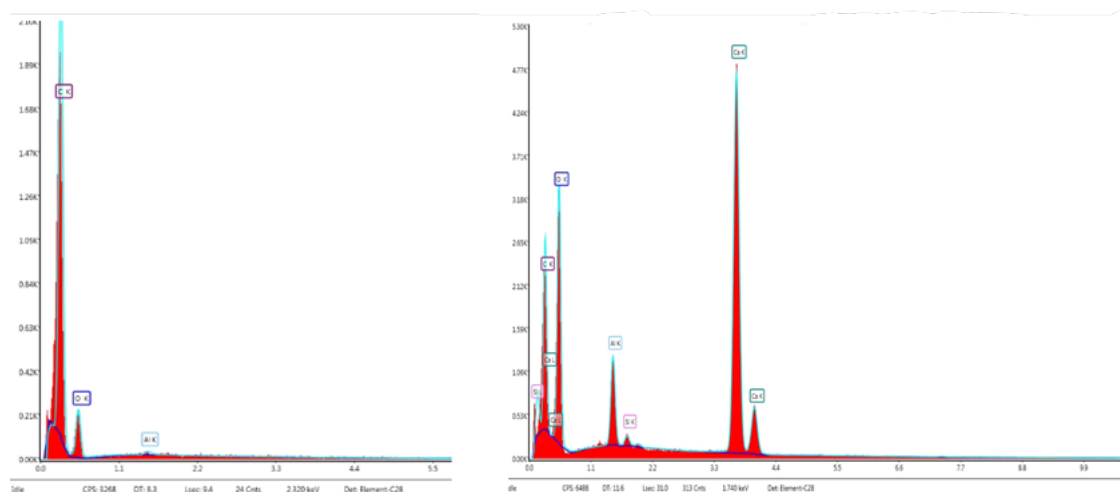


Figure 11: EDX spectra. On the left of an organic Polymer made of C and O, on the right of inorganic particle containing CaO, Al₂O₃, SiO₂.

The main problem encountered in this flight was the presence of undesired chemicals released from other experiments in the BEXUS 30 gondola. In fact, the presence of other devices on board the gondola and the choice of some of the materials, especially insulating ones, led to undesirable outgassing of alcoholic compounds and the presence of chemical species not in agreement with those found in the literature [13].

This obviously biased the sampling of some chemicals, whose concentrations were much higher than expected or showed an irregular pattern. Nevertheless, the device was able to collect many chemical substances and allowed to qualitatively estimate their concentrations. This confirmed the expected functional and design requirements and opened a window for quantitative estimates. Certainly, this must be proven by other dedicated launches where the experiment is not affected by other devices or materials that may alter the normal chemical composition of the analysed air, otherwise leading to an overestimation of concentrations.

Therefore, it is possible to further optimise this already promising device and then confirm data already known to the scientific community [16]. However, to make a consistent comparison between literature and chemicals collected by O-ZONE, sampling data or quantitative measurements of the same compounds sampled at the same time and in the same areas are required—both with regard to latitude and longitude but also with regard to altitude. This was not possible because of the variability of pollutants due to the historical period (Coronavirus pandemic [9]) but also due to the low frequency of data collection in those areas, which demonstrates the usefulness of the device designed as a tool for sampling areas under low surveillance but of high importance.

In fact, as described in the literature [17], more inert pollutants such as CFCs are distributed in the polar regions of the globe, making large-scale sampling and measurements in the upper atmosphere increasingly necessary.

5 *Conclusions and Future Uses*

In conclusion, O-ZONE proved to be an effective device for dynamic sampling at various altitudes. By refining the choice of the quantities of air sucked in, the atmospheric composition can be characterised more clearly. The ideal set-up of the payload should aim to avoid any interference between different devices.

Some of the chemical species found were produced onboard the gondola by outgassing of O-ZONE materials and other devices [18]. Therefore, calibration by adding a degassing phase to detect and eject unwanted chemical species should be made before the flight. The functioning of the device has been demonstrated even at high altitudes in complete autonomy, and this guarantees safety for future flights and confirms the choice of critical components, such as the pump, valves and onboard computer.

In situ sampling and ex situ analyses comported better reliability, avoiding the implementation of systems with hard to fulfil at high altitudes requirements. Economically speaking, the prototype proved to be very affordable given that most of its components are easy to get, low cost and reusable.

As anticipated, the results cannot be confirmed from a quantitative point of view as similar analyses are few in number and do not examine the same atmospheric stages considered during flight. However, from a purely qualitative point of view, it can be stated that, barring a few anomalous species whose presence has been justified (e.g. other experiments on board the gondola), there are no other compounds that could invalidate the analyses. This makes understandable the need for devices that fill the analysis gap left by satellites and ground bases both for better spatial resolution and for reaching the areas of interest.

The potential applications of O-ZONE are enhanced by its ability to sample many VOCs simultaneously, as the sampling bag results table shows (Table 5). Additionally, the ability to collect pollutants of interest, such as VOCs, CFCs and PM, at all assigned altitudes was demonstrated during the flight (Table 4). Furthermore, considering the high variety of pollutant sources, tools such as the one developed can improve large-scale environmental monitoring by identifying natural and man-made sources of the main climate change actors.

This instrument is open to different possible future uses: aside from its original monitoring nature, the device could also be used in a horizontal way instead of the BEXUS ascending flight. This way, it would be easy to obtain data on phenomena area of effect. One example could be finding out how far from a volcano its ashes are still present in the air at a certain percentage. The set-up can also vary and be made lighter depending on the environmental requirements and the host vehicle, e.g. the device could be on top of drones for monitoring crops or industries. A future development could precisely be the monitoring of agricultural crops for which standards are difficult to verify and often lead to scandals and investigations concerning organic certification [19].

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Data availability All data collected by the O-ZONE experiment are freely accessible and available in the experiment's technical document [20].

Declarations

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

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3. Paper II: First ATEMO payload

Role in the research project: *ATEMO developer*

Paper Contribution: *Drafting of the entire manuscript, definition of testing procedures, data collection and processing, corresponding Author.*

This chapter presents the second core scientific paper underpinning this thesis, focused on the development and preliminary testing of the ATEMO multi-purpose sensing platform for Earth observation. Building directly on the foundational experiences and lessons learned through prior experimental campaigns—including the O-ZONE stratospheric pollutant collection, and the group’s parallel work on sensor integration, flight dynamics characterization, and trajectory optimization—Paper II explores the conceptual and engineering evolution necessary to create a modular, scalable system capable of supporting a broad array of environmental monitoring tasks.

The ATEMO platform was conceived in response to the identified need for adaptable, cost-effective, and scientifically robust payloads deployable on both UAVs and balloon-based missions. The design philosophy integrates commercial off-the-shelf cameras and sensors, versatile optical filtering, and advanced data acquisition and synchronization protocols, ensuring that the system remains accessible and reproducible for a variety of research applications and campaign profiles. The preliminary testing described in this contribution marks a significant step from proof-of-concept experimentation to the realization of a full-featured, reconfigurable monitoring apparatus.

It is important to note that the engineering work, data analysis, and publication efforts described in this paper were largely initiated and matured after the start of the doctoral program, reflecting the cumulative growth in technical and scientific capability developed within the research group. The results not only validate the key architectural choices and technical solutions underpinning ATEMO but also set the stage for its subsequent deployment in field campaigns and collaborative projects, such as E-FORESTER and the Rewatering PRIN project.

As this chapter unfolds, the reader is invited to consider how ATEMO embodies the broader progression from necessity-driven innovation to systematic implementation, technical refinement, and methodological maturity. The platform’s flexible architecture and preliminary test results provide both a concrete demonstration of its capabilities and a roadmap for future expansion in multi-platform Earth observation, guiding the work presented in the remaining papers of this thesis.

Development and Preliminary Testing of the ATEMO Multi-Purpose Sensing Platform

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Abstract

In the current global context, where the issue of climate change has gained significant prominence, the ATEMO (Aerospace Technologies for Earth Monitoring and Observation) project introduces an innovative and scalable platform capable of measuring multiple environmental factors, including air pollution, light pollution, and vegetation analysis. This versatile platform can be seamlessly integrated onto various aerial vehicles, such as drones, stratospheric balloons, and tethered balloons. Its primary goal is to establish a comprehensive framework for environmental analysis on multiple fronts, while also contributing valuable data to the scientific literature. Furthermore, it offers a cost-effective alternative with enhanced spatial and temporal resolution for ground-based comparisons. During the initial year of research, ATEMO project focused on amalgamating the technological expertise of the research group into a single device. This device facilitated ground-based light source observations, multi-spectral vegetation analysis, and air quality assessments. The first test campaign, carried out during the summer of 2023, was aimed at estimating vegetation indices and comparing them over time with satellite-derived data. This article provides insights into the current configuration of ATEMO, outlines the testing procedures, and presents the preliminary findings.

Keywords Earth monitoring, Light pollution, Air pollution, Vegetation indices.

1 Introduction

In environmental protection, monitoring activities are crucial for determining preventive strategies or large-scale solutions; Earth observation from space is of particular interest. To date, such analyses are carried out via satellite [1], however, due to the low spatial and, above all, temporal resolution of this technology, the information on an area or site of interest is often insufficient and may have to be validated by other methods of measurement and analysis. For example, easily accessible satellite data concerns passages that can be up to 3 days apart and with a resolution of 30 m on the ground and therefore of little use for applications such as precision agriculture.

There are, of course, methods with high resolution, also satellite-based [2], but they could be considerably expensive while only partially addressing the issue. This paper, for example, will mention Planet [3], a constellation of multiband satellites that are excellent for satellite comparisons but still confirm the need to use other technologies to complement current Earth observation data.

The ATEMO project [4], therefore, aims to increase knowledge on environmental issues with the development of a compact, low-cost and versatile device that can be used in different contexts and environments, from the analysis of the composition of the atmosphere, through

the detection of substances and pollutants such as VOCs (Volatile Organic Compounds), NO_x (Nitrogen Oxides), SO_x (Sulphur Oxides), CO₂ (Carbon Dioxide), O₃ (Ozone), to the determination of light sources on the ground and their characterisation. Furthermore, in order to understand how these factors may influence ecosystems, ATEMO also aims to determine ground vegetation indices (e.g. NDVI—Normalized Difference Vegetation Index). Another important goal is to compare these data with those obtained from satellites and seek a correlation between the various parameters under investigation. Indeed, while the influence of atmospheric pollutants and night lighting on ecosystems [5], plants and humans is already known, dated [6] and more recent [7] studies have suggested that the combined effect of light and atmospheric pollution may lead to harmful and worsening phenomena.

The first field of application of ATEMO, during the summer of 2023, was the determination of vegetation indices for agriculture in the framework of the PRIN (Project of Significant National Interest) project called ‘Rewatering’ [8]. This activity exploits the collaboration between several departments of the University of Padova: DAFNAE (Department of Agronomy, Food, Natural Resources, Animals, and the Environment), DII (Department of Industrial Engineering) and CISAS “G. Colombo” (Centre for Space Studies), as well as other Italian research institutions. In this context, the device was used on board a tethered balloon to evaluate the results on crop performance following water stress on soybean crops [9].

Despite the existence of satellite and airborne technologies (such as microwaves [10]) in the case of water stress assessment, the type of analysis conducted by ATEMO focuses on vegetation indices processed from the visible and infrared spectrum, as is the case with the most common smart agriculture satellites [11]. Monitoring the growth status of crops and biomass using SAR (Synthetic Aperture Radar) is also still in the early stages of development [12] and the use of low-cost alternative technologies such as ATEMO will allow it to be implemented.

The remainder of this paper is organized as follows: the next sections will describe the design of the system and the ATEMO integration. After that, field tests are introduced, and a selection of the collected results is presented.

2 *Design of ATEMO experiment*

2.1 Design Overview

ATEMO is designed to be a versatile, compact and easily scalable device; therefore, it is modular and its mass as well as the on-board devices change depending on the type of analysis conducted, area of interest and vehicle employed for the experiment. In fact, the platform can be integrated on board drones, stratospheric balloons and tethered balloons. The latter system proved to be a good trade-off for the first tests conducted in the framework of PRIN project: ATEMO was used for analysis on soybean fields, which required good resolution over long periods of time over the same area, both of which could not be satisfied by stratospheric balloons or drones.

Turning to how the experiment was developed, ATEMO represents the compact merge of similar devices designed and manufactured by the research group and which operated in the

three fields of analysis of interest: MINLU [13], three cameras for characterization of the spectrum and the intensity of light pollution sources, ARIA [14], a system of sensors for air pollutants, O-ZONE [15] an air trapping system for stratospheric pollution analysis, and AREO (the results of which have yet to be published) for the estimation of vegetation indices.

In more details, ATEMO has a weight of 2.5 kg, a base of 17 cm × 17 cm and a height of 25 cm as shown in Fig. 1, the instrument consists of an external aluminium frame to which 3D printed components are attached, guaranteeing both the secure integration of the various sensors and cameras, and their easy attachment and removal in the event of a change of setup.

The heart of ATEMO is the sensitive part consisting of several sensors, mainly consisting in cameras. In more details, the scientific payload consisted in the following instruments:

- Two Basler ace 2 cameras, one colour and one monochrome, both with Sony's IMX546, an 8MP square CMOS sensor with a wide relative response spectrum (from approximately 400 nm to 1000 nm).
- A FLIR Vue Pro R, a thermal imaging camera (7.5– 13.5 μm) adding useful information in both day and night contexts.
- A GPS tracking system.
- One or two SQM-L (Sky Quality Meter—type L), measuring the brightness of the night sky in magnitudes per square arc second.
- Environmental sensors for temperature, humidity, and pressure.

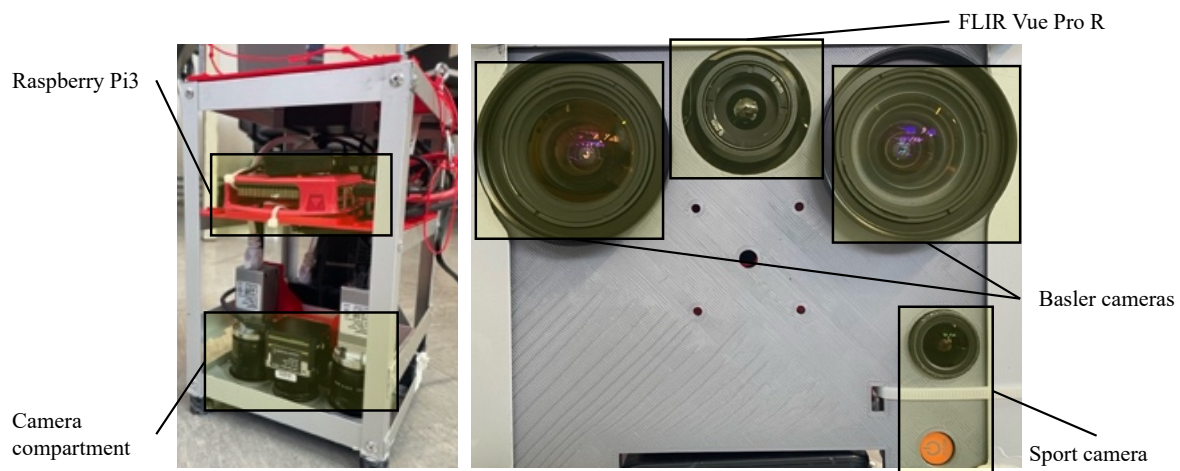


Figure 1: On the left, ATEMO experiment front view; on the right, ATEMO experiment bottom view (camera compartment)

As far as the air pollution aspect is concerned, on the other hand, the use of sensors that can provide a qualitative picture of the composition of the air is still being considered. It is expected to detect the presence of harmful compounds or pollution indicators and, after extensive testing, turn this qualitative results in a quantitative one to measure the concentration of the most harmful pollutants.

The choice of the cameras depended on several factors: such as the possibility of acquiring images from each camera at the same time with ease, the size of the sensor (square) which was therefore easier to manage for reprocessing and comparison with satellite acquisitions, the possibility of easily removing any IR filters and the friendly customisation in general, and finally the low cost for advanced and medium–high resolution sensors.

The systems and sensors described above are managed and acquired by a Raspberry Pi3 with the Raspbian operating system; however, the acquisition is carried out autonomously by means of a C++ programme that guarantees the acquisition of the cameras and saves raw scientific data on an SD card on board. In the case of non-stratospheric experiments, real-time connection with ATEM0 is still possible for remote control, data exchange or manual setting of acquisition parameters. Except for the Basler cameras, which were chosen for the reasons listed above and because the company also procures space grade instrumentation; all on-board instrumentation is the cheapest alternative that meets the functional requirements. Starting with the power bank, which is the only one on the market above 16,000 mAh that can select voltage up to 24 Volt and simultaneously supply 5V to the USB sockets. But also, the FLIR which is one of the cheapest models at low weight, the raspberry which is in fact a miniaturised computer that is easy to use and low cost, and the SQMs which are basically among the few sensors of this type at such low prices. The easy availability of the instruments was also considered.

Both the cameras and the SQM are connected via Ethernet by means of a switch that allows the Raspberry port to be split. Everything is powered by a 21,000 mAh power bank that provides a 5V output for all the systems and a 15V output for the Basler cameras. The power consumption of the experiment and, therefore, its duration is strictly dependent on the acquisition frequency. Table 1 shows a comparison between different acquisition rates and the relative autonomy of ATEM0. Obviously, it is not only the frequency of images captured that is characteristic of the type of analysis underway but also the actual setup of ATEM0 is closely linked to the application sector and the host aircraft. In fact, the optics combined with the two Basler-type cameras are not the only possible configuration; two possible alternative solutions used according to the flight in progress are the Kowa LM35HC (mainly for high altitude flights) and the Tuss LYM0814 (for low altitude flights). The comparison of these solutions can be seen in Table 2.

Table 1: Power budget with difference acquisition rates

<i>Acquisition rate</i>	<i>Camera and sensors consumption (W)</i>	<i>Other systems consumption (W)</i>	<i>Total (W)</i>	<i>Duration (h)</i>
every 5 minutes	7	3	10	6
Every minute	11	3	14	5
Continuous acquisition	14	3	17	4

As will be discussed in more detail later, in the case of both light pollution assessment and calculation of vegetation indices, it is essential to receive specific information from the two on-board cameras; therefore, readings from the two cameras are filtered with band-pass or triple-band filters. For this reason, the next chapter focuses on describing the acquisition strategies and the preventive actions taken to maximise the scientific output.

2.2 Acquisition System Description

The two on-board cameras are used for two main purposes: the estimation of vegetation indices during the day and the analysis of light sources during the night. For these two cases, the configuration of the cameras changes slightly depending on the required light filtering. In the case of vegetation analysis, the colour camera is equipped with a triple-band filter (475, 550, and 850 nm) and the monochrome camera with a band-pass filter (735 nm), both designed to reproduce indices already employed in literature and calculated by Planet satellites. The rationale behind the choice of these specific bands is related to vegetation indices (which will be described in more detail later in Chapter 3), but which essentially express the health and vigour of plants based on the fact that chlorophyll, a descriptive variable of health, emits at certain frequencies [16]. In fact, the first real comparison that is made is between what is calculated through ATEMO's acquisition and ordinary GIS (Geographic Information System) results, which for these application sectors can be obtained mainly from satellite data.

In the night-time application, however, the two cameras are used with a filtering solution similar to that of the MINLU experiment, another project conducted by our research group [13]. To date, the setup of the experiment is decided and fixed according to the flight scientific goals; in the future, the implementation of a filter wheel driven by a stepper motor will allow changing the filters during the flight. The filter wheel attachment points can be seen in Fig. 1, right, at the centre of the camera compartment.

As mentioned, the camera's field of view (FOV), is another key point to consider. In fact, the choice of optics is made according to the host vehicle; in the case of integration on drones or balloons tethered at an altitude of 50–100 m, optics with wide apertures (Tuss) are used, while in the case of stratospheric balloons, optics with much narrower apertures (Kowa) are favoured.

For proper interpretation of the data provided by ATEMO, calibration with a commercial spectrometer (Black Comet C-SR-14) was necessary; the on-board cameras were characterized both individually and with some filtering conditions, since the input information is affected by the transmission of the optics, the filter, the response of the CMOS sensor, and, in our case, reflections from the soybean leaves. First, the chamber was characterized with only the optics minus the filters, including the IR filter (integrated into the chamber and physically removed), in fact the 3 channels sum around the NIR spectrum above 700 nm wavelength (Fig. 2 left side) showing that the filter is no longer present. Next, using a selection of known sources and the spectrometer, the response of the instrument was thus defined: the sources were first acquired with the spectrometer and then with the chambers obtaining the RGB channel response for the light sources (these, on the right in Fig. 2, are at the filter passbands in the triple-band plus single-band filter configuration mentioned at the beginning of Section “Acquisition system description”). In this way, by normalizing the obtained signals, the right relationship between camera input and output is obtained. This is important in order to have consistent results in fact, a significant example is the one that highlights the response for the 850 nm source, which is redundant for all 3 channels and therefore, without calibration, the light information would erroneously appear to be three times as large as it actually is.

Table 2: Optical systems comparison.

Lens model	Focal Length	Angle of View	FOV @ 50 m height	Ground resolution @ 50 m	FOV @ 25 km height	Ground resolution @ 25 km
Kowa LM35HC	35 mm	13°	12 x 12 m	0.42 cm	5.7 x 5.7 km	2 m
Tuss LYM0814	8 mm	62°	60 x 60 m	2,11 cm	- *	10 m

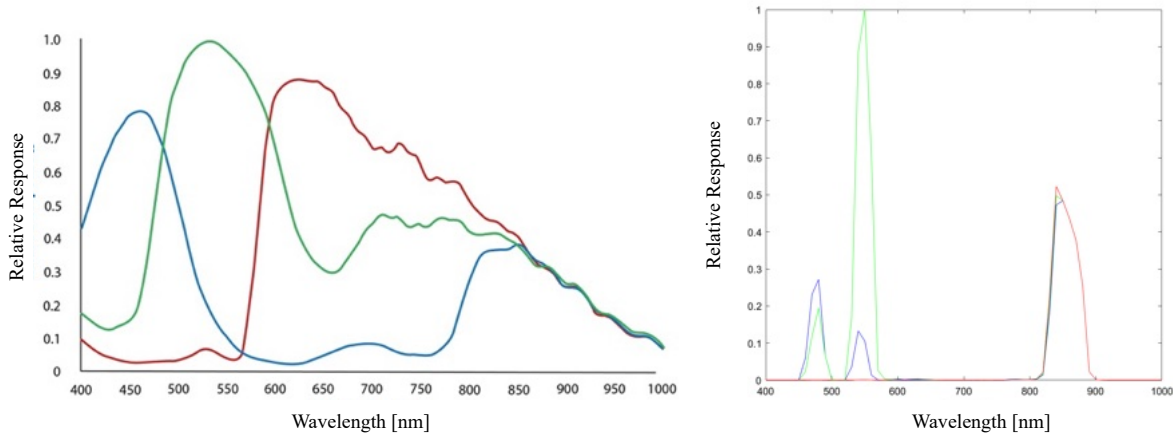


Figure 2: On the left is a graph representing the camera response over the entire visible and NIR spectrum; on the right, also on the same spectrum, is the cameras response acquiring three light sources (475, 550, and 850 nm) and considering the response of the spectrometer, the CMOS sensor, optical path, filtering, and soybean leaf reflections to normalize the output signal. For both graphs, the lines correspond to the 3 RGB (Red Blue Green) channels, respectively

The calibration process and the setup described in this section were chosen for the application of the PRIN project called “rewatering”; the aim was to investigate the reduced irrigation effects on Soya crops with the estimation of vegetation indices. The next section will describe the activities, procedures, and results of the field tests carried out during the summer of 2023.

3 Field Test Results

3.1 Tests Framework

The goal of ATEM0 is certainly to provide a global image of a given area of interest; therefore, in order to ensure consistent results, it will be necessary in the future to carry out tests on the other areas of analysis (air and light pollutants) as well. As mentioned, the configuration described will mainly deal with the analysis of aspects related to the health of vegetation that is also the main goal of the PRIN project previously highlighted: differentially irrigated soybean crops were monitored (one part at 70% of requirements and the other at 100%) investigating on the consequences of this action (deficit irrigation can be a strategy to reduce water consumption) [8].



Figure 3: Basler cameras with internally mounted filters (C-mount).

Ground data included the measurements of leaf saturation, humidity, and soil temperature, and finally the results were compared with each other and with what was seen from satellites and with ATEM0. Space images were obtained using Sentinel [2] or Planet [3] data; however, only in the second case (Planet) images could be compared, as the ground resolution is higher and the passes more frequent.

Image data analysis for agriculture and biomasses is usually carried out by means of vegetation indices, i.e. dimensionless numbers that give information on plant vigour and can be of various formulations depending on the analyte and the type of information sought. In practical terms, these are calculated by spectral analysis and as an algebraic recalculation between results on the various levels of a spectrum. The index most employed in literature is the NDVI (Normalized Difference Vegetation Index) a recombination of the information of the response of instrument on the bands of NIR (Near InfraRed) and Red, which formula can be found below.

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

The specific wavelength it depends on the acquisition system and on the procedure, to be consistent with the presented research we will take the values defined in Table 3.

In the case of ATEM0, we focused on 3 additional indices: GNDVI (Green-NDVI), ENDVI (Enhanced-NDVI) and NDRE (Normalized Difference Red-Edge), defined according to the following formulas.

$$GNDVI = \frac{NIR - Green}{NIR + Green} \quad (2)$$

$$ENDVI = \frac{(NIR + Green) - 2Blue}{(NIR + Green) + 2Blue} \quad (3)$$

$$NDRE = \frac{NIR - RE}{NIR + RE} \quad (4)$$

where Green, Blue and RE (Red Edge) values are, another time, the one expressed in Table 3.

In order to determine these indices, the specific spectral bands required were then acquired using bandpass filters on the monochrome camera and triple bands on the colour camera. Below, in Table 3 you can see the bands that can be acquired with ATEMO in this specific setup and in the same table, the 8 bands of the Planet satellite case [3]. Figure 3 shows the optical filtering system on board ATEMO.

Obviously, it is not easy to have the same band average values for ATEMO and Sentinel, mainly due to the type of technology being different. However, especially in the present case, ATEMO's bands intersect in a good way with the ones of Planet, and it is, therefore, easy to correlate the two results. In general, there are many strategies to determine vegetation indices, and the easy access to them makes them useful tools for consistent simplified information from lot of instruments [17].

Table 3: Band selection comparison between ATEMO and Planet satellites [3].

Band name	ATEMO		Planet	
	<i>Nominal Value</i>	<i>Bandwidth</i>	<i>Nominal Value</i>	<i>Bandwidth</i>
<i>Coastal Blue</i>	475 nm	20 nm	441,5 nm	21 nm
<i>Blue</i>			490 nm	50 nm
<i>Green I</i>	550 nm	20 nm	531 nm	36 nm
<i>Green</i>			565 nm	36 nm
<i>Yellow</i>	-	-	610 nm	20 nm
<i>Red</i>	-	-	665 nm	30 nm
<i>RE (Red-Edge)</i>	735 nm	20 nm	705 nm	16 nm
<i>NIR (Near-Infrared)</i>	850 nm	20 nm	865 nm	40 nm

3.2 Tests Setup

As explained above, the payload was placed on board of a tethered balloon. This is the most congenial solution, with respect to drones or free balloons, as it allows ATEMO to be stationed on the same field and be able to observe significant changes within the same day. The setup includes three safety rods arranged at 120° to each other (Fig. 4) and a central emergency rod which is not tensioned and is only employed for emergency or in case of strong wind. With this configuration, the balloon can remain at an altitude of about 50 m for several hours (6–7); both the heat and the balloon yield and porosity can influence the duration of the floating phase; in any case, the balloon, which contains about 2 m³ of helium to lift the 2.5 kg of ATEMO, can be quickly lowered and refilled to ensure a few extra hours in the event of prolonged testing. In the event of an accidental breakage of the balloon, a parachute is inserted halfway between the balloon and the payload. In addition, this parachute is connected through two joints (one upper and one lower), making the flight chain similar to a double pendulum and helping to dampen the various oscillations caused by the wind.

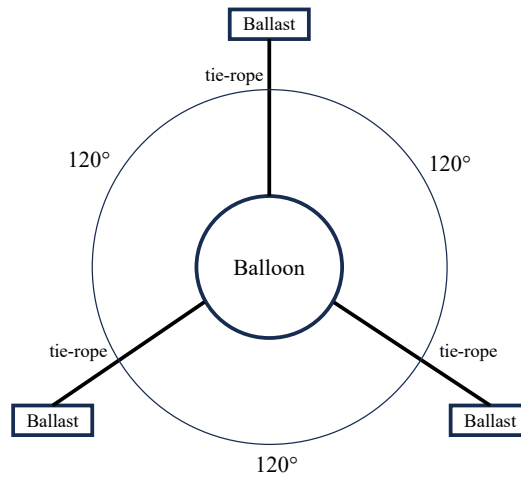


Figure 4: Tie ropes arrangement.

It is precisely this latter which is the most problematic part of the experimental phase; in fact, in the ideal case, in the absence of wind, the balloon sits independently for several hours, while in the case of wind, the adjustments to be made by means of the tie-rods are various and the altitude varies several times during the day. Figure 5 compares the altitudes on two different test days, in the case of wind (left) and in the case of calm (right), both on the same field in Cortona, for the half hour following the balloon release and stabilization. This comparison of the two ascent phases shows that the practical difficulty of the tests is to manoeuvre the ball to keep it in the desired position. The tests are not affected by this as the acquisition takes place at the desired height but keeping the balloon in place is complicated in windy conditions and must be considered.

Before commissioning the device, several function checks are carried out, but above all, the exposure and gain values of the cameras are set. After a few on-site tests, the balloon is inflated and slowly raised to the desired height. For the evaluation of vegetation indices, the acquisition rate is about 1 per min, which is done in favour of safety, but this ensures a good amount of data that is also useful for fine georeferencing and more accurate attitude estimation.

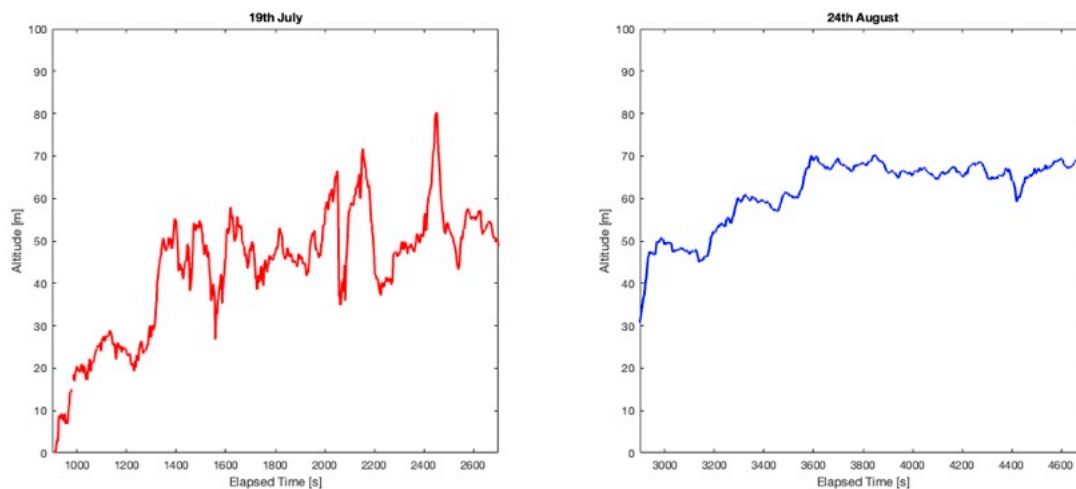


Figure 5: Comparison of the altitude graph in the early stages (ascent phase) of flight on 19 July and 24 August both at the Cortona field

4 Results

The test campaign took place in a total of five sessions from May to August 2023, three of which were carried out at a soybean field in Castelfranco Veneto (Treviso, Italy) and the other in Cortona (Arezzo, Italy), both composed of 4 closely spaced plots, 2 irrigated at 70% of water requirements and 2 at 100%.

Being a test methodology never carried out before, summer 2023 was mainly a way to test the functionality of the systems, understand the goodness of the acquisitions, define which indices were most descriptive of water stress and then compare the various sessions with each other and with satellite data.

Figures 6 and 7 show an acquisition carried out in Castelfranco Veneto by the two cameras and the calculation of the GNDVI, ENDVI and NDRE indices.

Another information that can be obtained via ATEMEO is the ground temperature; this is not redundant but rather very useful for understanding the temperature of the cultivated field under water stress; in Figs. 8, 9 and 10, it is possible to see an acquisition made in Cortona, the relative vegetation indices, and the thermal camera images showing the irrigation that has just taken place and, therefore, the different temperature of the two portions of the field.

Furthermore, a comparison of the same indices calculated by satellite can be seen in Fig. 11. This comparison has only been made for the Cortona field; the reason is related on the fact that the data for the day worked on Castelfranco are absent, or rather the images present clouds that therefore prevent visibility in the field. In fact, this reconfirms what the limitations of low-cost satellite only observation can be.

Considering the index evaluation images (Figs. 7, 9 and 11), visually, it can be seen quite immediately how the differences in vegetation are, especially in the Castelfranco Veneto area, almost imperceptible. As a matter of fact, the images considered take a portion of the field irrigated at 70% and a portion of the field irrigated at 100% in a single shot, therefore, they should present a different and clear behaviour through graphic representation. To investigate the reasons for this discrepancy between the PRIN objectives and the ATEMEO results, rainfall data were retrieved during the season in which the tests were conducted.

Table 4 shows these data, which are available and can be obtained from ARPAV (Veneto Regional Agency for Environmental Protection) [18] or ISPRA (Institute for Environmental Protection and Research) [19].

The irrigation provisions of the 2023 summer season were defined according to the previous season, which, as shown in Table 4, were significantly lower. While this represented a significant limitation for the scientific results of the experiment, it only partially affected the validation of the ATEMEO acquisition system: the comparison with satellite data still provides valuable information. Precisely regarding this topic, before moving on to the conclusions, it is interesting to note that for some indices what is obtained by satellite has a slight difference in terms of the relative scale of the index. One of the reasons for this could be the different software elaboration of the data between the acquisitions of the balloon device compared to the satellite.

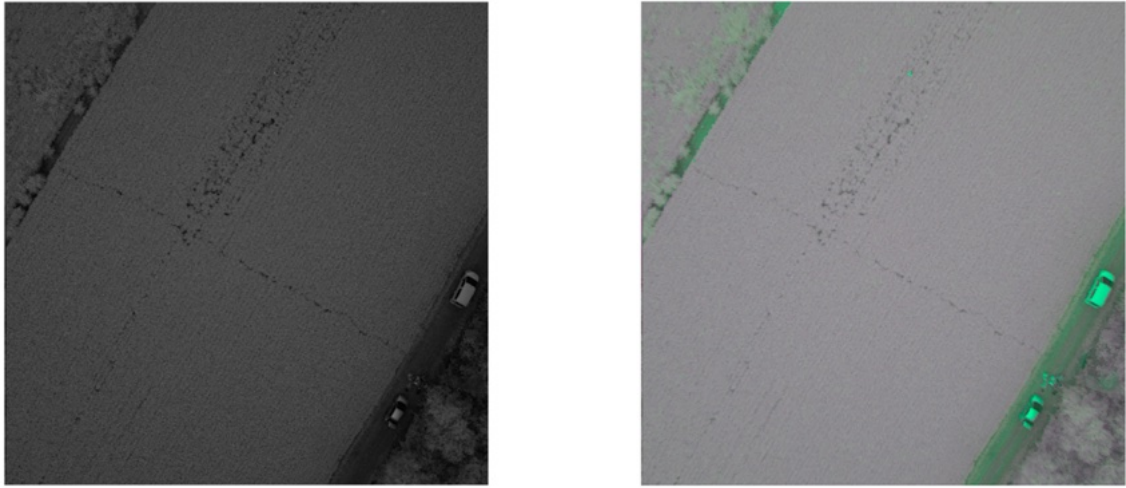


Figure 6: images acquired by the two cameras in Castelfranco Veneto on 9 August 2023, on the left the image of the monochrome camera with the Red-Edge filter and on the right the colour camera with the triple-band filter.

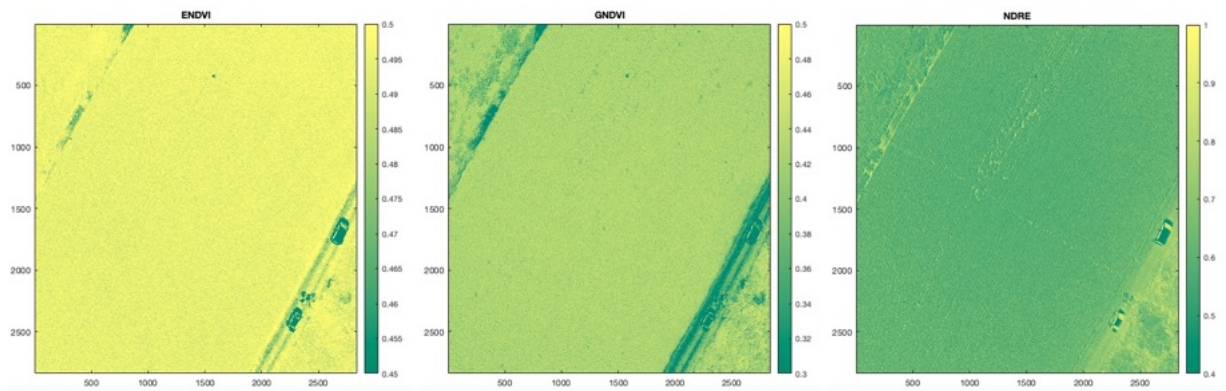


Figure 7: Starting from left to right ENDVI index, GNDVI index and NDRE index made starting from the acquisition in Figure 6.

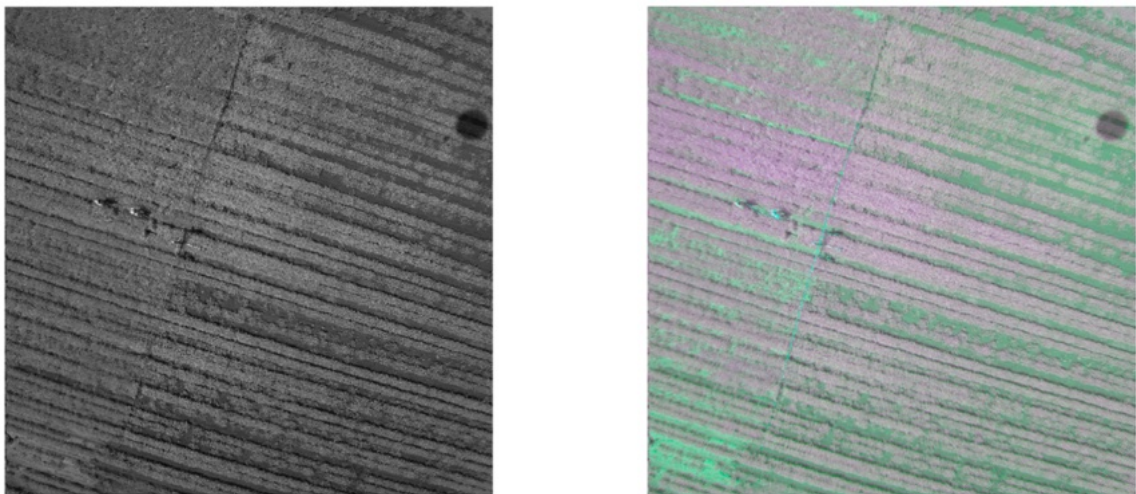


Figure 8: images acquired by the two cameras in Cortona on 24 August 2023, on the left the image of the monochrome camera with the Red-Edge filter and on the right the colour camera with the triple-band filter.

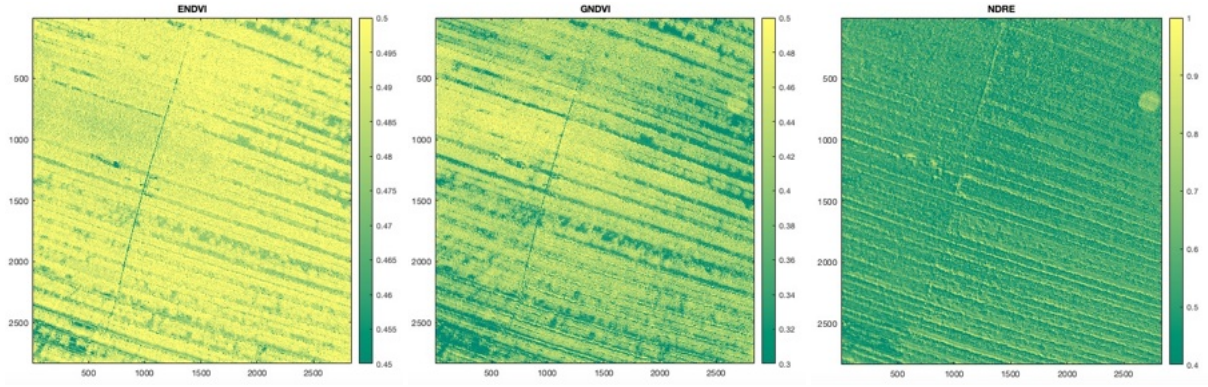


Figure 9: starting from left to right ENDVI index, GNDVI index and NDRE index made starting from the acquisition in Figure 8.

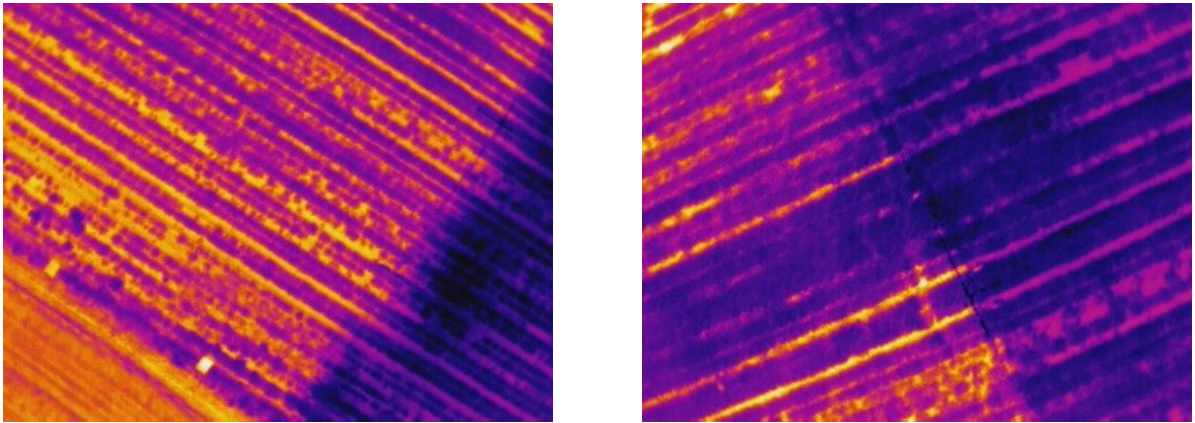


Figure 10: two different orientation images of the thermal camera on the Cortona field following a partial irrigation of the field.

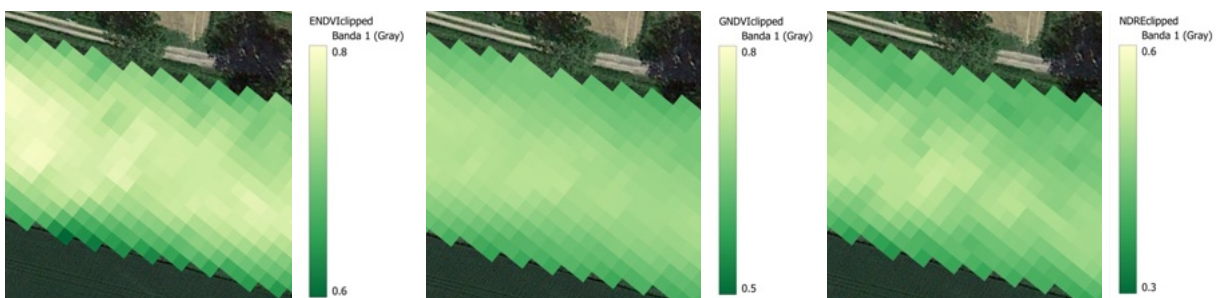


Figure 11: calculation of the indices in Figure 13 (ENDVI, GNDVI, NDRE) using Planet satellite data [3].

Not only, it could be connected to the consideration of certain variables like the reflections (such as those of the soya leaves) and atmospheric filtering that could have different models used for the two technologies.

To effectively compare the results obtained with ATEM0 and the Planet data, we rescaled the GNDVI values to have the same average and variance as the index calculated from the satellite. The ATEM0-based GNDVI is then down sampled to match the spatial resolution provided by Planet (3 m) by averaging the values of neighbouring pixels (Fig. 12).



Figure 12: ATEM0 based GNDVI down sampled on Planet [3] (Figure 11) spatial resolution.



Figure 13: Graphic representation in pixels of the modulus of difference between the two technologies

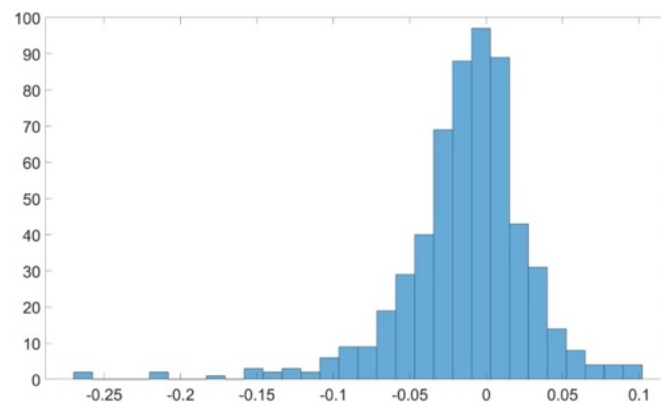


Figure 14: Pixel Differences representation between ATEM0 and Satellite.

The difference between the two is computed and the distribution of the pixel GNDVI values is represented in Fig. 13 and is plotted in Fig. 14: the distribution presents an average value of -0.0137 and a standard deviation of 0.0424 .

This operation accounts for the differences in the acquisition methods, e.g. cloud coverage, atmospheric absorption and different camera sensitivities.

Table 4: Seasonal rainfall data for the sowing and cultivation period in the Castelfranco area.

[17]	2022				2023			
Month	Jun.	Jul.	Aug.	Sep.	Jun.	Jul.	Aug.	Sep.
mm of water	30.8	19	112.6	100.8	71.2	173.4	>120.2*	41.8

* During the month of August, the maximum water storage capacity of the sensor was exceeded.

5 Conclusions

Looking at the results, ATEMО confirms all functional requirements, thus managing to acquire shots of the fields below with a high resolution. The tethered balloon solution proved to be an excellent solution in several aspects, above all the stationary time and the autonomy even in the altitude; it shall be mentioned that the latter needs some correction in case of wind gusts but is very stable in calm conditions.

The device is also functional when it comes to calculating vegetation indices; and for this reason it is noticeable that the effect of differential irrigation is very low. This is not due to the ability of the soybean to withstand water stress, but rather, by appropriately cross-referencing the seasonal rainfall data, it is due to the large quantities of water that, especially in the Castelfranco Veneto field, resulted in an almost total cancellation of irrigation at 70% in the half of the field under stress.

The ground temperature can also provide important information on the analyses conducted and also anticipate future uses in the night-time field, which, also for the other analytes for which ATEMО was built, will arise in the coming years of research.

In addition to what has been observed via balloon, confirming the usefulness and consistency of the data collected, it can be seen that via satellite the results are compatible with what has been done. Another important note is the slight discrepancy that exists between the average value of the satellite and balloon observations: this is due to the automatic adjustments that are made from satellite (removal of atmospheric disturbances and reflections) which do not follow the same set-up as the calibrations made for Basler and described in Section “Design of ATEMО experiment”. However, although there is this shift, the correlation between satellite and balloon data can be found. In the future, it could prove useful to use the same correction factor used by balloon for satellite data as well, which considers more variables such as, for example, reflections from soybean leaves.

Last, it should be emphasized that in the cases of the more economically accessible satellite services, the quality and resolution of satellite images is lower (4 m for services such as Planet and 0.0042 m for ATEMО mounted on a wire balloon). In the case of the more expensive satellites, on the other hand, again looking for the evaluation of vegetation indices in the visible

spectrum, less frequent passes and, in some cases, poor visibility due to cloudy conditions, result in obstacles to clear vision on specific dates of interest.

It can be concluded that, with a view to future analysis, the use of ATEMO can be of extreme interest for an in-depth analysis during a satellite observation campaign, reducing costs by using a compact, inexpensive device that adapts to the user's needs.

Acknowledgements We would like to thank the support of the researchers involved in the PRIN 'Rewatering' project, especially Professor Borin of DAFNAE (University of Padova) as project leader. Satellite image data services were provided by Planet team (2017), Planet Application Program Interface in Space for Life on Earth, San Francisco, Ca. <https://api.planet.com>

Author Contributions F.T. wrote the main manuscript. A.A. provided help in the device coding and testing C.B. provided help in the manufacturing of the device and in the indexes formulation. G.C. provided help in the manufacturing of the device. I.T. provided information about the indexes. S.C. provided thermal data and related figures. L.O. provided help in the test phases and wrote a big contribute in the manuscript writing. G.T. provided satellite data, related images and perform the comparison between the two technologies.

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Declarations

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

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4. Paper III: ATEMO Flight Dynamics Assessment

Role in the research project: *ATEMO developer*

Paper Contribution: *Drafting of the manuscript, launch and operation manager, data collection, corresponding Author.*

This chapter presents the third fundamental scientific paper of the thesis, focusing on the experimental in-flight characterization of sounding balloon flight train dynamics. This work represents the natural evolution of the theoretical and experimental studies conducted in the previous contributions, providing for the first time a direct validation of the relative dynamics between the balloon and payload during an actual stratospheric flight.

The research addresses a critical gap in understanding oscillatory phenomena that significantly influence payload stability and the accuracy of environmental data acquired during stratospheric missions. Through the implementation of an innovative dual synchronized inertial measurement system, the work enables direct observation of relative motion between the balloon and payload during atmospheric ascent.

The methodological framework developed in this study systematically connects laboratory modal analysis to real operational conditions, providing quantitative evidence of the evolution of relative dynamics as a function of altitude. The results reveal significant altitude-dependent dynamic coupling effects, with relative oscillation amplitudes that evolve considerably during atmospheric ascent.

Particularly relevant is the experimental validation of laboratory models through spectral agreement with flight data, establishing for the first time a quantitative bridge between controlled characterization and operational behavior. The work also integrates an ATEMO Earth observation payload, named AREO (Attitude Reconstruction and Earth Observation), allowing direct evaluation of the impact of dynamics on environmental data quality and sensor pointing accuracy.

The results not only contribute to the scientific literature—where data on real flight chain dynamics are limited—but also provide practical insights for trajectory planning optimization, payload design, and data correction protocols in stratospheric Earth observation. The developed framework therefore enables improvements in payload stabilization strategies and the reliability of future scientific balloon operations.

In Flight Characterization of a Balloon-Payload Dynamic through a Sensorised Sounding Balloon's Chain

(accepted with minor revision by Aerospace Science and Technology, 2025)

Federico Toson, Carlo Bettanini

Graphical Abstract

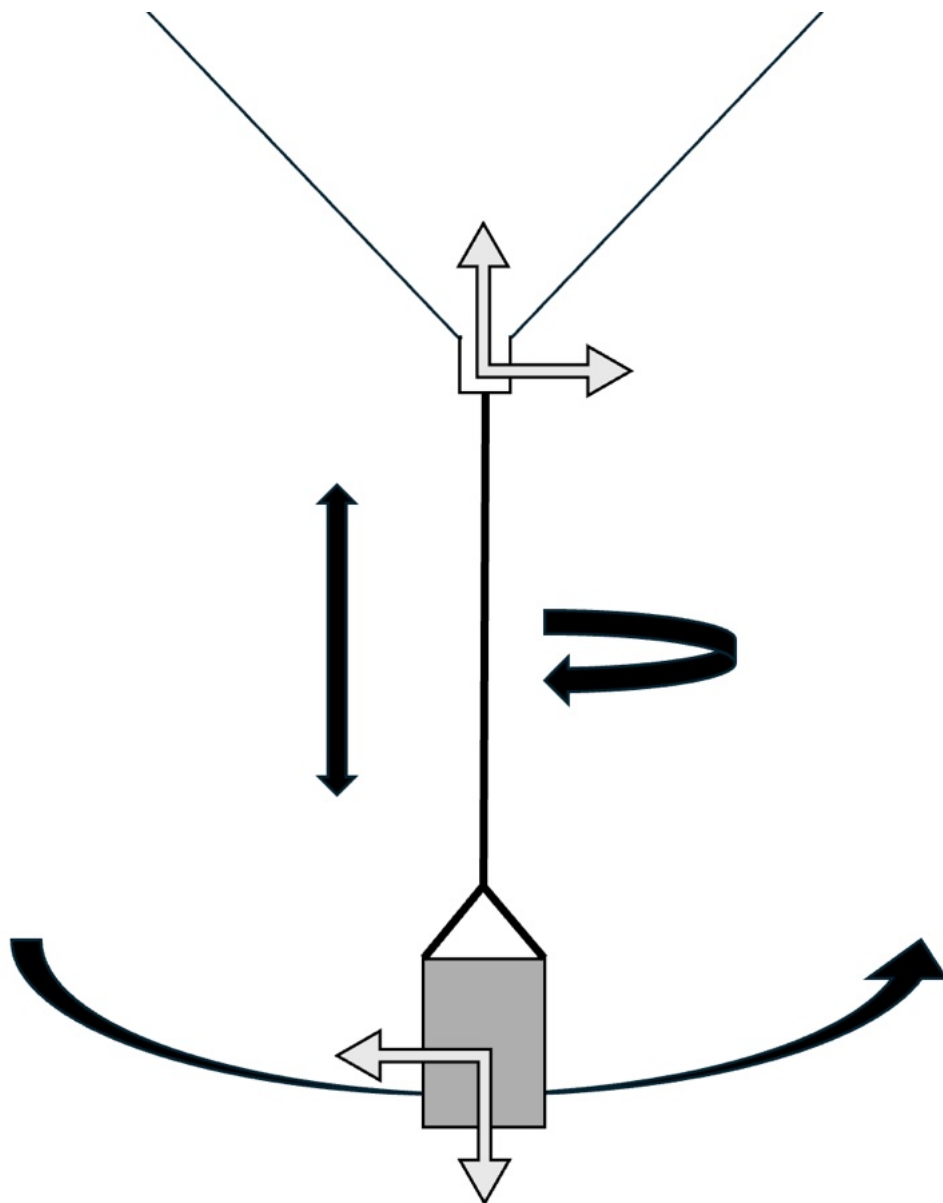


Figure 1: Minimalist design of the flight train highlighting the balloon and payload reference systems with representation of their relative movements.

Highlights

- In-flight quantification of flight chain relative dynamics using synchronized dual IMUs.
- Altitude-dependent dynamic coupling effects identified during atmospheric ascent.
- Significant eastward drift observed due to strong stratospheric winds.
- Comparison between ground-lab modal analysis and flight data.
- Earth observation payload used to assess dynamics impact on data quality and pointing.

Abstract

Understanding the in-flight relative dynamics between a balloon and its suspended payload is essential for stratospheric mission, as these interactions directly affect payload stability and scientific data quality. This work presents a flight data analysis characterization framework that links laboratory-based modal analysis of the flight chain to real operational conditions, focusing on the quantification of relative motion between balloon and payload.

A stratospheric mission was launched from Livorno, Italy, using a sensed flight train with two inertial units, one attached to the balloon and the other attached to the payload, aimed at capturing the evolution of relative oscillations.

Furthermore, flight data analysis revealed the activation of relative motions as a function of altitude. Compared to estimates conducted in the laboratory, clear altitude-dependent deviations emerge due to vibration modes coupling and excitation within the flight chain. The analysis compared the dynamic behavior resulting from laboratory tests with flight data to highlight the coupled movements due to atmospheric disturbances.

The resulting framework enables a validation of pre-launch models, the identification dynamic couplings, and provides actionable insights for improving payload connection strategies, stabilization approaches, and future mission design in scientific ballooning.

Keywords sounding balloon, flight train dynamics, relative dynamics analysis, attitude reconstruction, stratospheric flight data processing

1 Introduction

High-altitude balloons represent cost-effective platforms for atmospheric research, Earth observation, and space technology validation, accessing near-space altitudes up to 42 km, an investigation area which lies between aircraft and satellite operational domains. Beyond scientific missions, such balloons are increasingly employed in precision agriculture [1], light pollution assessment [2], and air pollution analysis [3], providing monitoring platform for environmental safeguard [4]. However, the dynamic behavior of balloon–payload systems during flight significantly affects measurement quality due to variable pointing and measurement dynamic induced noise. Complex interactions between balloon, suspension ropes, parachute, and payload are activated by lateral and vertical winds, and results in pendular oscillations, longitudinal vibrations, and torsional movements that can degrade payload stability.

Early balloon dynamics modeling established by Kreith and Kreider [5] provided foundational trajectory prediction capabilities, though with significant simplifications, including constant

ascent rates and constant drag coefficients. Recent advances in trajectory forecasting have incorporated Monte Carlo uncertainty analysis [6] and comprehensive stratospheric thermal modeling [7], yet critical weaknesses persist in characterizing relative motion between balloon and payload components, limiting stabilization strategies. Most existing approaches rely on single accelerometer or GPS measurements, fundamentally limiting the ability to distinguish between absolute system motion and relative dynamics between components.

Recent research has started addressing flight train dynamics through accelerometer-based measurements. Current models often approximate flight chains as simple pendulum systems without comprehensive validation against real stratospheric conditions. Laboratory characterization efforts lack systematic validation against actual flight environments, and most trajectory models neglect dynamic variations in system coupling during complex ascent phases. Marlton et al. [8] pioneered single accelerometer approaches for atmospheric turbulence detection, identifying pitch and roll oscillations up to 1 Hz and accelerations exceeding 5 g during balloon flights. Chaffee et al. [9] conducted the first dual-sensor investigation comparing dynamics at apex and gondola positions, revealing longer coupled motions oscillation periods at the apex and in the gondola.

Recent work by Gemignani and Marcuccio [10] demonstrated IMU-based (Inertial Measurements Unit) attitude reconstruction for balloon payloads, identifying characteristic pendulum frequencies in stratospheric conditions and establishing the feasibility of real-time dynamics monitoring. Their Fourier analysis revealed distinct frequency signatures corresponding to theoretical pendulum modes, though validation against controlled laboratory characterizations remained limited. Other modeling advances by Wang et al. [11] and Fernández-Soler et al. [12] have developed dynamic models incorporating horizontal wind effects and relative velocity predictions, yet experimental validation using synchronized multi-sensor data is not addressed. Understanding relative dynamics is essential for two critical mission requirements: payload stabilization, that may be improve by properly damping flight vibrations increasing pointing accuracy, and environmental noise reduction, that can be limited by reducing flight train vibrations.

Previous laboratory work [13] characterized the AREO payload flight chain dynamics through spring-damper modeling under controlled conditions, quantifying oscillation frequencies and damping ratios. However, validation against actual stratospheric flight data may provide supplementary data improving practical application for mission planning and real-time payload functionality.

2 *Flight Train Setup and Sensor Integration*

The scope of the work was to design a dual IMU configuration enabling direct measurement of relative dynamics between balloon and payload during actual stratospheric flight. The methodology facilitates direct validation of laboratory predictions against in-flight behavior, bridging the gap between controlled testing and operational conditions.

Specifically, this study presents a framework for validating pre-launch chain models against real stratospheric flight data using lab test data and synchronized inertial measurements from a stratospheric flight from Livorno, Italy (>33 km altitude). The work enables possible

improvements in trajectory prediction accuracy and informing payload stabilization strategies for enhanced balloon operations reliability. The framework provides actionable insights for future missions requiring precise attitude control and identifies lateral current influences on system dynamics as a key area for continued investigation.

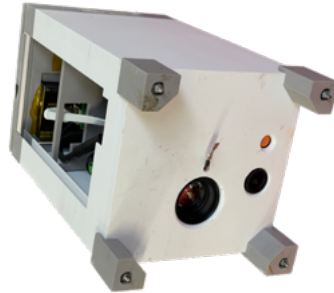


Figure 2: Payload with integrated sensor and cameras for stratospheric Earth monitoring.

3 Payload and Instrumentation

The AREO (Attitude Reconstruction and Earth Observation) payload consist in two units both equipped with a Pixhawk Mini 4 flight controller. The first unit is suspended at the end of the flight chain and the second is placed on the inflation interface of the balloon (Figure 3). The total mass attached to the balloon is 2.5 kg. The main part of the payload (Figure 2) carries atmospheric sensors, a sport camera and triple-band filtered colored cameras for Earth observation; this underlines the dual function of AREO, combining aspects of dynamics assessment with environmental monitoring. Specifically, the on-board filtered camera allows calculation of vegetation indices such as NDVI (Normalised Difference Vegetation Index) to be obtained; this not only allows to assess the health of plants on the ground but can also help for noise correction in Earth observation measurements. Every Pixhawk unit is equipped with inertial triaxial accelerometers, rate-gyros, magnetometers, pressure sensors and GPS. All the sampling rates of the sensors are listed in Table 1. Power distribution was provided by a battery pack, with an expected duration of 5 hour; data were logged on a 32 GB SD card, and dual SPOT GPS units ensured redundant recovery tracking.

Table 1: Sensors and sampling specifics.

Sensor	Sampling rate	Full-scale
<i>PixHawk accelerometers</i>	1000 Hz	± 16 g
<i>PixHawk rate-gyro</i>	1000 Hz	± 2000 °/s
<i>PixHawk barometer</i>	20 Hz	10-1200 mbar
<i>PixHawk magnetometer</i>	100 Hz	± 1300 μ T
<i>PixHawk GPS</i>	5 Hz	N/A
<i>GPS spots</i>	0.5 Hz	N/A
<i>GoPro camera</i>	60 fps	N/A
<i>Colour camera</i>	0.02 fps	N/A
<i>Temp DS18B20</i>	1 Hz	-10 to +85 °C
<i>PT100 (4 wire)</i>	1 Hz	-60 to +500 °C

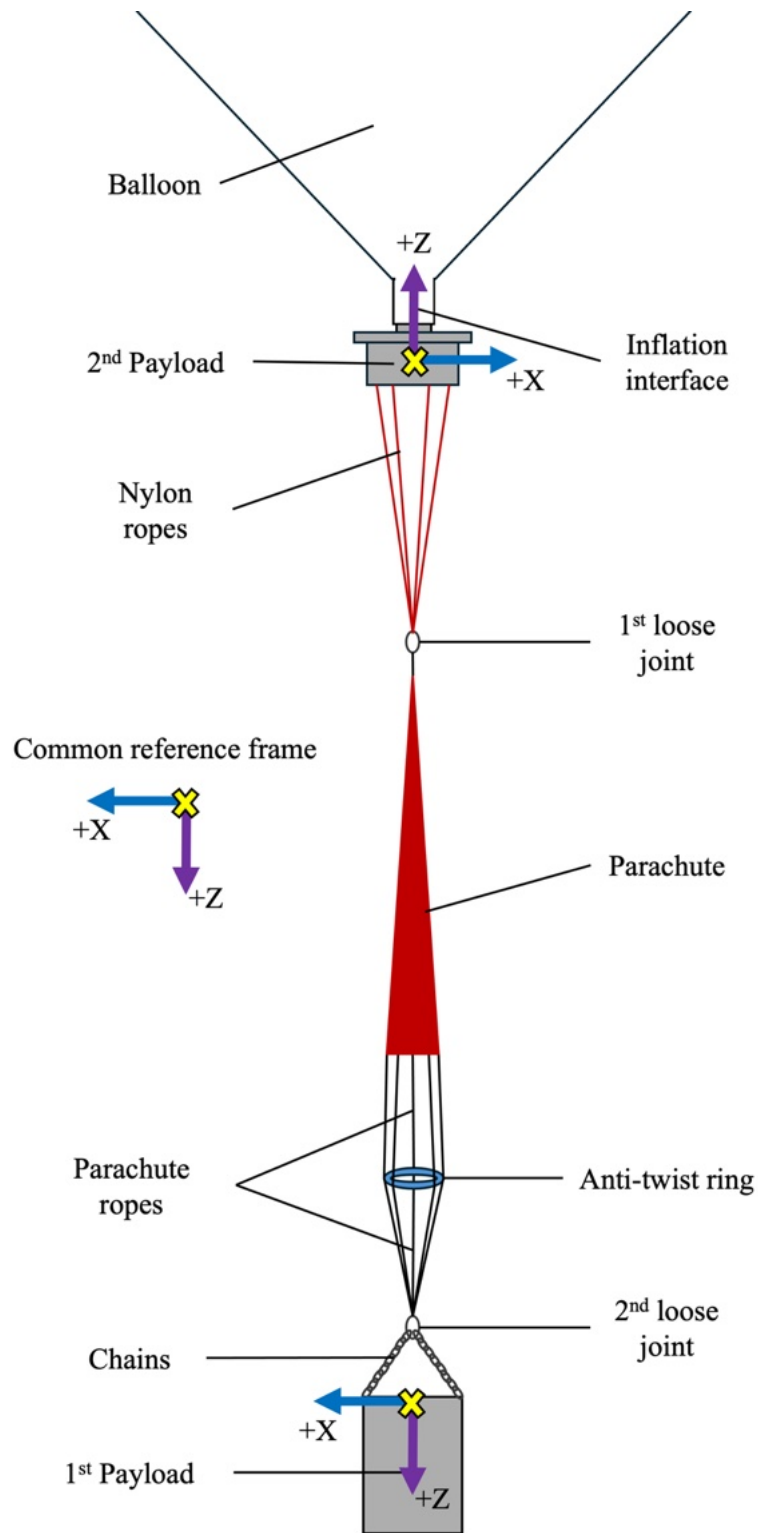


Figure 3: Flight train configuration showing the four-section design and the orientation of the two IMUs; X axis in blue, Y in yellow and Z in violet.

3.1 Flight Train Design and Sensors

The flight train featured a four-section design—nylon suspension cords, parachute, mixed nylon ropes, and stainless-steel chain links—totaling 2.50 m with 2v ring-shaped joints for section connection (Figure 3). As already stated, the two Pixhawk units were mounted at the top and at the end of the flight chain to capture absolute and relative motion. The orientation is shown in Figure 3; It can be noted that for both the laboratory and flight, the IMU reference systems are rotated to facilitate assembly. Data processing ensures measurement consistency by correctly transforming these two systems into a common reference frame using rotation matrices (Figure 3).

2.3 Laboratory Characterization

Experimental modal analysis on a reduced-scale model confirmed theoretical predictions, pendular frequencies, longitudinal modes and torsional oscillations served as benchmarks for in-flight data comparison.

For the characterisation of the chain, as discussed in the previous work [13] and here presented in a more structured way, the train was subjected to known longitudinal stresses and pendulum motion (in both directions). From the raw data measurements (Figure 4), the oscillatory behaviour along each axis was extracted, and by applying a Fast Fourier Transform (FFT), the frequencies of main vibrational modes associated with roll, pitch, and yaw motions were identified, as reported in Table 2. In Figure 5 and 6 is notable the response of XY axes accelerometer in function of the two pendulum-imposed movements. Instead, in Figure 7, is shown the FFT of the response to the longitudinal movements of Z axis accelerometer.

Finally, mixed motion, typical of balloon flight, was applied to the chain, in order to simulate the real environment with coupled frequencies; this is shown in Figure 8 in which we can see the FFT of the coupled oscillation input results.

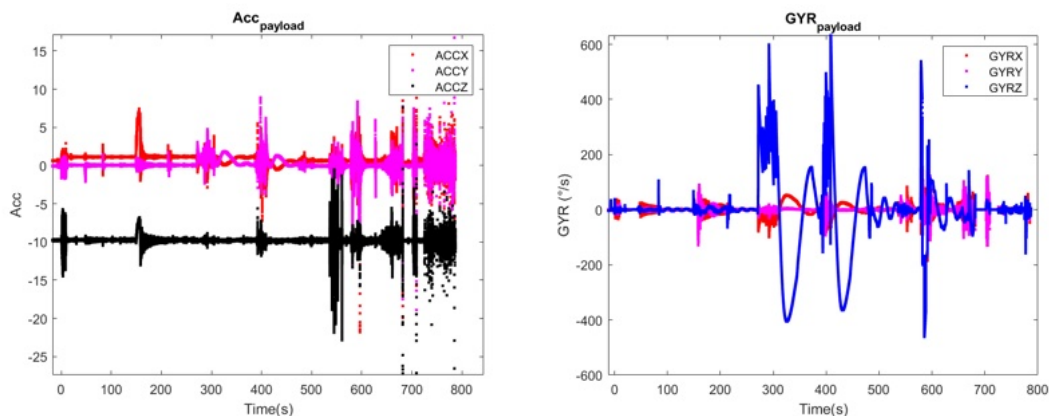


Figure 4: Raw data of payload accelerometers (on the left) and rate gyros (on the right) for all the test duration. The ‘quiet’ areas correspond to moments when the system is not under stress. This was done to clearly identify the various outputs based on the inputs. In the image, all the three axes are shown.

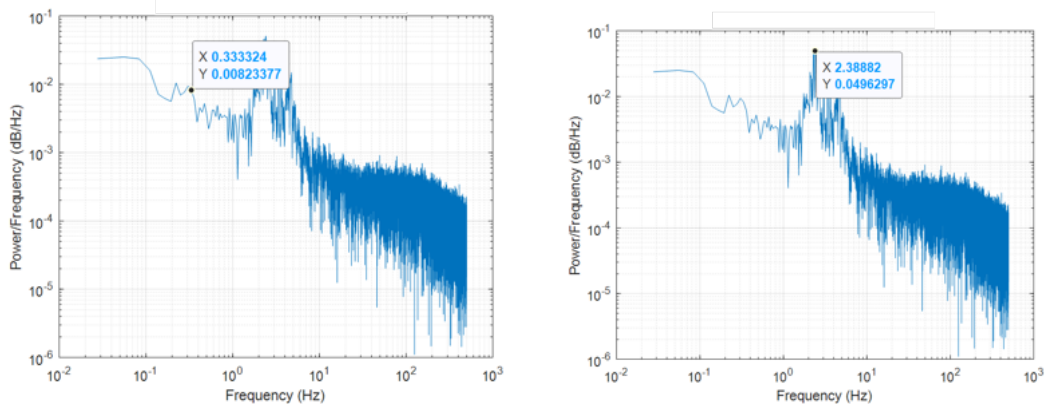


Figure 5: Response of the XY axes accelerometer to the pendulum input movement on the first direction.

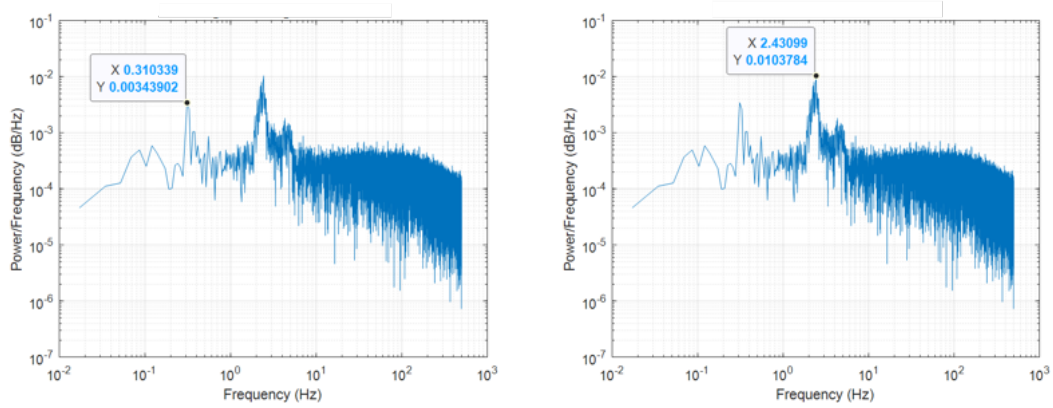


Figure 6: Response of the XY axes accelerometer to the pendulum input movement on the second direction.

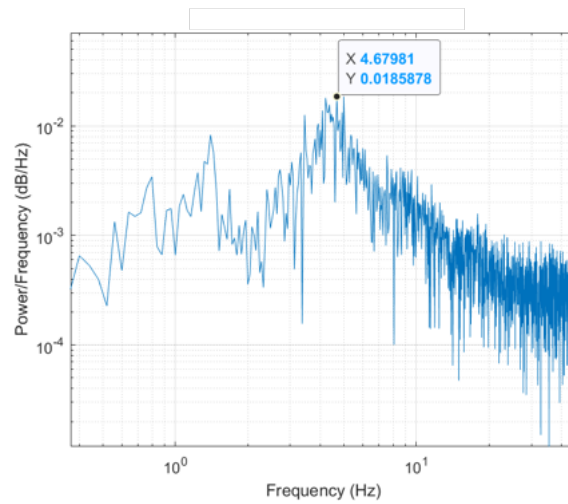


Figure 7: Response on the Z axis accelerometer to the longitudinal input oscillation.

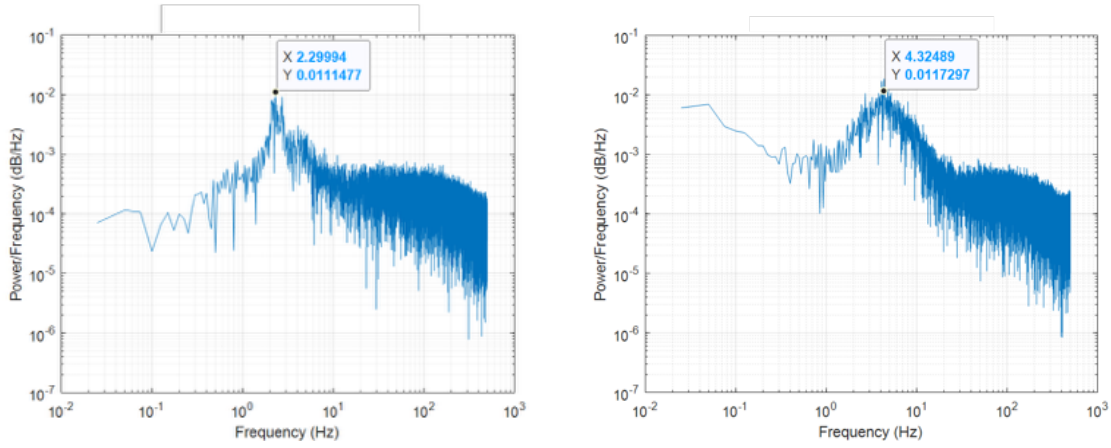


Figure 8: Response of XY accelerometer (left) and the Z accelerometer (right) to the coupled and mixed movement imposed in input on the chain.

Table 2: Flight Chain Characterization dominant frequencies summary.

Description	Frequency [Hz]
<i>f pendulum (all chain)</i>	0.310 ± 0.015
<i>f pendulum (lower part of chain)</i>	2.431 ± 0.015
<i>f longitudinal on Z</i>	4.68 ± 0.15

The results in the Table 2 show that with the input forcing the mixed oscillations, the output responds very clearly around 0.3 Hz; a value referable to the pendulum as demonstrated in laboratory and by the simplified model of previous studies [13]. As for the other pendulum frequency, around 2.4 Hz, this is due to the iron chains, as the train behaves like a compound pendulum (see joints in Figure 3).

3 Flight Campaign

The experimental campaign was conducted in December 2024 from Livorno, Italy, using a zero-pressure stratospheric balloon filled with helium, which exceeded an altitude of 33.5 km. The flight lasted approximately 2 h and comprised an ascent phase with a significant south-east drift and a rapid descent that ended on the border between the Marche and Umbria regions.

This section presents the key findings of the flight campaign, including the reconstructed balloon trajectory, sensor data, processed attitude dynamics, the relative motion analysis between balloon and payload, and the comparison with laboratory characterization.

3.1 Flight Trajectory

Figure 9 shows the reconstructed three-dimensional trajectory of the balloon from launch to the maximum reached altitude of 33.5 km. The two-dimensional ground track (Figure 9) reveals an eastward drift of approximately 150 km, indicative of strong crosswinds during flight above 18 km altitude.

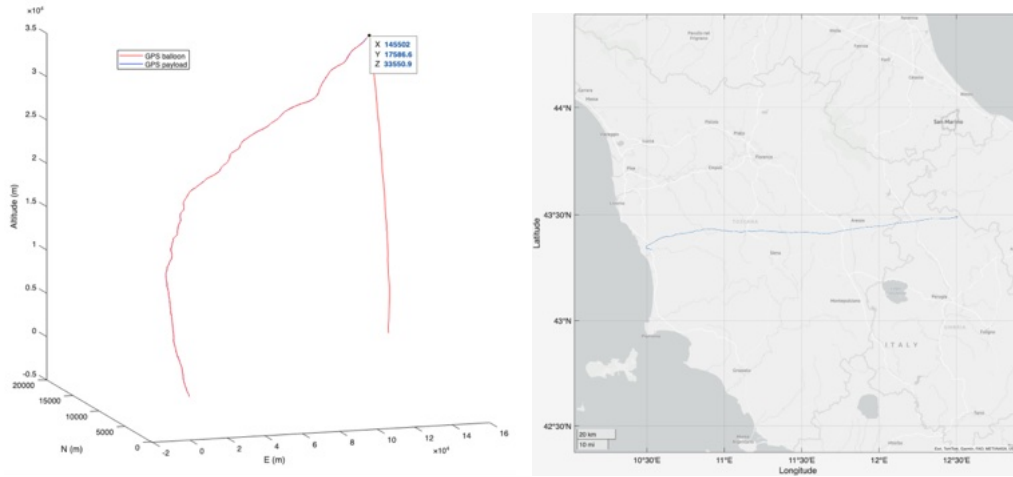


Figure 9: Left: 3D trajectory from the take-off to the landing. Right: 2D ground track showing 150 km eastward drift due to strong stratospheric winds.

3.2 Raw Inertial Measurements

Raw accelerometer and rate-gyro data highlight the unfiltered dynamics encountered during ascent. Processed pitch, roll, and yaw time series demonstrate the corrected attitude responses of both IMUs. Figure 10 presents the time series of raw accelerometer and rate-gyros measurements from both Pixhawk units during the flight. Looking at the raw data, it can be seen that the noisiest part is linked to the descent of the payload; the parachute generates chaotic dynamics, as can be seen from the graphs in Figure 10

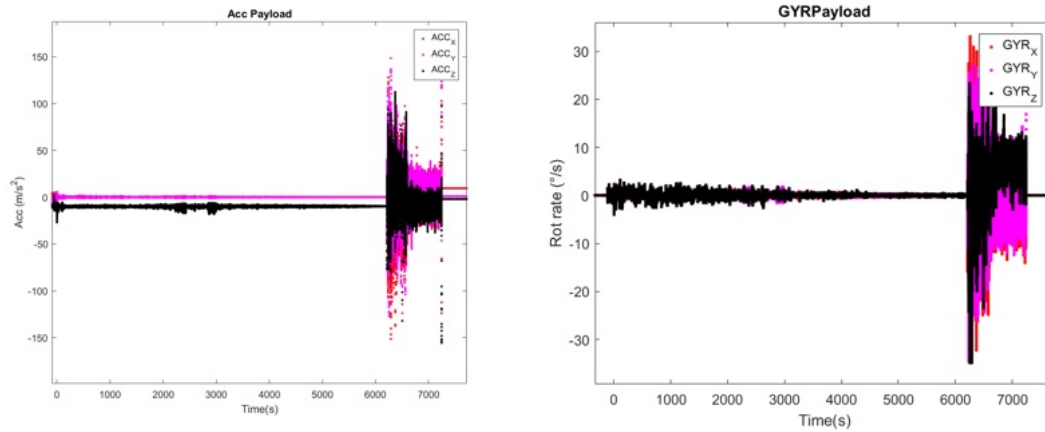


Figure 10: Raw tri-axial accelerometers data (on the left) and gyroscopes data (on the right) from the Payload Pixhawk. The X, Y and Z axes are respectively red, magenta and black.

3.3 Attitude Dynamics

Differential analysis reveals altitude-dependent relative oscillations, correlating in-flight behavior with laboratory benchmarks.

Pitch, roll, and yaw angles were computed by fusing IMU data from accelerometers, rate gyros and magnetometers and corrected for the different reference system of the two IMU (as explained before and shown in Figure 3). Figures 11 and 12 show the processed attitude time series for both sensors, accounting for their mounting geometry.

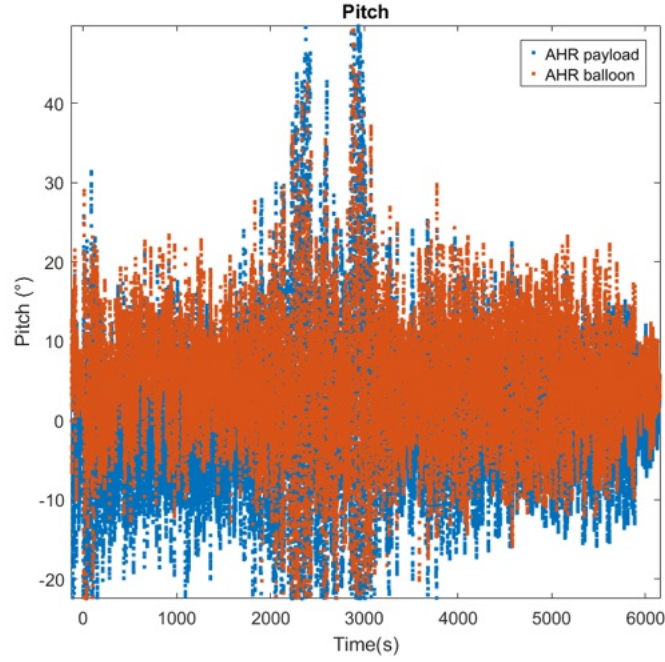


Figure 11: Pitch time series for balloon and payload IMUs.

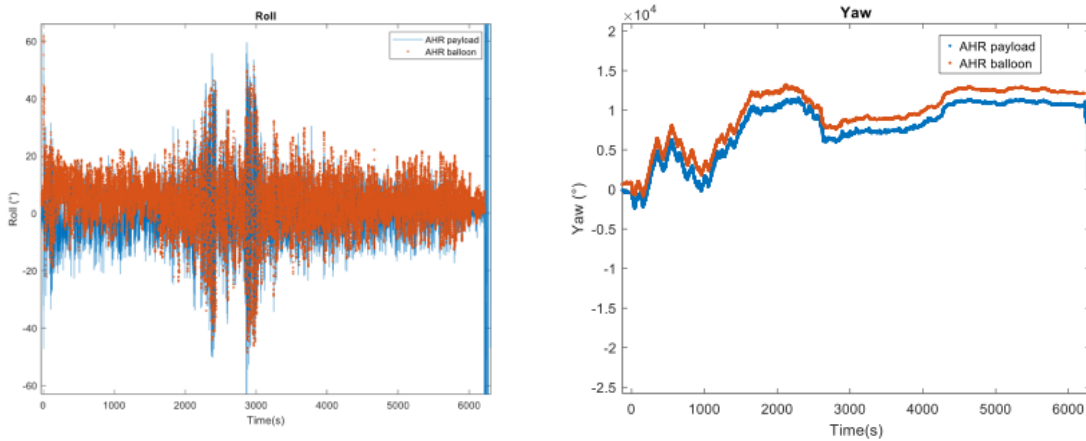


Figure 12: Roll (on the left) and yaw (on the right) time series for balloon and payload IMUs.

3.4 *Relative attitude between Balloon and Payload*

The differential attitude between balloon and payload was obtained by subtracting the processed attitude signals (the payload output was subtracted from that of the balloon one). Figures 13, 14 and 15 plot the relative pitch, roll, and yaw variations as functions of altitude. As the balloon ascends, the magnitude of relative oscillations changes, indicating altitude-dependent relative motion induced by winds. At the highest layer of the flight ascent profile the relative motions tend to be lower; this is clearly due to the atmospheric rarefaction and the absence of lateral flows.

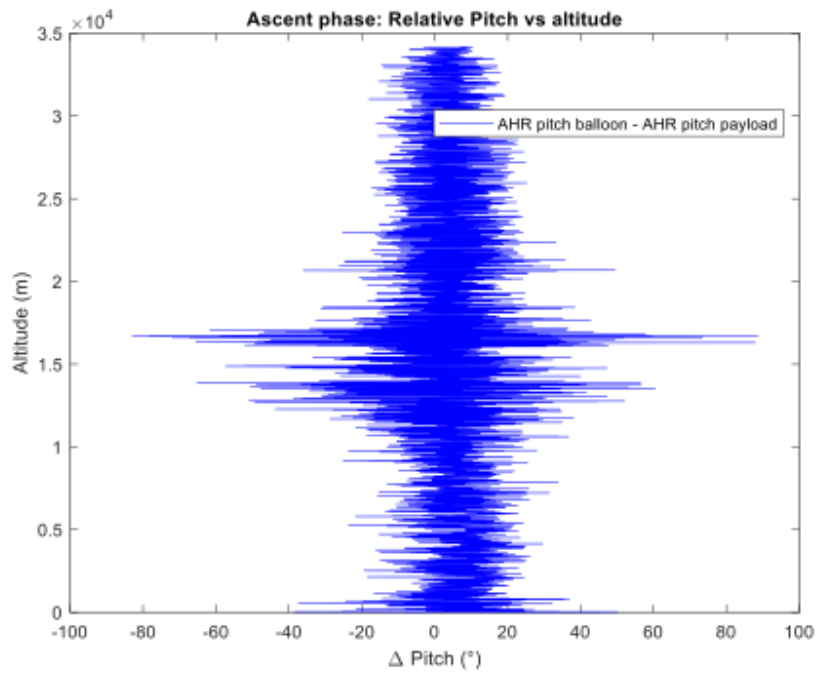


Figure 13: Relative pitch between balloon and payload versus altitude.

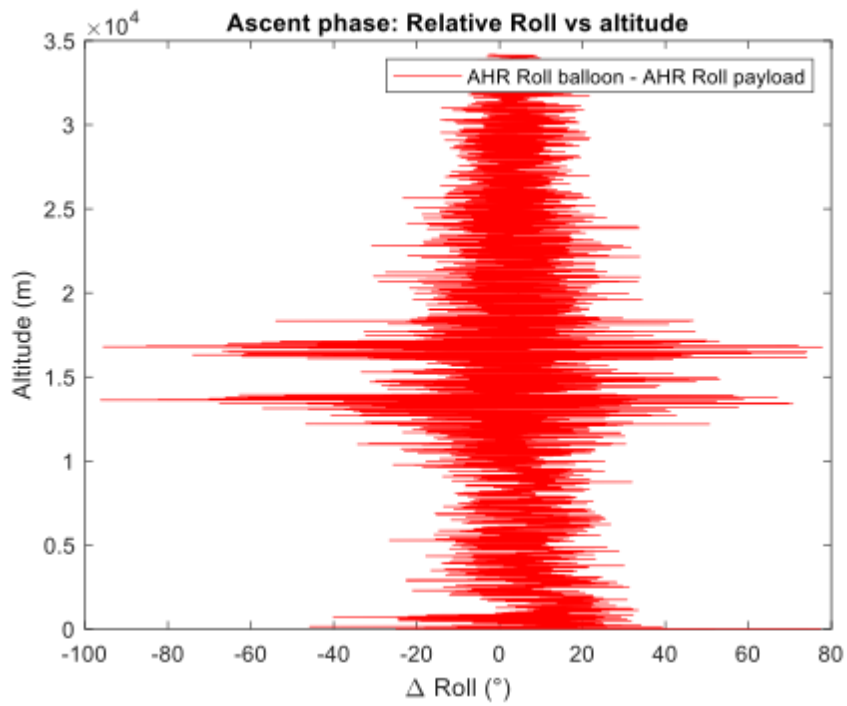


Figure 14: Relative roll between balloon and payload versus altitude.

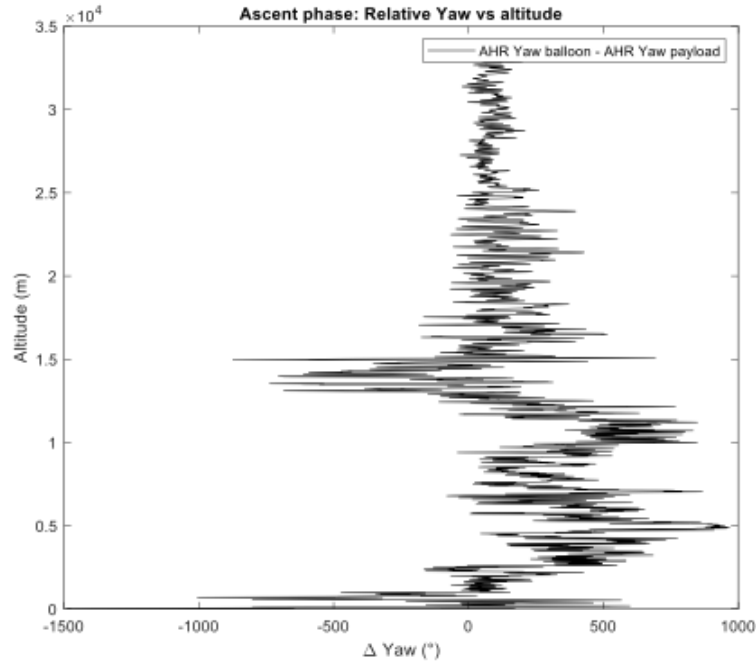


Figure 15: Relative yaw between balloon and payload versus altitude.

3.5 *Flight Vibration Modes*

In addition to aspects relating to dynamics, investigation of vibration modes within flight were studied. As mentioned above, the coupled frequencies easily highlight the compound pendulum. This evidence is shown in the three Figures below (Figures 16, 17 and 18) where the FFTs and the relative dominant frequencies can be noted.

Observing what the balloons' accelerometer reads on the Z axis (Figure 16), it is immediately evident that the entire train is swinging around 0.3 Hz, confirming the model and laboratory tests. Also in Figure 16, the frequencies already observed during the tests can be recognized; the oscillation of the lower part (around the 2 Hz value) and the longitudinal vibration (between 4.5 and 5 Hz) are clearly visible; however, a dominant frequency of approximately 0.5 Hz appears. Performing the FFT on the relative acceleration on the Z axis the same peak is revealed. This is because, considering that, as already mentioned, the chain is a compound pendulum, a relative frequency of 0.5 Hz may be calculated for the relative swing of the lower part of the chain under the parachute (Figure 17).

Concluding the comparison, Figure 18 shows the various peaks due to the relative acceleration between the balloon and payload on the XY axes. Once again, the various oscillations, of the pendulum, and the longitudinal vibration are highlighted.

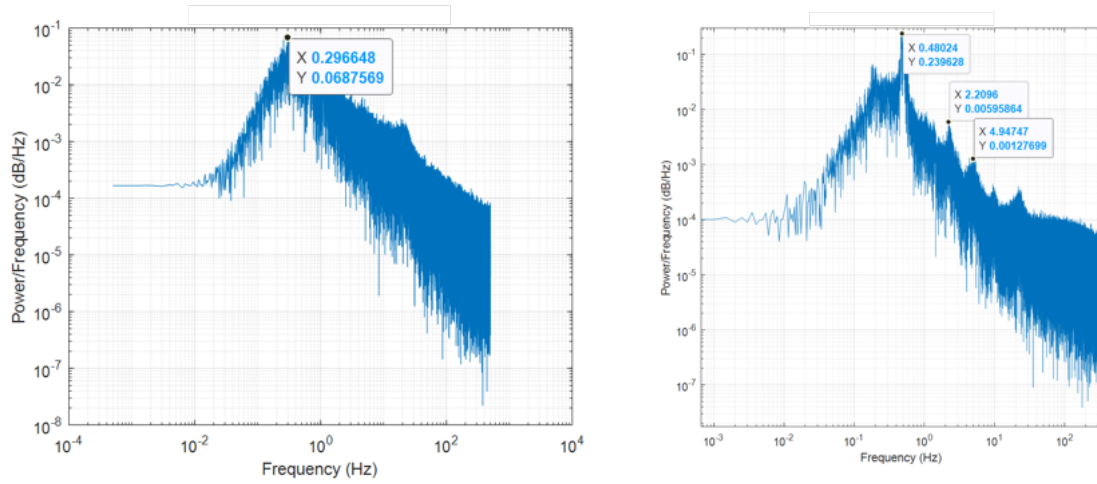


Figure 16: FFT on flight accelerometers data on Z axis. On the left, FFT of the balloon accelerometers output; on the right FFT of the relative output (balloon-payload).

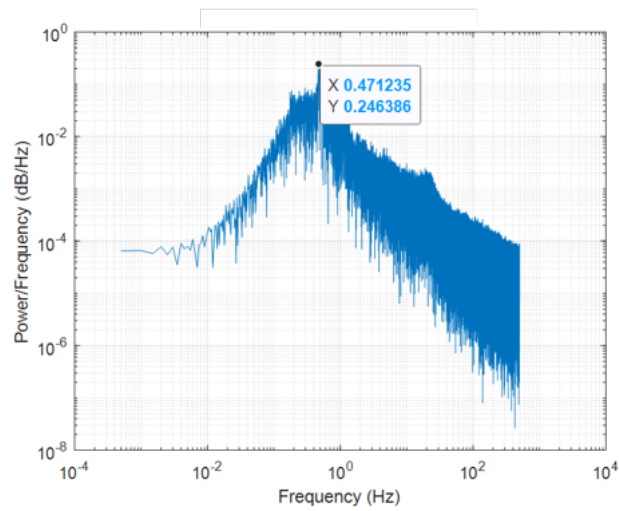


Figure 17: Relative pendulum frequencies enhancing the remain compound pendulum peak.

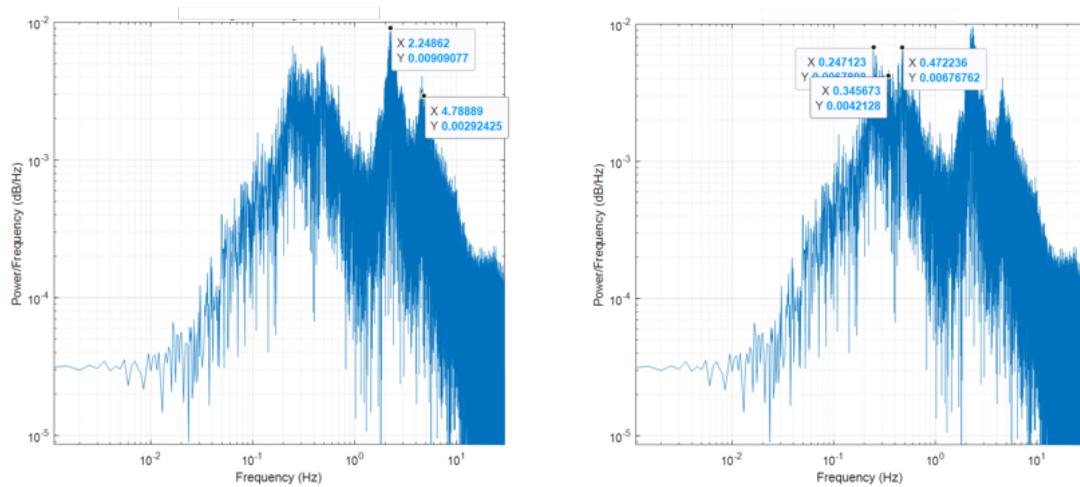


Figure 18: FFT on flight accelerometers data on XY axes. On the left and on the right the same spectrum with the peaks highlighting.

4 Discussion

The flight trajectory indicates that strong stratospheric winds dominated the ascent phase especially after 18 km of altitude, producing an eastward drift of approximately 150 km. This lateral displacement underscores the significance of wind field characterization for trajectory prediction and recovery planning.

Raw inertial measurements exhibit substantial sensor noise and variability, particularly at the payload, between 12 and 15 km of the ascent. These unprocessed data highlight the dynamic environment encountered by the flight train.

Processed attitude dynamics (Figures 11-15) reveal clear oscillatory behavior over pitch, roll, and yaw. Larger amplitudes at the payload IMU suggest amplification of motion downstream of the suspension points. The relative mounting geometry correction provides confidence in the alignment of measured angles between sensors.

Relative dynamics analysis demonstrates altitude-dependent coupling effects. Ascent profiles of relative pitch (Figure 13), roll (Figure 14), and yaw (Figure 15), show that the magnitude of differential oscillations decreases up to 20 km, likely due to decreasing atmospheric density and reduced aerodynamic excitation, then increases slightly during the flight as wind shear and thermodynamic variations intensify. These trends confirm that the flight train behaves as a tuned mass–spring–damper system (as modelled during the chain characterization [13]) whose parameters evolve with ambient conditions.

The spectral agreement between flight and laboratory benchmarks validates the experimental modal analysis framework.

The comparison between laboratory and ascent oscillation modes suggested that ground-based characterization could reliably predict in-flight dynamics when boundary conditions are well understood.

Overall, the dual-IMU approach successfully quantified relative motion between balloon and payload, demonstrating its utility for relative dynamics assessment. These insights support improved payload stabilization strategies—such as tuned damping elements or active control—and enhanced trajectory forecasts by accounting for altitude-dependent dynamic coupling. Future work should investigate lateral wind shear effects in greater detail and explore adaptive flight train designs that mitigate relative oscillations under variable atmospheric conditions.

5 Conclusions

This study presented a comprehensive in-flight characterization of a sounding balloon flight train's dynamics by integrating laboratory modal analysis with synchronized dual IMU measurements collected during stratospheric flight in December 2024. The analysis quantified altitude-dependent relative motion between the balloon and payload, revealing significant coupling effects that evolve throughout the ascent.

The spectral agreement between laboratory and flight data confirms the effectiveness of ground-based experimental modal analysis for predicting in-flight dynamic behavior, provided real atmospheric conditions and boundary effects are adequately modeled.

The dual-IMU approach demonstrated its capability to directly measure and distinguish relative motion patterns, offering valuable insights to improve payload stabilization designs and optimize trajectory forecasting models. In particular, the results support the future development of advanced damping strategies and active control mechanisms to mitigate payload oscillations and improve mission reliability.

Future work should focus on expanding the characterization of lateral wind shear impacts, refining real-time model adaptability, and exploring innovative flight train configurations that adapt to variable atmospheric disturbances to further enhance payload stability and data quality. These advancements will contribute to the efficacy of scientific balloon missions, with improvements in payload pointing and noise reduction in the stratospheric environment.

Acknowledgments The authors gratefully acknowledge the support of CISAS “G. Colombo” facilities at the University of Padova for laboratory and launch operations. Special thanks to the University of Pisa Space Systems group for technical and logistical assistance, and to the SUNFLOWER project students of the DII Department for their help during launch and recovery. Finally, a necessary mention goes to the forestry unit of the Carabinieri of Città di Castello (Perugia, Italy) for their support in the recovery activities.

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Appendix A: Additional Figures



Figure A.1: On the left is a shot from the sports camera taken a few moments after the balloon was released. On the right is the image captured at the same time by the colour camera with the triple band filter. The footprint is different because the camera used for analysis has a much narrower lens than the fisheye lens of the sports camera.

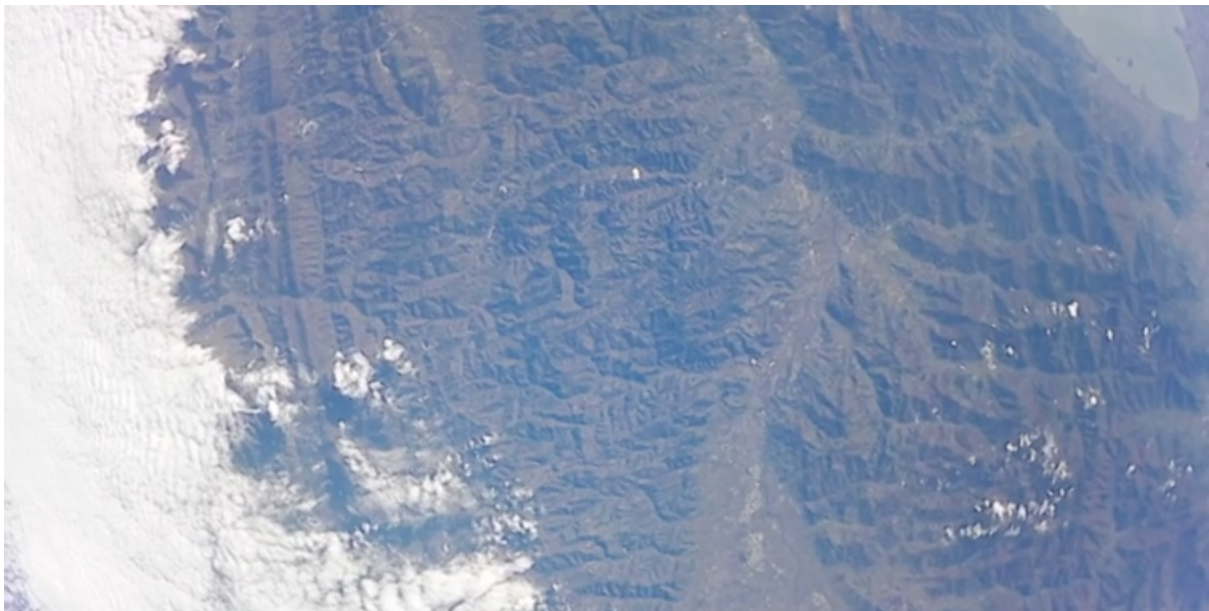


Figure A.2: Image captured by the sports camera shortly before the fall.



Figure A.3: From left to right: image of laboratory tests carried out on the flight chain; two images of the moments before launch.

Declaration of the Authors

- The document described above was submitted to ACTA Astronautica on 30 September 2025.
- The article was transferred to the journal Aerospace Science and Technology on 6 October 2025.
- Finally, on 17 November 2025, it was accepted with minor revisions.

5. Paper IV: Flight Chain Characterization

Role in the research project: *ATEMO developer*

Paper Contribution: *Drafting of the entire manuscript, test campaign operator, data collection, corresponding Author.*

This chapter introduces the fourth core scientific paper of the thesis, which focuses on the thorough experimental characterization of the flight chain used in sounding balloon missions. Building on both modeling efforts and preliminary flight dynamics studies carried out in earlier works (notably in Paper III), this contribution presents a comprehensive analysis of the mechanical and dynamic behavior of the flight chain connecting the balloon to its payload.

The research addresses the critical need to understand oscillatory phenomena—such as pendular, longitudinal, and torsional modes—that significantly influence the stability of the payload and the accuracy of environmental data acquired during stratospheric missions. By combining laboratory vibration tests, in-flight data collection with distributed inertial measurement units (IMUs), and comparative analysis with analytical models, the study validates and refines dynamic characterizations that are essential for improving mission reliability and measurement fidelity.

The experimental campaign detailed in this paper constitutes a methodological advancement by providing high-resolution insight into the dynamic interactions within the balloon-payload system, enabling more precise attitude reconstruction and informing design improvements for future campaigns. The findings not only contribute to the scientific literature—where data on real-chain dynamics are limited—but also underpin the optimization of trajectory planning, payload design, and data correction protocols in stratospheric Earth observation.

As such, this paper plays a pivotal role in bridging theoretical modeling and operational deployment, representing a cornerstone of the broader ATEMO research framework and reinforcing the platform’s capability to deliver high-quality, scientifically rigorous Earth monitoring data from high-altitude balloons.

Characterisation of the Flight Chain for Sounding Balloon Missions

Federico Toson, Carlo Bettanini

[3]

Abstract

The deployment of sounding and stratospheric balloons poses a substantial technological difficulty in characterizing the launch chain, which runs from the balloon's nadir to the payload. This chain exhibits complicated dynamic characteristics such as pendular oscillations, longitudinal vibrations, and torsion movements and a thorough understanding of these events is required for an accurate determination of payload attitude during flight. Sounding balloons are increasingly utilized in numerous scientific initiatives, such as Earth observation projects, in situ atmospheric study, and microgravity simulations and lack of a comprehensive understanding of the chain's dynamic behavior could undermine the functionality of onboard instruments like sensors, imaging systems, and inertial measurement units. This paper presents an experimental campaign aimed at characterizing the chain used prior to the launch of an experimental payload called AREO (Attitude Reconstruction and Earth Observation) and highlights a first qualitative comparison with the actual flight conducted following this characterization.

Keywords: balloon flight, stratospheric ascent, attitude reconstruction, vibration analysis.

1 Introduction

High-altitude balloons, particularly sounding and stratospheric balloons, play a crucial role in scientific research and technological testing [1]. These platforms offer a cost-effective and versatile method for accessing the near-space environment, providing unique opportunities for Earth observation [2], atmospheric studies [3], and experiments in reduced-gravity conditions [4]. Stratospheric balloons, capable of reaching altitudes of up to 42 kilometers, operate in a region inaccessible to satellites and aircraft while remaining more affordable than rocket-based systems. Their advantages have made them an essential tool for governmental agencies, private companies, and academic institutions alike [5].

Despite their benefits, the dynamics of these systems pose significant engineering challenges, particularly in the characterization and control of the flight chain. This chain connects the balloon to its payload and is subjected to various forces during ascent and descent. Its dynamic behaviour directly impacts mission success, as it influences payload stability and the accuracy of data collected during flight [6]. The chain is prone to multiple modes of vibration, including pendulum-like swinging, longitudinal vibrations, and torsional movements. These oscillations arise from aerodynamic forces during ascent or interactions with environmental factors such as wind shear. If not properly understood, they can complicate the stabilization and attitude determination of the payload.

For instance, pendulum oscillations can lead to deviations in sensor readings or inaccuracies in camera pointing, while longitudinal vibration may affect the structural integrity of the chain. Torsional vibrations can interfere with sensitive instruments like inertial measurement units (IMUs), compromising data reliability. Given these challenges, understanding the behavior of

the flight chain is critical for optimizing payload performance and ensuring successful missions.

This paper addresses these issues by presenting an experimental campaign aimed at characterizing the flight chain dynamics prior to the launch of an experimental payload named AREO (Attitude Reconstruction and Earth Observation). The study involves developing a detailed model of the flight chain that incorporates its mechanical properties and interactions with environmental forces. It focuses on analyzing the three primary modes of vibration—pendulum swinging, longitudinal vibrations, and torsional movements—and evaluates their impact on payload stability. Furthermore, it compares pre-launch characterization data with actual flight performance to validate the models and identify discrepancies.

By systematically investigating these aspects, this study seeks to enhance our understanding of high-altitude balloon dynamics and contribute to more reliable mission planning and execution. The findings aim to provide valuable insights into mitigating complications arising from flight chain vibrations, thereby improving the functionality of sensors, cameras, and inertial platforms during balloon missions.

II Chain Design and Model

First For the attitude reconstruction, two Pixhawk Mini 4 flight controllers were positioned at opposite ends of the flight chain: one near the balloon's valve and the other on the interface supporting the payload. The flight chain consists of four distinct sections, as illustrated in Figure 1. From top to bottom, these sections are as follows:

- Nylon cords: Four specialized nylon cords designed specifically for stratospheric flights.
- Parachute: A synthetic-material parachute essential for ensuring a controlled descent in the event of balloon burst.
- Mixed nylon ropes: Five pairs of mixed nylon ropes attached at five points beneath the parachute, ensuring its proper deployment and providing a secure connection to the payload.
- Stainless steel chains: Four stainless steel chains connected to the four upper corners of the payload structure.

Between the upper nylon cords and the parachute, as well as between the lower stainless steel chains and the ten ropes attached to the parachute, a ring-shaped joint is present.

However, experimental observations revealed that these joints do not decouple pendulum-like oscillations within the chain. As a result, they were not considered as decoupling elements in the dynamic analysis.

This configuration was carefully designed to ensure structural integrity during ascent and descent while providing sufficient flexibility for dynamic behaviour analysis. The placement of Pixhawk Mini 4 controllers at strategic points along the chain allowed for precise measurements of oscillatory modes and facilitated a comprehensive characterization of its behaviour under flight conditions.

Table I shows the known physical and mechanical characteristics of the various chain sections.

After defining the actual design of the flight chain, its components are simplified and modeled as a series of springs with specific stiffness values, arranged in parallel with a damper. In this case, the damper is assumed to provide total damping, with its damping coefficient initially estimated theoretically and later determined experimentally. This is not the only simplification that can be applied to the model. For instance, it can be reasonably assumed that the stiffness of the stainless steel chains is several orders of magnitude greater than that of the nylon cords. Additionally, the parachute and its associated ropes can be treated as a single unified component.

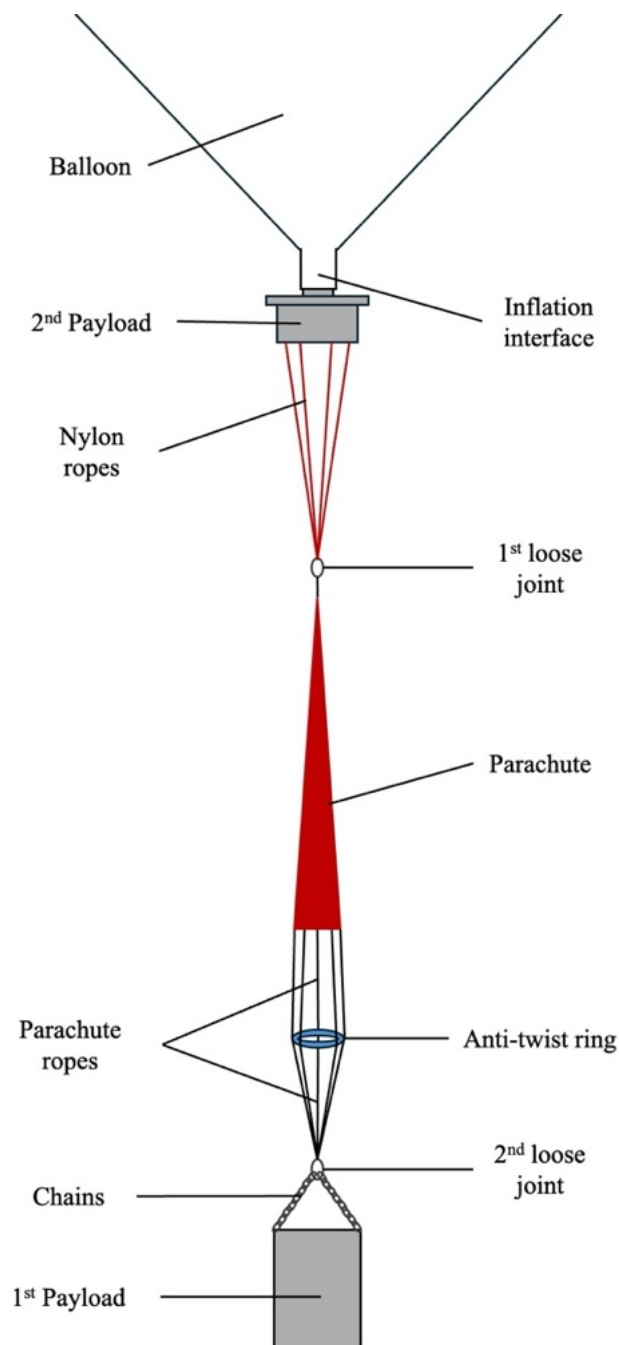


Figure 1: Actual chain scheme.

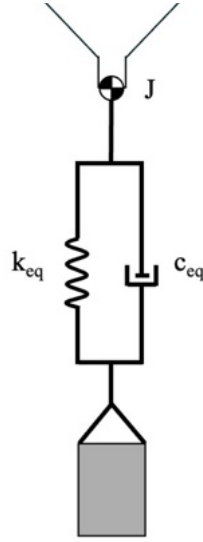


Figure 2: Simplified chain system model. J is the fulcrum of the pendulum, k_{eq} is the total stiffness of the system, and c_{eq} is the total.

Table I: Chain and Payload characteristics

Payload weight	2.50	± 0.01	kg
Chain total length	2.50	± 0.01	m
Nylon cords diameter	0.0012	<i>given</i>	m
Nylon cords length	0.8	± 0.01	m
Nylon tear strength	180	<i>given</i>	N
Parachute length^a	0.80	± 0.01	m
Parachute radius	0.20	± 0.01	m
Parachute cords length	0.80	± 0.01	m
Parachute cords diameter	0.001	<i>given</i>	m
Parachute cords Young Modulus	150 1e6	<i>given</i>	Pa
Fabric thickness	0.001	<i>given</i>	m
Fabric Young Modulus	250 1e6	<i>given</i>	Pa

a. The length of the parachute is the length it occupies when stretched out under tension as in Figure 2

This assumption is justified by the fact that the parachute and its ropes function as an integrated system, and mechanical tests to determine their elongation were conducted on the entire assembly rather than on individual elements. These simplifications allow for a more streamlined analysis of the dynamic behavior of the flight chain while maintaining sufficient accuracy for practical applications.

The schematic representation of this model is shown in Figure 2, where the total equivalent stiffness and damping are depicted. This visual representation provides clarity in understanding how the mechanical properties are distributed within the flight chain.

III Model Analysis and Lab Characterization

A Model Analysis and estimation

Before conducting the tests, all the characteristic parameters shown in Figure 2 were calculated or estimated, as a first approximation, based on the previously described model and the known data of the flight chain. This preliminary step was undertaken not only to gain familiarity with the problem but also to enable a comparison between theoretical predictions and experimental results.

For the calculation of the stiffness of the nylon cords, the manufacturer provided the diameter and tear strength values. Using this information, the Young's modulus was determined (1).

$$E = \frac{\text{Tear Strength}}{L \cdot A} \quad (1)$$

Where L is the length and A is the rope section area. Then a first calculation of the stiffness (k) was conducted.

$$k = \frac{E \cdot A}{L} \quad (2)$$

The same approach was applied to the parachute. In this case, the Young's modulus was already known; however, it was necessary to define an equivalent area of the fabric that was effectively involved in tension. This adjustment was required because the ropes were attached at only five points on the parachute. Consequently, an equivalent area value equal to 40% of the total parachute area was used. For the ropes, the stiffness was calculated using the same method as for the nylon cords in the previous case. Finally, the total stiffness of the system was determined (3).

$$k_{eq} = (4 \cdot k_{\text{nylon}}^{-1} + k_{\text{parachute}}^{-1} + 10 \cdot k_{\text{cords}}^{-1})^{-1} \quad (3)$$

As mentioned above, the damping coefficient has been assumed to be around 5%.

A preliminary estimation was also conducted for the torsional behaviour of the system. In this case, the greatest contribution was attributed to the four upper nylon cords, which, due to inflation requirements, were arranged 5 cm distant from the centre of the chain. From this it was possible to estimate their torsional coefficient (4).

$$kt_{\text{nylon}} = \frac{4 \cdot k_{\text{nylon}} \cdot d^2}{L_{\text{nylon}}} \quad (4)$$

with d distance from the centre.

Based on these data and the known information, the frequencies for pendulum-like oscillations were estimated using (5),

$$f_{pendulum} = \frac{1}{2\pi} \sqrt{\frac{g}{L_{tot}}} \quad (5)$$

for longitudinal vibration using (6),

$$f_{longitudinal} = \frac{1}{2\pi} \sqrt{\frac{k_{eq}}{m_{payload}}} \quad (6)$$

and for torsional oscillations using (7).

$$f_{torsional} = \frac{1}{2\pi} \sqrt{\frac{kt_{nylon}}{m_{payload}}} \quad (7)$$

In addition to the laboratory calculations, a quick experimental comparison was made by applying a force of 50 N to the four nylon ropes. The elongation measured was approximately 10 mm. Then applying Hooke's classic formula (8) a k of 1250 N/m was obtained, in line with previous calculations.

$$k = \frac{Force}{Elongation} \quad (8)$$

The results of the calculations (with consequent determination of frequencies) are summarized in Table II.

Table II: Model analysis results.

k	k_{nylon}	1125	± 10	N/m
	k_{parachute}	1.571 1e4	± 10	N/m
	k_{cords}	1.473 1e6	± 10	N/m
	k_{tot}	1.049 1e3	± 0.10	N/m
	kt_{nylon}^a	3.516	± 0.10	N·m/rad
f	f_{pendulum}	0.315	± 0.20	Hz
	f_{longitudinal}	3.475	± 0.20	Hz
	f_{torsional}	0.201	± 0.20	Hz

a. Torsional

B Laboratory Characterization of Flight Chain

Following the estimations, laboratory tests were conducted by setting up the flight chain and isolating the three previously mentioned motions:

- Pendulum-like oscillation, induced by forcing the movement along two axes;
- Torsional oscillation, achieved by twisting the payload and then releasing it;
- Longitudinal vibration, generated by applying slight downward tugs and then allowing the system to return to its equilibrium position.

As previously mentioned, Inertial Measurement Units (IMUs) were installed both at the balloon attachment point and at the payload interface. Synchronisation of the two IMUs is possible by means of controlled shocks to the system and easily identified during data analysis as ‘trigger

moments'. This setup enabled the collection of acceleration data for the configurations described earlier. Figures 3 through 10 display the results obtained from the accelerometers and rate gyros during the test session. Figures 3 and 4 present the data collected on all three axes over the entire duration of the test. These data were then isolated in Figures 5, 7, and 9 to highlight longitudinal vibrations, pendulum-like oscillations, and torsional oscillations, respectively.

In Figures 6, 8, and 10, the FFTs of the corresponding time windows were calculated, revealing the dominant frequencies for each type of motion.

Regarding the calculation of the damping ratio for the flight chain, this was determined using the logarithmic decrement formula (9).

$$\delta = \frac{1}{n} \ln \left(\frac{x_1}{x_{n+1}} \right) \quad (9)$$

where x_1 is the first peak taken into account and x_{n+1} the last one. The damping ratio is then obtained (10).

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \quad (10)$$

Obviously, taking more peaks into account results in an increase in accuracy both because of the calculation over a longer interval and because it reduces possible experimental errors and the effect of noise in general.

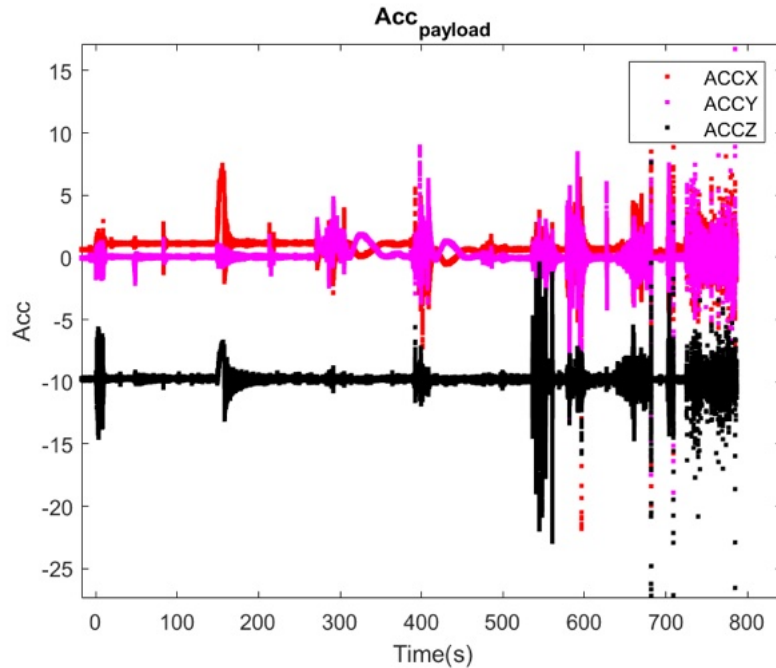


Figure 3: All accelerometer data collected during the test session are presented in this figure. The intervals between steps have been introduced to facilitate the identification of different areas of interest and to allow for their individual analysis.

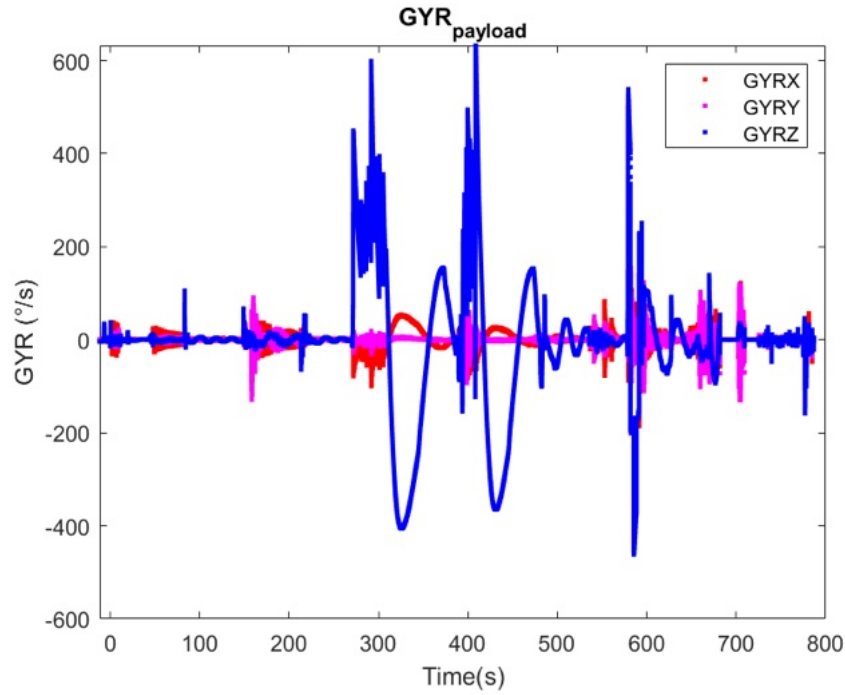


Figure 4: As in the previous figure, this time the data on all three axes are shown for the gyroscopes (rate gyros), covering the entire duration of the laboratory test (approximately ten minutes).

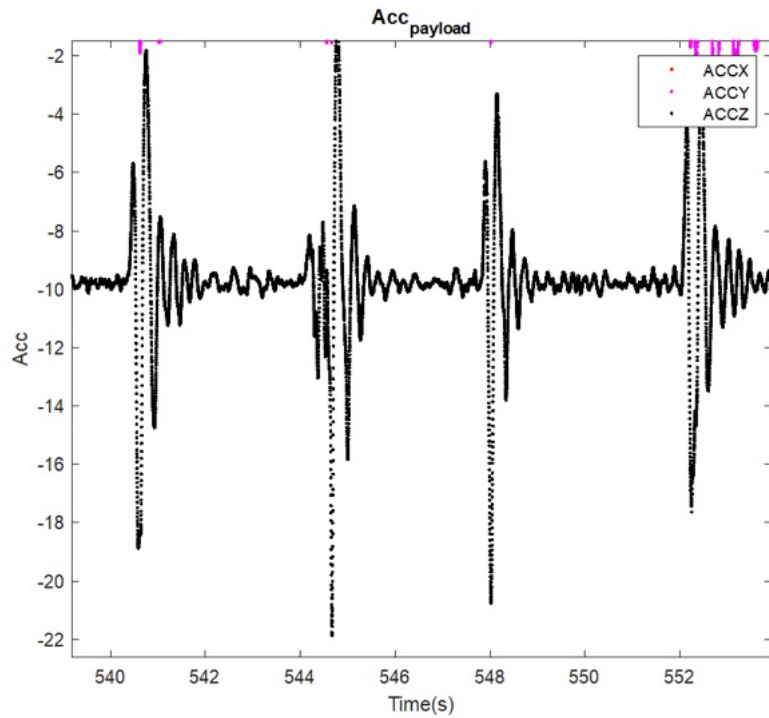


Figure 5: By isolating the section of the graph in Figure 3 corresponding to this known interval, the longitudinal vibration of the payload can be observed, as illustrated in this figure. This focused analysis provides a clearer representation of the dynamic behavior specific to this mode of oscillation.

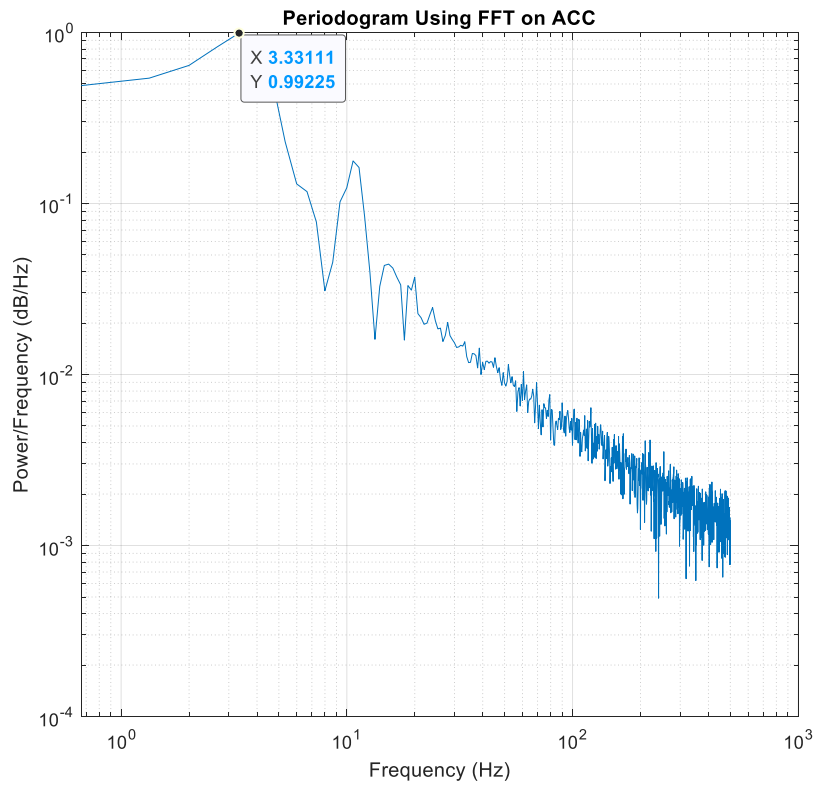


Figure 6: By applying the Fast Fourier Transform (FFT) to the longitudinal data, the resonance frequency was identified. As shown in the figure, the dominant frequency component corresponds to a resonance frequency of approximately 3.33 Hz.

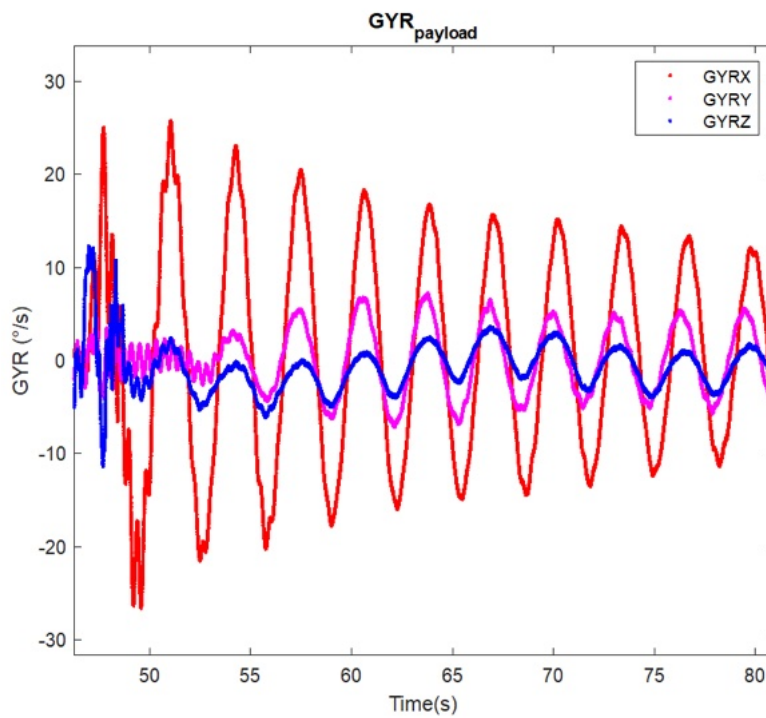


Figure 7: By isolating the section of the graph in Figure 3 corresponding to this known interval, the pendulum motion of the payload can be observed, as illustrated in this figure.

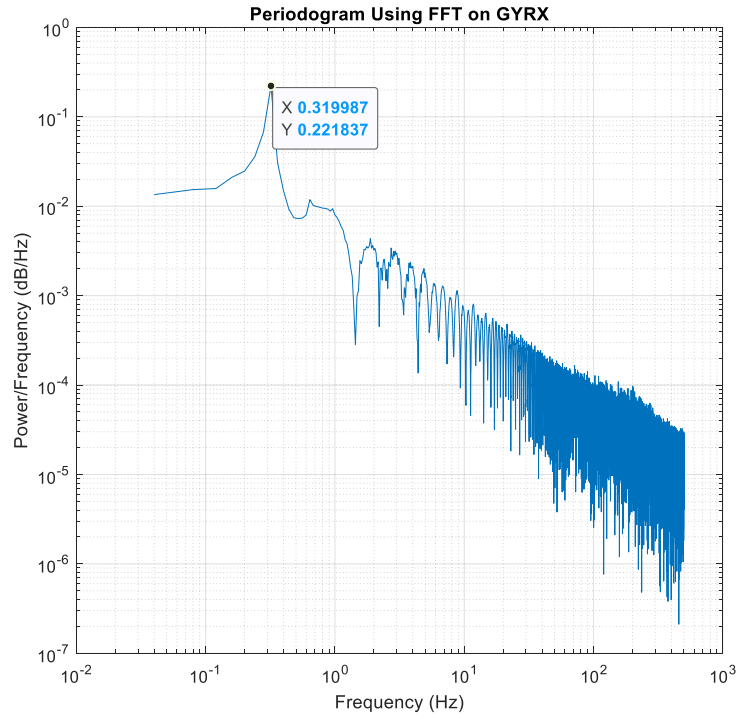


Figure 8: As with the longitudinal motion, the FFT was applied to the pendulum motion data, revealing a dominant frequency of 0.31 Hz, as shown in the graph.

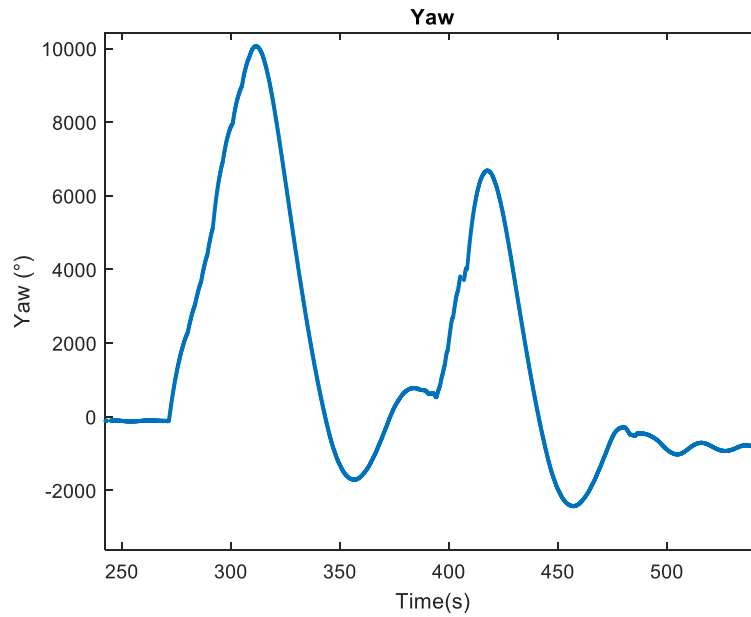


Figure 9: By isolating the time window corresponding to the torsional phase, the observed motion is presented in this figure.

The results obtained during the tests are summarised in Table III, where the calculated damping ratio is also presented. However, each of the 3 movements was repeated several times before moving on to the next one in order to create a data pool that would allow an average and uncertainty to be derived for the different values.

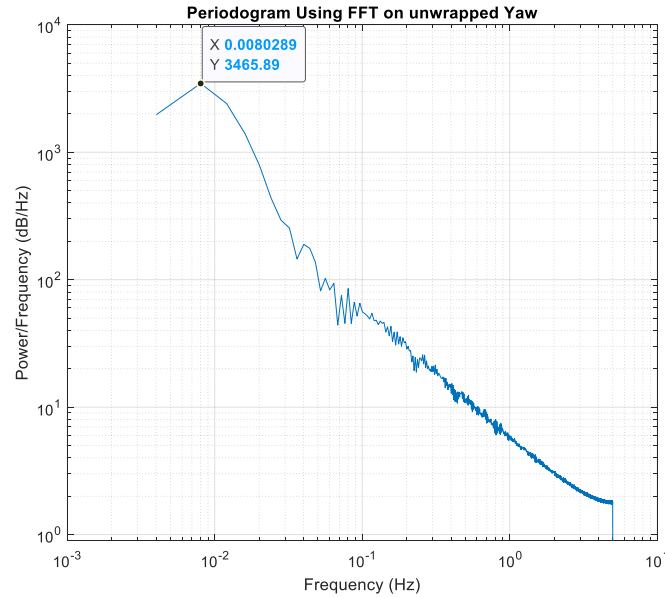


Figure 10: As with the other cases, the FFT was applied to the torsional motion data, revealing a dominant frequency of 0.08 Hz.

In addition to analyzing the three studied motions, in the last part of the test window (Figure 3), the flight chain was subjected to a random and coupled movement designed to simulate, to some extent, the potential oscillations and pendulum-like dynamics experienced during stratospheric flight. This final test serves as a foundation for completing the characterization prior to launch and will provide a basis for subsequent comparisons with flight data.

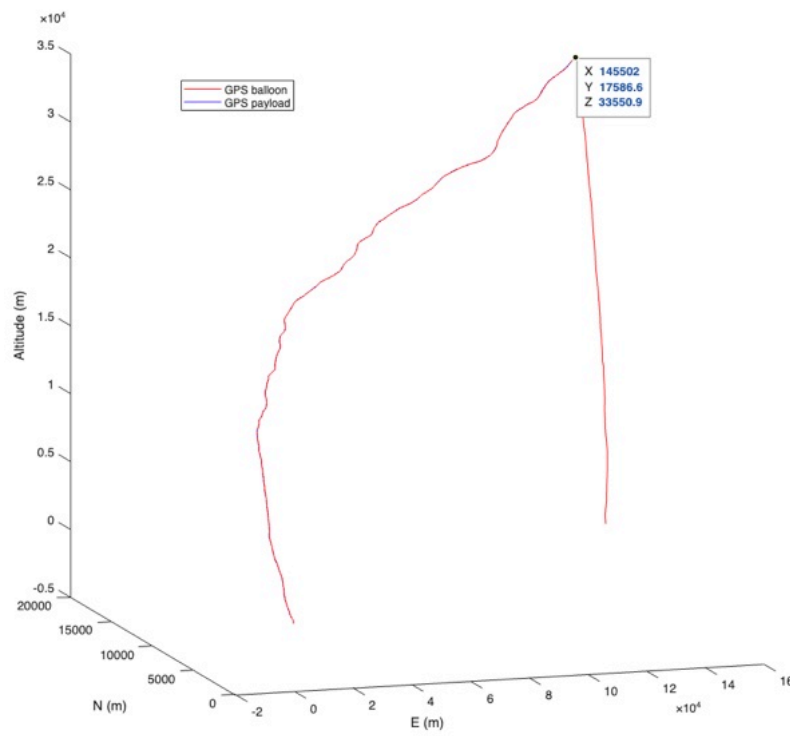


Figure 11: Balloon Trajectory: This graph shows the trajectory of the ball recorded by the two GPSs; the traces are obviously superimposed. On the x-axis you can see the m travelled to the

east, on the y-axis the metres travelled to the north and finally on the z-axis the metres in altitude

Table III: Characterization Results

c	ζ	0.066 ± 0.001
f	f_{pendulum}	$0.314 \pm 0.015 \text{ Hz}$
	$f_{\text{longitudinal}}$	$3.15 \pm 0.15 \text{ Hz}$
	$f_{\text{torsional}}$	$0.08 \text{ Hz} \pm 0.15 \text{ Hz}$

C Flight First Results

On December 12, 2024, the payload was launched from Livorno, Tuscany, Italy, using the same flight chain configuration previously described. As outlined in the system description, the chain was equipped with two Pixhawk units, enabling the study of differential dynamics between the two inertial platforms (balloon and payload). This analysis will be further explored in the coming months.

Currently, trajectory data from the flight are available and will allow the research team to conduct a more detailed study of wind dynamics and their interaction with both the balloon and its payload. Figure 11 illustrate the displacements of the balloon, along with the altitude reached during the flight. It can be seen that the altitude reached is over 33 km and laterally the balloon moved almost 150 km to the east (in fact the recovery site was very close to the Italian east coast). These data provide an essential foundation for understanding the environmental forces acting on the system during stratospheric missions.

IV Conclusions

The data collected during the tests were sufficient to perform an initial characterization of the flight chain. The first-approximation frequencies derived from the model proved to be reasonably close to the actual values, making this work valuable to the scientific community as it provides insights into the dynamics of the flight chain even in the early stages of calculation. Furthermore, the approach described in this study is notably innovative, as this type of dynamic analysis has limited prior data and few comparisons with real flights. The only deviation observed pertains to the torsional oscillation, which is inherently challenging to predict. This discrepancy suggests that additional factors may need to be considered, as the proposed simplification appears to be insufficiently accurate for modeling this type of motion.

Certainly, a model such as the one shown here can present risky simplifications when one wants to use such data for very advanced instrumentation. However, as a first analysis, as there are no similar studies in the literature, it is a good step forward. Other studies focus on post-flight analyses, but even these are few in number and do not target chain dynamics but rather ball dynamics [7].

As for the flight data, these will be refined and analyzed in greater detail in the coming months. Plans are underway to conduct similar studies, expanding upon the findings presented in this work.

Acknowledgements The experiments were conducted at the facilities of the CISAS G. Colombo (Centre for Space Studies at the University of Padova). A special thanks to the colleagues of the University of Pisa in the Space Systems group for providing technical and logistical support during the balloon launch operations. Finally, a mention to the students of the SUNFLOWER innovative project of the DII (Department of Industrial Engineering) of the University of Padova, for their support during the launch and especially recovery phases.

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6. Paper V: Miniaturization Application

Role in the research project: *Team Manager*

Paper Contribution: *Drafting of introductory and connecting parts between chapters, main revision, CRYSTALS payload Advisor, corresponding Author.*

This chapter presents the fifth scientific paper contributing to the thesis, focusing on the development and application of miniaturized aerospace systems for multifaceted space missions with an emphasis on Earth observation and environmental sustainability. While the core of this research centres on atmospheric and terrestrial monitoring using modular payloads on drones and balloons, the scope naturally extends to compact satellite platforms, exemplified by the J2050 PocketQube initiative.

This extension reflects the interdisciplinary and technology-driven nature of the work, where advances in miniaturization, integration, and mission design converge to enable versatile environmental sensing solutions spanning from near-Earth atmospheric layers to low Earth orbit. The platform developed incorporates innovative optical sensing and attitude determination technologies, crafted to meet both scientific and engineering objectives with cost-effectiveness and scalability in mind.

An important dimension of this work is its alignment with broader environmental preservation goals. By advancing tools that enable precise Earth monitoring and careful assessment of the orbital environment, the research contributes indirectly to sustaining the near-Earth space habitat—complementing terrestrial environmental efforts with responsible space stewardship. This perspective resonates with the overarching motivation of the thesis to foster sustainable aerospace technologies supporting comprehensive environmental understanding.

The contribution also retains strong ties to the thesis’s central themes of flight dynamics and trajectory optimization. Although orbital missions introduce distinct physical regimes compared to atmospheric platforms, the principles of dynamic behavior, robust attitude control, and precision mission planning remain pivotal to achieving scientific and operational success. Lessons derived from atmospheric payload dynamics inform design and operational strategies for these miniaturized orbital systems, underscoring the synergy between different aerospace domains in the thesis.

Overall, this chapter situates the miniaturized satellite platform as both a logical continuation and an expansion of the research line, reinforcing the thesis’s vision of integrated, scalable, low-cost and environmentally mindful aerospace technologies for Earth observation and sustainable space operations.

The J2050 student PocketQube for space debris investigation and optical observation technology development

Federico Toson, Giacomo Porcarelli, Greta Rosa, Lorenzo Olivieri, Giacomo Colombatti [4]

Abstract

Among the main trends of the new space economy, miniaturisation makes it possible to build mass-produced or customised spacecraft at a reduced price compared to older technologies; it encourages technological innovation, as in-space technology demonstrations are easier in cost, design, and legal and compliance aspects.

In this context, the J2050 project has been selected by the European Space Agency to develop and launch their 2p PocketQube in the framework of the 4th cycle of the hands-on “Fly Your Satellite!” programme; this is the first cycle that included the possibility to launch fractions of CubeSats. The current PocketQube configuration includes three main payloads: a miniaturised debris detector, an optical dimming system for cameras and telescopes, and a system for attitude determination and pointing consisting of LEDs and photodiodes. The three payloads will be integrated on board a platform fully designed and produced by the students, from electronic boards to the software and mechanical interfaces. This will also enable the team to achieve its main educational goal, preparing the next generation of space engineers.

In this paper, the specifics of the PocketQube, the design process, the resource management aspect, manufacturing, integration, testing, and outreach activities undertaken by the team will be described.

1 Introduction

With the new space economy trend, miniaturization turns out to be a key tool to reduce the mission failure, cost and pollution impact (on Earth and in orbit) of a satellite. For this reason, year after year, there are more and more constellations of small and medium-sized satellites, cooperating and non-cooperating, with objectives ranging from collection to information exchange with a marked improvement in safety, environmental management, and the orbiting technology network [1-2].

In this context, access to space has also been made possible by small and medium-sized investors but, above all, by researchers and students. In fact, space agencies, such as the ESA (European Space Agency), rely heavily on interdisciplinary training in space, and, with so-called “Hands-on” activities, bring students and young researchers to design and implement small space missions.

In general, the involvement of educational institutions has resulted in the growth of the space community and the emergence of many student teams with ambitions related to putting innovative technologies into orbit.

As mentioned above, the trend in the new space economy is increasingly moving towards smaller satellites that can be rapidly developed and launched. PocketQubes, due to their small size (5 x 5 x 5 cm per unit), align with this trend and offer cost-effective opportunities for

training and technology validation. They have lower costs for development, production, launch, and operations [1]. PocketQubes are effective demonstrators of new technologies and payloads that can later be implemented in larger, more complex satellites. The small size of PocketQubes encourages innovation and experimentation in satellite design and mission concepts; while simplifications make it possible to design and produce a workable satellite at low cost [2].

It was from this very premise that J2050, a team from the University of Padova, was born, with the primary goal of growing and educating the students through the construction of a PocketQube, a 5 x 5 x 10 cm satellite.

The team is currently composed of students from different departments, at different levels of education (bachelor, master, PhD) and it is supported by professionals, researchers, and professors of the Department of Industrial Engineering. This project aims to include students from other faculties and institutions or early-career professionals to build a variegated and interdisciplinary team. J2050 wants to be the first student team from the University of Padova to launch a satellite into orbit.

The picosatellite is named "RedPill" (for its tiny size and the university's pantone colour, red), and after only five months of work, it was selected as one of three European teams for ESA's "Fly Your Satellite! 4" programme. RedPill aims to demonstrate three different technologies, with the following main objectives:

1. study the feasibility of non-mechanical space telescope covers.
2. collect in-situ measurements of the sub-mm space debris environment in LEO (Low Earth Orbits).
3. assess satellite tracking and attitude determination methods through observations of LEDs from ground and with on-board photodiodes data.

For each objective, the spacecraft will include a dedicated payload: CRYSTALS (Chromatic, Yielding, and Smart Technologies for Anti-Light Shielding), CLOUD (Classifying Orbital Undetectable Debris) and CLEAR (Compact LEDs and Attitude Reconstruction). These three payloads are the result of students' ideas, which in some cases are inspired by the heritage of the University of Padova's research groups.

With CRYSTALS, J2050 aims to develop non-mechanical covers for space telescopes. Current technologies for protecting space telescopes involve mechanical covers, which present several challenges and risk of failures during operations [3-4]. One of the main problems with these mechanisms is deployment and folding. Space telescopes are often launched folded and must deploy their covers once in space. The unfolding mechanism must be reliable and precise to ensure the cover unfolds as planned without a hitch [5]. Folding the cover for deployment and ensuring it's stowed compactly is also challenging.

In short, this new technology involves a device that uses an electrolyte that can darken and then become transparent again, thanks to a chemical reduction process when a voltage is applied. In this way, the telescope can be protected from solar rays when CRYSTALS is in dark mode and can observe space when the electrolyte is transparent during observation mode. This new telescope cover concept aims to have much lower failure rates than the mechanical telescope

covers on the market today and those currently used in orbiting telescopes. Deployment-related failure is practically non-existent as the system will be already integrated into its final configuration before launch. Therefore, it does not require mechanical folding and unfolding during telescope operations, eliminating additional failure risks during the system's operational life. At the same time, it will offer all the properties and characteristics that space telescope covers must have. To ensure the device is functioning correctly, both a camera and photodiode will be integrated behind CRYSTALS to measure its performance.

As for CLOUD, Space debris represent a critical hazard for space missions [6]; while ground tracking allows the continuous monitoring of objects larger than 1 cm in LEO [7]. However, since the population of small debris is not observable from the ground, it is essential to carry out in-situ measurements [8] to validate the debris environment models [9]. For this reason, the payload consists of a debris sensor mounted on board of the PocketQube. Its objective is to measure the number of impacts with small debris (sub-mm size range). To achieve this, the team is working alongside the Alba CubeSat university team [10-12] to develop and manufacture a miniaturised impact sensor suitable for 2P picosatellites that will be placed on the +Y and -Y face of the satellite (where solar panels do not cover the surface). In addition to the scientific outcome, this payload will allow validating the sensor technology and increasing its TRL (Technology Readiness Level), with the final goal of obtaining a sensor board that could be easily scaled and adapted to a large number of space missions.

CLEAR is payload born from the necessity to better track nano and picosatellites in space. The increasing number of small satellite cluster launches [13] leads to a greater risk of confusion and collision after deployment [14]. This calls for further enhancement of space surveillance capabilities. The team's main aim is to develop and launch a PocketQube equipped with LEDs for optical tracking with ground-based telescopes [15]. By having LEDs as an on-board payload to actively illuminate the satellite the number of passes in which the satellite is visible with ground-based telescopes is higher. Thus, it is possible to increase the accuracy and the precision of tracking objects in LEO (Low Earth Orbit), as already demonstrated by the LEDSAT CubeSat team of the University of Roma "La Sapienza" [16]. On the satellite, the utilisation of different colours and pulse periods with the LEDs on the spacecraft faces will allow the determination of its attitude during the observation and, in case of tumbling, its rotation rate. In addition, photodiodes will be installed on the spacecraft to determine the direction of solar and/or albedo radiation, to evaluate the possibility to reconstruct the spacecraft attitude with such low-cost sensors [17-18]. While on-board attitude determination will not be used to determine which LEDs to switch on, it is expected to employ such information to validate ground observations.

The data collected by the technical experiments performed during the mission will contribute to the technology development of space payloads; in addition, it will enrich the current knowledge of the space environment and will support research activities currently carried out within the University of Padova. The data produced by a successful mission will vary for each payload.

In addition to the achievement of these mission objectives, it will also be considered successful and worth of producing technical advancements and academic return:

1. The proper functioning of the PocketQube during the operational period.
2. The correct attitude achieved by the permanent magnets on board the satellite.
3. The successful communication with the ground station to perform uplink and downlink with the LoRa technology.
4. The re-entry within the timeframe envisaged by calculations and compatibility with the ESA Space Debris Mitigation Requirements.

A secondary technical objective of the J2050 project is to validate the design of a PocketQube bus for future mission launches using the acquired heritage. The aim is to validate the self-developed design, specifically for the OBC (On-Board Computer), EPS (Electric and Power System), and other subsystems, which occupy less than one unit of the two used without the Payloads. This will provide other possible PocketQubes, not only from the University of Padova but also from other universities, with access to a tested and qualified design at a low cost.

In the remainder of this paper, the technical features of RedPill and its potential will be described in detail, starting with the satellite's layout and mission objectives, and ending with the team's technical and educational return.

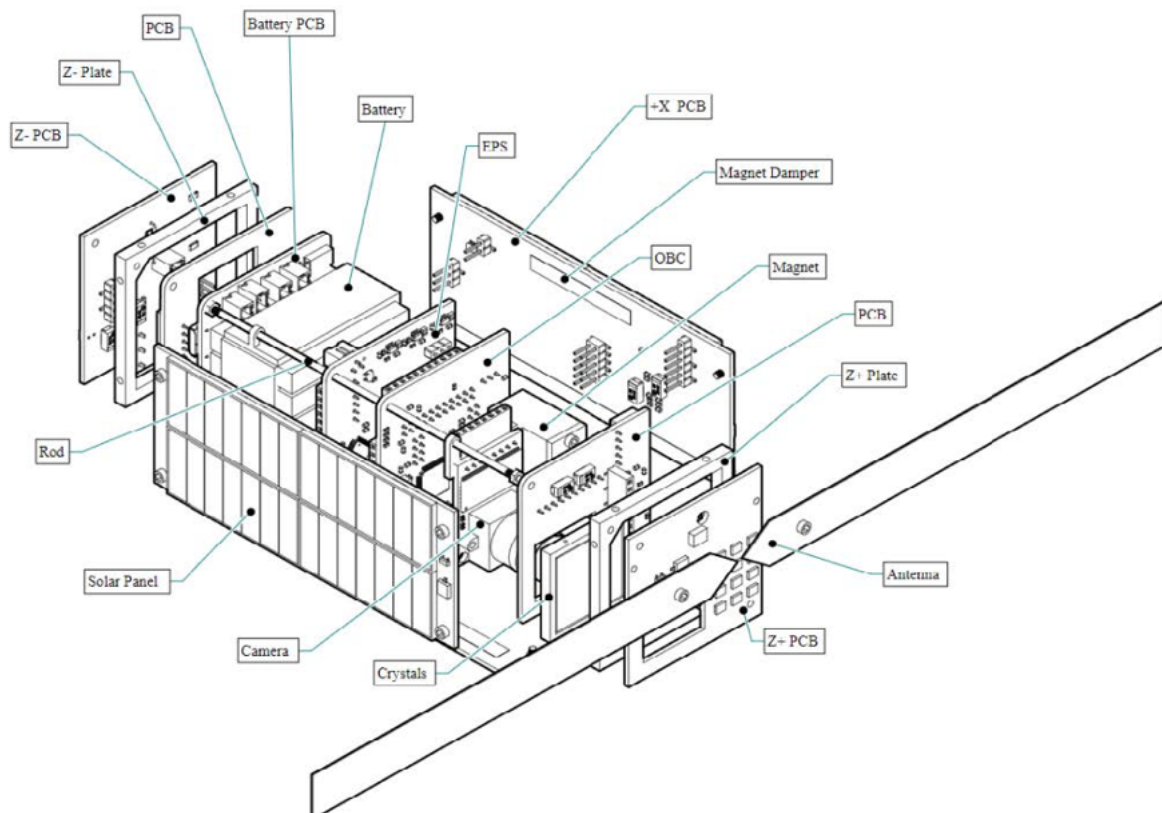


Figure 1: global overview of RedPill satellite.

2 Satellite Layout and Mission Profile

For the satellite, the team chose a 2P form factor PocketQube (5 x 5 x 10 cm). The PocketQube's layout is designed to optimize efficiency, compactness, and functionality within the constraints of its small form factor, enabling a wide range of space missions despite limited size and resources. The RedPill PocketQube is built using mostly COTS components for the bus and the three on-board payloads, and the architecture of the standard 2P platform includes all necessary subsystems. The bus is based on the design in Figure 1; its main functional tasks are summarized in the following list:

1. Supporting payloads in terms of structural rigidity, power, and data handling.
2. To power the satellite subsystems through solar panels and batteries.
3. To collect payload data, such as the conditions of the stripes that compose the space debris sensors, photodiode data, and CRYSTALS data.
4. To transmit the temperatures of the batteries and the external surfaces of the PocketQube.
5. To accomplish autonomously simple task to prevent system failure (ex. thermal control and power distribution).

The bus is provided with AOCS (Attitude and Orbit Control System), EPS, OBDH (On Board Data Handling), a dedicated OBSW (On-Board Software), the Telemetry, TT&C (Tracking and Command) and thermal control. A propulsion system is not required to fulfil the mission goals.

With respect to the payloads, their main characteristics are listed below. CRYSTALS is a prototype of a device that functions as a non-mechanical space telescope cover. The design was completely developed in-house and will be manufactured in the chemistry laboratories of the DII (Department of Industrial Engineering). CLOUD is an impact sensor that will be placed on one of the outer faces of the satellite. It will count the number of debris impacting the spacecraft. The University of Padova has a strong background in this field, with several impact sensor prototypes already evaluated and under calibration in the CISAS hypervelocity impact laboratory. Last, CLEAR consists of several COTS LEDs placed on the faces of the PocketQube. These LEDs are used to collect data on the satellite's position and attitude with ground telescopes. Photodiodes will also be strategically placed to on board assess the satellite's attitude and cross-validate the ground reconstruction. For the CLEAR payload, a site for ground-based observations has been preliminarily identified in the Asiago Observatory. Chapter 3 will cover the detailed design of the satellite and its payloads.



Figure 2: workflow schedule of the mission phases.

As shown in Figure 2 the team has identified 3 mission phases: Launch and Early Orbit Phase (LEOP), Operations and Decommission.

2.1 LEOP

During the LEOP phase, the spacecraft will be commissioned into orbit, and it will be prepared for nominal operations. The phase is further subdivided in sub-phases, tracing the development of the mission.

- **Launch:**
This procedure is expected to last for some hours (TBC); during this phase all the satellite subsystems shall be turned off.
- **Orbit Insertion:**
After the in-orbit delivery, the OBC and EPS subsystems are activated, and start the boot-up sequence. In addition, the passive AOCS starts the detumbling process to lower the rotational rate of the PocketQube. Payloads are not active during this phase. After a little over 30 minutes the antenna is deployed and after 45 minutes radio communications in the form of a beacon begin.
- **Find the Satellite:**
PQ (PocketQube) tracking is determined by TinyGS network [19], vital values are assessed from received beacons.
- **Asses of Functionality:**
After the satellite's actual orbit is assessed and first communications with the GS UniPD (University of Padova) are established, a series of extensive tests are done to further validate PQ status and detumbling status. After that payloads will be activated to reach operation readiness.

2.2 Operations

This phase will be initiated once all the subphases of LEOP are successfully completed. During the Operations phase, the spacecraft will be fully operational into orbit performing its main mission tasks. It will collect scientific data, activate, and run the payloads and perform PDTs (Payload Data Transfer). The phase is further subdivided in sub-phases, to accomplish the objective of the mission:

- **Scientific Data Collection:**
During this phase, all the functional and performance requirements of the payloads will be executed. All data collected will be downloaded and analysed by the GS UniPD at the University of Padova.
- **Outreach and Scientific Data Collection:**
Once enough data has been collected for the scientific purpose of the mission, the Outreach phase commences. It is noteworthy that scientific experiments are planned to be conducted during this phase as well, aiming to fulfil the performance requirements of CLOUD and validate the PQ Bus by assessing its behaviour over an extended orbit time.

2.3 Decomission

During this phase all payloads and instruments of the satellite will be switched off and the ability of the battery to recharge via solar cell will be inhibited thus leading to battery depletion. The programmed duration of the mission is 1.5 years. J2050, thanks to the support of the University of Padova, doesn't rule out investing more effort and resources in prolonging the mission (and thus further developing the outreach purpose and CLOUD performance) until re-entry.

More precisely, the mission is designed through operational phases and follows a series of steps to ensure that the mission tasks are performed correctly. During LEOP, the satellite follows the start-up procedures and remains under observation for two weeks without performing any major activities. The system's vital values are verified and, thanks to the TinyGS network, the satellite's position in its current orbit is estimated; the time parameters on board are also synchronized with GS (Ground Station) UniPD. The next LEOP phase, which will also last two weeks, will verify the values of on-board thermal sensors and accelerometers, carry out preliminary tests to ensure the collection of data during payload operations, analyse the performance of the infrastructure and verify the status of detumbling. Payload tasks are performed in the Operations phase by means of GS commands. Satellite activities are managed by “operational states”. The operational states, battery management and software architecture are managed autonomously by the OBSW, leaving the payload executions to be activated by a software alias sent by the GS UniPD.

In order to study the orbital behaviour of the mission and select the most suitable orbits to achieve the mission objectives, a MATLAB script has been developed and specific software has been used. The MATLAB scripts use the GMAT API to simulate multiple orbits (iterating on the orbital elements) and output the average data exchanged with the GS UniPD. In future development, this MATLAB will be integrated with the AOCS simulation to evaluate the performance of passive magnetic attitude determination in the chosen orbit. The de-orbiting time is assessed using the DAS software. Airbus SYSTEMA was also used to evaluate the performance of CLOUD on several orbits and all the results were taken into account in the analysis.

3 *Satellite Design*

The design phase involved several students from the J2050 team who had the chance to apply what they learned during their years of study. The main design philosophy was to create a versatile and sufficiently reliable bus that, once validated through the RedPill mission, can be reused to carry other payloads into orbit at a relatively low cost, thus facilitating access to space for innovative payloads and technologies.

Following a literature review of the state of the art of PocketQubes, a stack design with 2 M3 bars and supports in the Z+ and Z- faces was chosen to ensure a sturdy structure. All faces of the PQ and internal layers are made of in-house designed PCB (FR4 material) mounted on the aforementioned structure. Vibrational and stress analyses were conducted to ensure that the satellite could withstand launch loads. Shake tests are also planned.

Regarding energy management, the PQ is equipped with a LiPo battery accumulator that has a capacity of up to 15 Wh. The accumulator is recharged by solar panels, which are widely available. These decreases lead times and speeds up the prototyping process. The solar panels can nominally recharge 400 mWh per orbit. This production is suitable for the RedPill mission because it allows for a positive energy balance over several orbits, even when considering the power consumption of various subsystems with safety margin.

In future missions, power generation can be increased by adding solar panels to the faces currently occupied by CLOUD or by purchasing solar panels with higher efficiency and longer lead times.

Regarding the OBC and EPS, which are the two processors on board the PQ, microprocessors with flight heritage and low power consumption were chosen: in particular, the STM32L5 processor was chosen for the OBC and the STM32L1 processor for the EPS.

For the digital communication between the various subsystems, SPI (serial peripheral interface) was chosen as the communication protocol since, according to a literature study, it proved to be the most reliable and requires the least power.

These two boards have been equipped with several features: the EPS is able to manage the battery charge and monitor all the battery parameters, sending warnings about the status of the battery to the OBC when necessary. the OBC collects data from all the payloads and manages the power distribution within the satellite. it is also equipped with an IMU and can read different analogue signals, which makes it very versatile.

3.1 CLOUD

The aim of the CLOUD payload (Figure 3) is to validate the sub-mm debris environment models in LEO orbits [20]. A different version of the sensor has been first developed by Alba CubeSat UniPD [10-12], a student project based in the University of Padova, to be hosted on a CubeSat 2U. The same payload idea will be modified to be integrated in the 2P PocketQube. As of now the design of the debris sensor is at TRL 4 level thanks to the technology heritage inherited by AlbaCube Sat.

The experimental concept consists of 16 copper stripes integrated in the PCB schematics that, if struck by debris, could be ruptured. This rupture will be detected by the ADC (Analog to Digital Converter) and communicated via SPI to the OBC. It follows that the maximum number of detected impacts is 16 (one for every stripe). Stripes are designed to be 0.080 mm wide (as tight as possible for the PCB manufacturing process) spaced 0.2 mm between each other and arranged in a spiral configuration to ensure minimum sensible area loss after a stripe breach. Two CLOUD devices are placed in the +Y e -Y faces of the PQ, the total sensible area is 2400 mm² on the +Y face and 3500 mm² on the -Y face.

3.2 CLEAR

The CLEAR payload (Figure 4) is composed by LEDs mounted on the satellite (whose task is to make the system visible from Earth and to help reconstruct the attitude) organised in two, 12-LEDs arrays placed on the +Z, -Z faces of the satellite (i.e. the faces pointing towards the

Earth). Since the LEDs must perform a particular application which imposed high-efficiency, high-power requirements, the choice fell to LUXEON 2835 Colour Line LEDs. Concerning attitude determination through photodiodes, a method whose effectiveness has been widely proved in literature has been selected [18]. One photodiode has been installed on each PQ's face. Since photodiodes generate a current proportional to the light incident angle's cosine, by collecting the current signals from every face it is possible to estimate the precise orientation of the PocketQube relative to the Sun. Thus, a transimpedance amplifier is required to manipulate the analog signal to be read by the 10-bit μC OBC ADC with the correct accuracy. Additionally, a voltage buffer is in series with the transimpedance amplifier. The analog circuit was designed using 1800 W/m^2 as the peak light intensity (obtained using a safety factor on the solar peak light intensity and Earth albedo). The following steps consist of developing a Kalman filter to elaborate the collected data, especially to filter the Earth albedo disturbance. The CLEAR payload will also be crucial in attitude determination and in investigating the efficiency of the passive method for PocketQubes attitude control. Not an easy challenge that fortunately has varied analyses in the literature [21-28].



Figure 3: photo of CLOUD payload PCB.

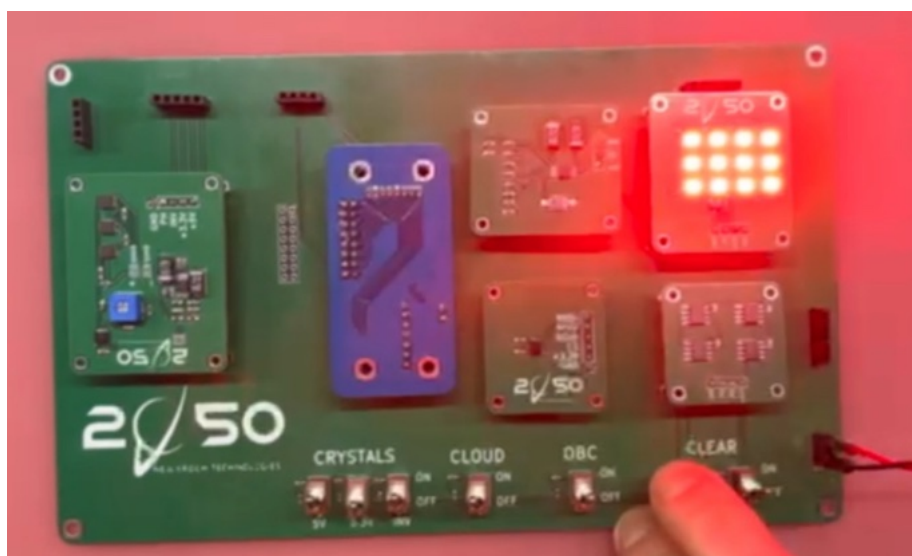


Figure 4: CLEAR payload LEDs in function on the FlatSat model.

3.3 CRYSTALS

CRYSTALS, as mentioned before is an innovative alternative to current telescope dimming mechanisms. The design of this instrument was among the most complex of the PocketQube being something that has never been done in the space environment and especially in such a small size. Taking a cue from the literature [29-31], several design solutions were tested, all involving ITO (Indium Tin Oxide) glass, i.e. conductive glass, an electrolyte (gelatinous and colourless, with metal salts dissolved in it) and an electrode.

The operating principle involves darkening and brightening of the ITO glass due to the deposition of dissolved metallic material in the electrolyte gel. This is possible by placing the gel between the ITO glass and the electrode; by applying a positive and negative potential difference between them, metal deposition or its solubilization in the gel is possible. Different recipes are still being tested as electrolytes and will be described in forthcoming work; for this reason, no gel preparation information is presented in this article. Depending on the direction of the potential difference, it is possible to control the darkening and brightening of the glass. The latest version (shown in Figure 6) utilises two ITO glasses on either side of the device, which act as the outermost layer of a 'sandwich' that has two PCBs inside, which enable the ITO glasses to be energised and which distance and insulate them from the electrode, which is in the inner layer. The whole device is filled with electrolyte gel. The device is watertight because both for bonding where there is electrical conduction and for other fixings, space-age epoxy glues (such as silver epoxy) are used. The points from which the current flows are the screws, which, being through all thickness of CRYSTALS, give current to both the internal electrode and the two ITO glasses. In this way, the design is truly compact and manageable, simple to integrate and put into operation.

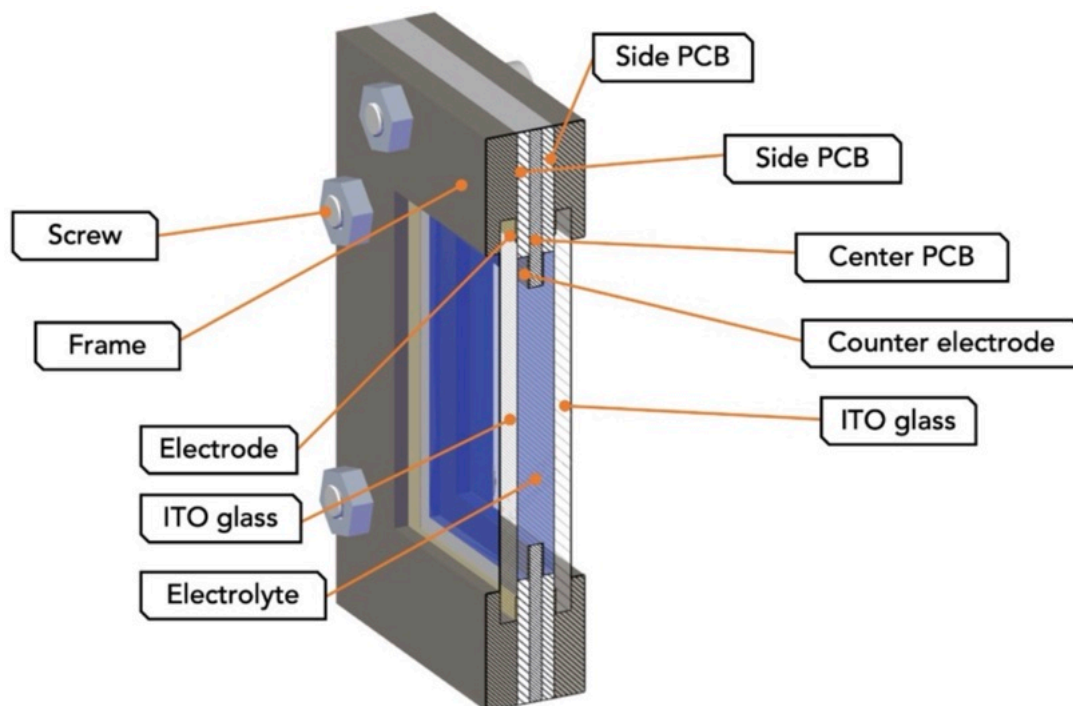


Figure 5: CRYSTALS 3D section with components overview.

The RedPill mission requires control of orbital positioning to ensure that the system, consisting of CRYSTALS and the camera, is pointing towards Earth. However, it is not necessary for the system to always be directed towards a specific point. The AOCS will only provide the required pointing accuracy and stability to ensure that, once the system is stabilised, the camera points towards Earth during different mission phases, and that the TT&C subsystem can receive and transmit data. Attitude control will be required for the satellite to detumble after deployment and for potential impact with space debris. Environmental torques acting on the satellite are estimated to be in the order of magnitude of 10^{-4} Nm, considering worst cases relative to the gravity gradient, magnetic, solar radiation, and aerodynamic effects. This estimation is valid at 450 km of altitude, and lower disturbances have been found for higher altitudes. Throughout the mission requirement definition and analysis phase, various AOCS solutions were compared based on their performance, compliance with requirements, and their mass, power, and envelope budgets. The AOCS will adopt a passive configuration, with the AOCS unit utilising COTS components, featuring a set of three stacked permanent magnets positioned along the X axis. The AOCS comprises three permanent neodymium magnets, N45 graded, stacked on top of each other. These magnets will be positioned inside the PocketQube so that their magnetic field is aligned parallel to the Earth's magnetic field (in the magnet's reference system, this will be the X direction). The satellite's internal walls on the +X/-X faces will be equipped with ferromagnetic hysteresis bars perpendicular to the permanent magnets' axis along the longitudinal Z direction. These bars aim to dampen oscillatory motions that may occur due to rotation in the geomagnetic field. The kinetic energy of the satellite is transformed into hysteresis losses through magnetization changes in the bars. A trade-off analysis was conducted, taking into account all potential disturbances affecting the satellite at various altitudes. It was found that the only significant disturbance was the magnetic torque caused by the Earth's magnetic field. Commercially available solutions for both permanent magnets and soft-magnetic hysteresis components were considered. Due to the limited space available inside the PocketQube and the restrictions imposed by other payloads and power systems, the optimal solution was found to be the use of flat, rectangular cross-section permanent magnets placed sideways to the camera, near the face pointing towards the Earth. Various materials and geometries for the soft-magnetic bars were reviewed, as these factors may significantly influence the damping effect. The optimal solution involves using elongated, rectangular, and extremely flat strips made of mu-metal. Although innovative materials such as amorphous Fe-B-Si have shown promise, a more reliable and commonly used material has been selected to minimise risks and avoid in-house production. In future works, the aim is to develop a mathematical model of the hysteresis strips to optimise their positioning. An excessively short distance between them may result in excessive energy losses. Simulations in MATLAB/GMAT/Simulink will be performed to test the system performance.

4 *Approach to Satellite MAIT*

In this section the manufacturing, assembly, integration, and testing process for RedPill is presented. The model philosophy that will be followed during the PocketQube implementation includes three different models: Development Model (DM), Engineering Model (EM), ProtoFlight Model (PFM). This approach allows to keep development and manufacturing costs low and to have relatively fast mission development. The latter is related to the need for the

mission to be ready for the upcoming integration and launch opportunities with ESA. The DM+EM+PFM is used for all the subsystems. For the DM, the AIV focuses on reaching TRL 4 for most components in order to meet functional requirements and subsequent assembly (this starts with Payloads such as CRYSTALS and goes up to entire subsystems such as EPS).

Having reached this level of technology, the second step of AIV of the DM involves testing different configurations to understand how they meet performance requirements. As far as EM is concerned, on the other hand, the AIV also plans to meet dimensional and design requirements, but always in FlatSat format (Figure 6).



Figure 6: FlatSat after first integration.



Figure 7: CISAS's thermo-vacuum chamber with window for exposition to the solar simulator.

After an initial verification step, the functional and performance requirements are again verified to export the model and transform it into the final stack version (PFM).

For all Payloads, the tests and procedures are being developed with the exception of CRYSTALS, which, being an innovative idea within the team, required additional preliminary testing to bring the technology to TRL 4 before Design confirmation. A brief description of the procedures used for CRYSTALS can be found at the end of this Section. Finally, the PFM is to all intents and purposes a flight version of the satellite, but, as mentioned earlier the team evaluates the possibility, if the low production cost is confirmed, to add an FM that will undergo less intensive functional testing. The various qualification tests will be carried out at the laboratories of CISAS G. Colombo (University Centre for Space Studies), which is equipped with thermo-vacuum chambers (example in Figure 7), electrodynamic shakers, and clean rooms. For the technical aspects of PFM verification, all tests in a critical environment will be carried out by means of connections between inside and outside the thermo-vacuum chamber, so as to supply power and communicate with the PocketQube in the event of malfunctions. The use of the solar simulator is carried out in combination with the thermo-vacuum chamber. The mechanical interfaces for vibration tests will be adapted and connected to accelerometers for testing vibration modes in the 3 axes with resonance and random vibration search. The function and performance tests of the payloads will be performed both at subsystems and system level. Tests will be mostly performed at the facilities provided by the University of Padova, inclusive of a shaker for mechanical loads and vibrations from a launch vehicle, a thermo-vacuum chamber for assessing the survivability to the thermal environment typical of low-Earth orbits.

5 Educational Outcome

The activities have enhanced the skills of the students involved. Additionally, education is another important aspect. As stated in the introduction, the objective is to educate students and develop their transversal skills. The training aims to equip participants with the ability to interact with each other, reference figures, and entities outside the university, such as companies or space agencies. This objective is shared with ESA and is one of the pillars of ESA Education and the 'FYS!' Program. To accomplish this, we have defined a precise team structure using a Work Breakdown Structure (WBS). The WBS outlines the lines of work shared among the team, ensuring practical application. The project timeline is summarized in a GANTT chart. The J2050 Team is divided into sub-teams with different applications. This allows for the definition of roles, resulting in accountability of members and development of soft skills such as teamwork, positive interaction, and collaboration. Scheduling is used to transmit the cruciality and importance of deadlines, train students in problem-solving, and teach them to organize their time so as not to find themselves unprepared. The organization of work in general was done following ECSS guidelines, such as those related to management, which also allowed students to become familiar with these standards [32].

The effectiveness of this method became apparent early on. Within a few months, students were able to design, develop, and receive positive feedback for their work in the ESA's 'Fly Your Satellite! 4' programme. Moreover, RedPill being almost entirely "new," the entire production was the result of the team's skills and the synergy established among the various sub-teams. The students involved will have the opportunity to showcase their designs and developments

in thesis papers, scientific reports, conferences, and scientific journals, highlighting their capabilities. This has implications for preparation for the world of work and research, which often relies heavily on young minds who have had the opportunity to experience what they have learned in their university studies.

Additionally, the Outreach sub-team has developed an important aspect of dissemination. Many schools will have the opportunity to interact with the RedPill project and J2050 in general through lectures, workshops, and satellite interactions. The Asiago Observatory, radio amateurs and other entities at the territorial level have offered their support to J2050 in its dissemination and education mission.

6 Conclusions

This paper presented the general overview of the RedPill PocketQube and the description of its bus and payloads. The satellite will provide a simple, functional, and low-cost solution to validate and verify in-orbit technologies for (1) non-mechanical space telescope covers, (2) in-situ sub-millimetric space debris detection, and (3) advanced satellite tracking and attitude reconstruction, both on board and from ground observatories. In addition, the J2050 team continues to pursue the goal of technical and educational training of participants. The team's achievements in both areas have been confirmed through its participation in ESA's 'Fly Your Satellite! 4' program. The team members are constantly developing their soft skills by learning to handle tight schedules, various problems, and relationships with stakeholders, supervisors, and external agencies and companies through their work on RedPill.

The design of the picosatellite is solid and will be refined in 2024, in preparation for a potential launch window as early as 2025. The team's strength lies in the originality and innovation of the payloads on board. They aim to continue testing innovative technologies in the future, not limiting themselves to producing only RedPill. Regarding CRYSTALS, the team plans to continue developing it as a dimming alternative for larger telescopes if the technology proves successful.

The experiment was successful in terms of broadcasting and school outreach, which proved to be an engaging and functional strategy for developing an aware, responsible, and growing scientific community.

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8. General Discussion and Synthesis

The preceding work has demonstrated ATEMO’s capability as a modular, scalable platform for high-resolution environmental monitoring across diverse aerial and near-space carriers. Section 8.1, “Key Findings and their Implications,” distills the core advances in payload architecture, flight-dynamics characterization, and multi-source data integration, highlighting how these innovations enhance measurement fidelity and operational versatility. Section 8.2, “Limitations and Challenges,” candidly addresses unresolved issues—particularly in modeling torsional oscillations, fully automating mission adaptation, and harmonizing heterogeneous datasets—thereby delineating the boundaries of the current framework. Section 8.3, “Integrative Applications and Interdisciplinary Impact,” examines how ATEMO’s methodologies and technologies have been leveraged in complementary projects and miniaturized orbital systems, underscoring the research’s broader relevance and collaborative synergies. Finally, Section 8.4, “Future Directions,” outlines promising pathways for refinement and expansion, from advanced data-fusion algorithms and autonomous mission planning to the integration of emerging sensing modalities and standardized small-satellite platforms. Together, these discussions establish a coherent roadmap for the continued evolution of cost-effective, scientifically rigorous aerospace environmental monitoring.

8.1. Key Findings and their Implications

The ATEMO project has yielded several pivotal findings that collectively advance our understanding of modular environmental sensing platforms and their operational efficacy. First, the successful deployment of interchangeable sensor modules—ranging from multispectral cameras to gas analyzers—demonstrated that a commercially driven, off-the-shelf approach can achieve scientific-grade data quality. This outcome challenges the conventional reliance on bespoke instrumentation, suggesting that cost-effective, widely accessible components can be integrated into robust airborne systems without compromising measurement integrity.

Second, the comprehensive characterization of balloon flight chain dynamics revealed that pendular and longitudinal oscillatory modes can be predicted with high fidelity through a combination of analytical modeling and targeted laboratory experiments. The identification of resonant frequencies and damping characteristics enabled the design of more effective vibration isolation and data-correction algorithms, directly improving the stability of imaging and sampling operations. In contrast, the more complex torsional motions exhibited greater variability than anticipated, indicating that further refinement of dynamic models will be necessary to fully mitigate rotational disturbances. Nonetheless, the insight gained into these coupled behaviors has already informed structural reinforcements and control strategies for subsequent campaigns.

Third, the integration of heterogeneous data streams—from ground-based reference measurements and UAV surveys to stratospheric balloon observations and satellite imagery—was achieved through a rigorously validated calibration framework. By aligning spectral responses, temporal sampling, and geospatial referencing across platforms, the ATEMO team was able to produce coherent datasets that reconcile differences in resolution and acquisition

conditions. This harmonization has significant implications for multi-scale environmental monitoring, as it enables localized, high-resolution observations to be contextualized within broader satellite records, thereby enhancing the temporal and spatial comprehensiveness of ecological and atmospheric assessments.

Finally, the adoption of fully 3D-printed structural elements and modular mechanical interfaces underscored the feasibility of rapid prototyping and iterative design refinement. The ability to iterate payload configurations based on real-world performance feedback has substantially shortened development cycles, supporting a more agile research paradigm. This flexibility carries important implications for addressing emerging environmental challenges, as it allows sensing systems to be rapidly tailored to novel applications—such as targeted pollution plume tracking or emergency response mapping—without the delays inherent in traditional aerospace development.

8.2. Limitations and Challenges

Despite the demonstrable strengths of ATEMO's modular framework and the integration of commercial off-the-shelf components, several interrelated limitations and challenges have emerged that warrant careful consideration. Foremost among these is the incomplete characterization of torsional dynamics within the balloon–payload flight chain. While pendular and longitudinal modes aligned closely with analytical predictions, torsional oscillations proved more variable and sensitive to subtle asymmetries in payload mass distribution and environmental forcing. This unpredictability undermines fine-scale attitude reconstruction and suggests that our spring-damper simplifications, though valuable for first-order estimates, require augmentation with higher-fidelity numerical models or active damping solutions.

A second significant challenge lies in the harmonization of data streams collected across heterogeneous platforms. Even with rigorous laboratory calibration of optical filters and camera responses, residual inconsistencies in spectral bandwidths and sensor sensitivities persist when comparing balloon-acquired imagery to satellite products. Temporal mismatches—owing to differing revisit intervals and the necessity of coordinating field campaigns with favorable weather—further complicate direct comparisons. Such discrepancies can introduce biases into multi-scale analyses of vegetation health or light pollution, underscoring the need for more sophisticated data-fusion algorithms and dynamic cross-calibration protocols that can adjust for these temporal and spectral offsets.

Operationally, the reliance on pre-programmed flight profiles limits true adaptive response to evolving atmospheric conditions. Although real-time telemetry permits remote adjustment of payload settings, the absence of onboard decision-making restricts the system's ability to optimize sampling or imaging parameters in response to changing wind shear, light levels, or cloud cover. Developing lightweight autonomous control algorithms—capable of adjusting pump flow rates, camera exposure, or flight altitudes in situ—remains an open technical task, made more complex by power and computational constraints inherent to small airborne platforms.

Finally, while COTS components have enabled rapid prototyping and cost containment, their environmental robustness can be marginal at stratospheric altitudes. Exposure to extreme cold, low pressure, and high ultraviolet flux may degrade sensor performance or electronic reliability over extended campaigns. Custom qualification testing in thermo-vacuum and UV exposure chambers has mitigated some risk, but long-duration flight validation and the development of hardened alternatives will be necessary to ensure consistent operation in harsher conditions or for missions requiring weeks rather than hours of continuous measurement.

Collectively, these limitations point toward a research agenda that balances the accessibility and flexibility of modular, COTS-driven designs with the precision and resilience demanded by cutting-edge environmental science. Addressing them will require an iterative cycle of enhanced modeling, targeted experimentation, and incremental hardware refinement—building on ATEMÓ’s successes to close these critical gaps.

8.3. Integrative Applications and Interdisciplinary Impact

The ATEMÓ framework’s adaptability has enabled its integration into a diverse array of scientific and operational contexts, amplifying its interdisciplinary impact well beyond its original Earth observation objectives. Notably, the modular sensor suite and calibration protocols have been adopted within the E-FORESTER project to support airborne measurements of forest canopy structure and health, demonstrating seamless transfer of optical and inertial sensing submodules for ecological monitoring. In Chile’s Light Pollution Source Detection campaign, ATEMÓ’s multi-camera payload was reconfigured to map urban glow from tethered balloons, combining data with GIS analyses to inform regional lighting policy.

Within the Italian PRIN “Rewatering” initiative, ATEMÓ’s vegetation-index payload was embedded in a larger agro-hydrological study, enabling fine-scale validation of satellite-derived water-stress metrics for precision irrigation planning. This integration fostered collaboration among agronomists, hydrologists, and remote-sensing specialists, highlighting the platform’s role as a versatile field instrument for cross-sector research.

The J2050 PocketQube mission extended ATEMÓ’s design philosophy into orbital applications, illustrating how modular payload architectures can be repurposed for space debris detection and optical tracking. The collaboration among aerospace engineers, chemists, and astronomers to develop non-mechanical telescope covers (CRYSTALS) and in-situ debris sensors (CLOUD) underscores the thesis’s capacity to bridge disciplinary boundaries and catalyze innovation in both terrestrial and spaceborne monitoring domains.

Educationally, ATEMÓ has served as a hands-on training platform for undergraduate and graduate students across engineering, environmental science, and computer science, fostering project-based learning and reinforcing systems-thinking. Outreach activities—ranging from school workshops to citizen-science balloon launches—have leveraged the platform’s simplicity and affordability to engage non-technical audiences in environmental data collection, thereby amplifying its societal relevance.

Collectively, these integrative applications attest to ATEMÓ’s modular architecture as a nexus for interdisciplinary collaboration, enabling rapid reconfiguration of core sensing components

to address emergent research questions across ecology, atmospheric chemistry, urban studies, and space science. This broad impact underscores the framework’s potential as a shared technological scaffold—one that lowers barriers to entry for diverse users while promoting cross-domain synergies in environmental monitoring and aerospace innovation.

8.4. Future Directions

Building upon the foundational successes and lessons learned from the ATEMO framework, a cohesive vision for its evolution emerges that integrates enhanced dynamics, intelligent autonomy, miniaturized payloads, advanced analytics, orbit-hybrid architectures, and open-source standardization into a unified system. First, the development of high-fidelity numerical models that capture pendular, longitudinal, and torsional modes under variable atmospheric profiles and time-dependent loading is essential to deepen our understanding of platform behavior. Coupled with real-time sensor feedback, these models will drive adaptive control algorithms capable of active damping and on-the-fly trajectory adjustments, thereby ensuring payload stability across balloon and unmanned aerial vehicle (UAV) operations. Simultaneously, embedding machine-learning-based decision systems onboard will enable ATEMO platforms to autonomously optimize sampling schedules, flight paths, and data-acquisition parameters in response to live environmental cues. Such onboard intelligence, when orchestrated across multiple assets—ranging from tethered balloons and UAVs to miniaturized satellites—will facilitate synergistic data collection and automated gap-filling in rapidly evolving scenarios.

In parallel, continued miniaturization of sensing modalities—incorporating compact hyperspectral imagers, LiDAR scanners, and advanced atmospheric chemistry detectors—will refine the modular bus design, while leveraging additive-manufactured composites and lightweight metamaterials will reduce system mass without compromising mechanical resilience. To fully exploit the heterogeneous datasets generated, automated calibration pipelines employing deep-learning techniques can perform cross-platform spectral correction, georeferencing, and anomaly detection, and cloud-based integration with global satellite archives will support near-real-time environmental analytics and decision support. Looking beyond the stratosphere, extending the modular payload concept to orbit-hybrid architectures requires radiation-hardened electronics, precision attitude control, and robust power management for long-duration missions; coordinated observations between airborne platforms and pocket-satellites promise a vertically integrated monitoring capability from ground level to low Earth orbit. Finally, establishing open-hardware and software standards for modular interfaces—and disseminating calibration datasets, dynamic models, and code repositories—will catalyze community engagement, accelerate prototyping, and ensure reproducibility across research groups. By converging these strategic avenues, the ATEMO framework can mature into an autonomous, multi-scale observation system that delivers high-resolution, adaptive environmental insights, thereby supporting sustainable management of Earth’s changing ecosystems.

9. Conclusions

This chapter presents the synthesis of the thesis’s principal findings, examines their broader implications, and outlines prospective directions for further investigation. In the Main Conclusions section, the key scientific and technological advancements achieved through the ATEMO framework are distilled, highlighting how modular payload design, refined flight-dynamics understanding, and robust multi-source data integration have collectively advanced environmental monitoring. The Outlook considers emerging challenges and opportunities—ranging from enhanced dynamic modeling and autonomous mission control to the integration of new sensing modalities and the extension of ATEMO principles to miniaturized orbital platforms. Finally, the Final Remarks reflect on the enduring significance of this work, emphasizing its contribution to accessible, scalable aerospace-enabled Earth observation and its potential to inspire future interdisciplinary innovation.

9.1. Main Conclusions

The research embodied in this thesis has established that a modular, reconfigurable approach to aerospace environmental sensing can reconcile affordability with scientific rigor. By integrating commercial off-the-shelf sensors—ranging from CMOS cameras equipped with bespoke optical filters to low-cost inertial measurement units and environmental probes—into a compact payload architecture, the ATEMO platform has demonstrated its capacity to deliver high-quality data across a spectrum of observation modalities. Deployments on tethered balloons, UAVs and stratospheric flights confirmed that the same core payload can be adapted to diverse operational requirements without compromising performance.

A key outcome lies in the rigorous characterization of balloon-payload flight dynamics. Analytical modelling paired with laboratory vibration tests and in-flight inertial measurements yielded quantitative insights into pendular, longitudinal and torsional oscillations, together with their damping characteristics. These findings informed refined structural and isolation designs, significantly improving payload stability and pointing accuracy during ascent.

Equally important has been the development and validation of multi-source data integration and calibration protocols. Systematic spectral response characterization of optical channels, coupled with geometric and radiometric calibration against ground references, enabled the harmonization of ATEMO’s airborne imagery with high-resolution satellite products. Synchronization of positioning and attitude data across platforms ensured coherent fusion of in-situ, aerial and orbital datasets, laying the groundwork for end-to-end environmental assessments.

The thesis further demonstrated that the ATEMO design philosophy extends naturally to miniaturized orbital systems. The J2050 PocketQube mission translated modular payload principles to a 2P picosatellite, validating non-mechanical telescope shielding, in-situ debris detection and active optical tracking technologies in low Earth orbit. This extension confirms the scalability and transferability of the core framework to spaceborne applications.

Overall, the Main Conclusions underscore that accessible, cost-effective hardware can be harnessed to achieve rigorous environmental monitoring across multiple atmospheric and orbital regimes. The synergy of modular design, comprehensive dynamic analysis and robust data integration provides a replicable blueprint for next-generation Earth observation architectures.

9.2. Outlook

Addressing the persistence of unmodeled oscillations and dynamics of balloon–payload flight chains will be a priority. Expanded in-flight instrumentation and refined numerical models are required to capture these complex modes and to inform next-generation damping or isolation strategies.

Advances in autonomous mission management should be pursued. Embedding onboard algorithms for real-time environmental assessment and adaptive flight control will enable platforms to dynamically optimize sampling and trajectory in response to evolving atmospheric conditions. Multi-source data fusion stands to benefit from machine-learning–driven calibration and anomaly-detection frameworks, which can reconcile high-volume, heterogeneous datasets more rapidly and accurately, supporting near-real-time decision-making. Technological innovation in payload miniaturization remains critical. Integrating emerging modalities—such as compact hyperspectral imagers, LiDAR systems, and advanced atmospheric sensors—into the modular architecture will expand the range of environmental phenomena that can be monitored. Extending modular, COTS-based design principles to orbital platforms will require tailored solutions for radiation hardening, thermal control, and precision pointing. Lessons from the J2050 PocketQube mission should guide the development of resilient small-satellite buses capable of sustained, high-fidelity Earth observation in low Earth orbit.

Sustained interdisciplinary collaboration—with industrial partners, space agencies, and the broader scientific community—will accelerate technology transfer, standardization, and the co-development of integrated observation architectures that link ground, aerial, and orbital assets for comprehensive environmental monitoring.

9.3. Final Remarks

The work presented in this thesis has demonstrated that modular, reconfigurable payload architectures—implemented with readily available commercial off-the-shelf components—can deliver scientific-grade environmental measurements across a spectrum of aerial and near-space platforms. By integrating calibration, comprehensive flight-dynamics characterization, and multi-source data fusion protocols, the ATEMO framework establishes a credible and cost-effective alternative to traditional satellite- and ground-based observation methods.

Key innovations include interchangeable sensor modules and optical filters—enabling rapid reconfiguration for missions ranging from vegetation-health monitoring to atmospheric-pollutant sampling and urban light-pollution mapping. Experimental campaigns demonstrate that this cross-disciplinary approach retains data quality and operational reliability under the

pendular, longitudinal, and torsional dynamics of tethered and stratospheric balloon flights. The fusion of mechanical-systems modeling with atmospheric-science objectives has driven payload-stabilization refinements that reduce motion-induced errors and expand scientific return.

Extending beyond suborbital platforms, the thesis applies ATEMOS's modular principles to miniaturized orbital vehicles, exemplified by the J2050 PocketQube project. This progression illustrates how aerospace structures, optical engineering, and remote-sensing analytics can converge to create a unified environmental-monitoring ecosystem—linking terrestrial, aerial, and spaceborne assets for enhanced spatial, temporal, and spectral resolution.

Remaining challenges—such as fully capturing complex torsional coupling, developing autonomous mission-planning algorithms, and ensuring long-term resilience of COTS components in extreme environments—frame a clear interdisciplinary research agenda. Addressing these topics will further strengthen ATEMOS's potential as a replicable blueprint for next-generation environmental sensing platforms that merge engineering innovation with earth-science imperatives.

In conclusion, the ATEMOS project delivers a compelling proof of concept: that flexibility, affordability, and scientific rigor can coexist across disciplines in aerospace environmental monitoring. This integrated framework lays a robust foundation for continued collaboration among engineers, ecologists, data scientists, and policymakers—advancing high-quality, multi-scale Earth observation toward more accessible and impactful applications worldwide.

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I've often been told that "I am not easy to get along with"; for a long time, I believed it. Perhaps this belief helped me to improve and smooth out some aspects of my character. In truth, it is not that my character is difficult; it is simply not convenient. My character is inconvenient for those who wish I were different, for those who would prefer I conformed to society's standard expectations.

While this concept may seem obvious to many, it took me a few more years to truly understand it. Now, at the end of this doctoral journey, I realize how much I owe to those who, whether through support or criticism, have helped me grow. To those who have seen me in my full humanity and celebrate this achievement with me—know that my heartfelt thanks are with you.

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