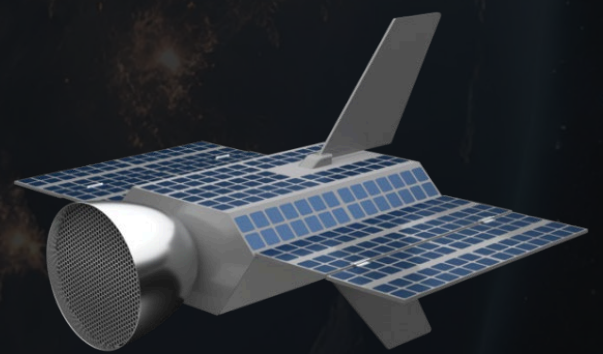


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Keynote Presentations

Keynote

VLEO2025-A-01

VLEO and Space Sustainability: How does Very Low Earth Orbit contribute to the shift towards more sustainable space activities?

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The use of Very Low Earth Orbit (VLEO) has often been cited as a possible solution to growing problem of space debris, especially as we enter the era of mega-constellations of thousands of satellites. By definition, interaction with the residual atmosphere in VLEO induces drag which rapidly pulls debris and failed satellites from orbit, minimising any long-term impact on the debris population. As such it provides a relatively consequence free environment for rapid and high-risk technological innovation.

The above, combined with the many benefits achieved from operating satellites at lower altitudes such as improved resolution for Earth observation and reduced latency and power requirements for communications constellations, continues to drive growing interest in, and the use of, VLEO.

However, the sustainable use of space also demands we consider other aspects of the impact of the use of low Earth orbit generally, including VLEO, on the Earth and orbital environments. This includes considerations such as light and radio pollution for optical and radio astronomy, and the carbon footprint of space activities.

Meanwhile the impact on the atmosphere of satellites re-entering the atmosphere at end-of-life is known to have impacts on ozone depletion and the Earth's radiative balance, the significance of which is still being assessed. One can imagine that in the future, with the drive for a circular space economy, moving end-of-life satellites to a reprocessing facility in-orbit becomes mandated. But this is realistically still a long-term goal.

In the near-term, what are the opportunities and benefits that VLEO can provide to space sustainability, and how do these need to develop to continue to be part of the solution in the long-term?

Keynote

VLEO2025-A-02

Motivation, Structure and Goals of the Collaborative Research Center 1667: Advancing Technologies of Low Altitude Satellites (ATLAS)

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Collaborative Research Centres (CRC) are supported by the German Science Foundation (DFG) and represent a unique format for a multidisciplinary, long-term research programme at a university. Following this philosophy, the CRC 1667 „Advancing Technologies of Very Low Altitude Satellites – ATLAS” has been established in April 2024 with the scientific goal to address the fundamental challenges of rendering very low Earth orbits (VLEO) accessible. These orbits are particularly beneficial for satellite services that have become indispensable to our modern knowledge, information, and communication society. Additionally, access to VLEO offers the opportunity to operate satellites without exposure or contribution to the increasing contamination of traditional orbits with space debris.

Attaining viable VLEO flight is, however, challenging due to the unique environmental properties of the lower thermosphere. Thus, the various advantages of VLEO, including its self-cleaning effect through the residual atmosphere, are to date offset by a prohibitively short operational lifetime. The leading research question of the CRC AT-LAS is therefore: How can the lifetime of a satellite in VLEO be increased by at least one order of magnitude without the necessity of huge amounts of fuel carried or resupplied continuously from Earth? The CRC ATLAS aims to answer this leading research question with an approach that encompasses various disciplines. The first funding phase (2024 – 2027) concentrates on the deployment of the know-how on the component level with subsystem and system level input. Seventeen highly interlinked projects have been selected to investigate and advance accurate numerical and experimental methods for gas-surface interactions, novel concepts utilising the residual atmosphere and minimising the satellite sizes, and mission-related challenges of a selected scenario. In a second funding phase (2028 – 2031), this know-how will be extended to reach subsystem level maturity. It will comprise a refinement and application of the established methods and facilities, as well as high-fidelity simulations and extensive experiments to enable an assessment of subsystem requirements. A third funding phase (2032 – 2035) will finally reach towards attaining system level know-

how through a multi-disciplinary validation of component and subsystem interactions using methods established in the preceding funding periods.

The research subject of the CRC ATLAS is considered to exhibit significant potential towards increasing public interest in spaceflight-related topics. The area of research has also experienced an exponential growth in interest within the scientific community over the past few years. It is expected that the establishment of the CRC ATLAS will result in a very strong interest for academic exchange, especially in an international context. To cover these highly important points, dedicated projects and actions are foreseen for public outreach as well as fostering of academic and educational exchanges. In summary, the CRC ATLAS is intended to constitute a research-oriented profile-building measure at the University of Stuttgart with strong international charisma.

Technical Session #1:
Science Mission Designs and Concepts

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Science Mission Designs and Concepts

VLEO2025-1-01

Mission and System Design for the EarthNext CubeSat VLEO Mission

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EarthNext is a CubeSat mission conceived in the framework of the ALCOR program, an incubator promoted and funded by the Italian Space Agency (ASI) to design prototypes of highly innovative CubeSat missions covering a wide range of space-related topics. The mission is designed for an In Orbit Demonstration (IOD) of operating a CubeSat in Very Low Earth Orbit (VLEO). Besides this main objective, the mission aims to provide value-added products and services for land and marine applications through the acquisition of high-resolution multispectral images of customer-selected targets over Italy, designated as the Area of Interest (Aoi). Additionally, EarthNext focuses on creating a synergistic dataset with other high-resolution multispectral missions, and on the IOD of a secondary camera designed for cloud detection over the AOI. The design and implementation of the project have been entrusted to Officina Stellare, the prime contractor and leader of a consortium that includes AIKO Space, Planetek Italia, T4I - Technology for Propulsion and Innovation, TSD-Space, and the Department of Industrial Engineering of the University of Naples "Federico II.". Thanks to its innovative approach and groundbreaking objectives, the project has recently completed the Preliminary Design Review and is ready to proceed to the next mission design phases. EarthNext has been designed to fly on a sun-synchronous orbit at 302 km of altitude to take advantage of the unique properties of VLEOs. These orbits are very promising for future Earth observation missions due to several benefits, including reduced costs from smaller payloads and lower launch efforts, reduced risks of collisions with space debris due to the "naturally" clean operational environment, and easier disposal at the end of life, thanks to rapid orbital decay. Besides, depending on the orbital configuration, VLEOs also offer good external radiation shielding, mitigating the total ionizing dose received by on-board electronics. However, despite these advantages, several technical and technological challenges need to be addressed. The non-negligible aerodynamic forces require the adoption of a reliable propulsion system for drag make-up manoeuvres. Furthermore, the platform must be equipped with an attitude control system capable of counteracting drag-related torques, ensuring high pointing accuracy and rapid manoeuvres to meet the accurate pointing requirements. Additionally, surface erosion due to the high concentration of atomic oxygen and high atmospheric speed require a careful selection of coating materials, possibly supported by experimental campaigns. Finally, the complexity and the dense scheduling of activities (e.g. drag-make manoeuvres) can be optimized through on-board Artificial Intelligence (AI)-based algorithms for real-time mission operations management. As regards the space platform, EarthNext mission relies on a 16 Us CubeSat with 8 Us allocated to the multispectral electro-optical payload and 8 Us to the platform

subsystems. The subsystems are based on state-of-the-art technologies, many of which plays the role of enabling-technology due to operational difficulties. The EarthNext platform includes an integrated electric propulsion system, which guarantees the thrust level necessary for the altitude restoration, an attitude control system capable to perform a forward motion compensation manoeuvres to increase time integration over target areas, an electrical power system with deployable solar arrays, an external structure design able to withstand atomic oxygen erosion effects, and a state-of-the-art automation capability based on AI, to overcome the constraints of conventional operation management. Stemming from the previous considerations, the following contribution will focus then on the science mission design of the EarthNext mission, presenting the main outcomes of the mission analysis and an overview of the mission's concept of operations. The contribution will be further enhanced by including the most recent advancements in platform design, aimed at achieving the mission's objectives.

Keywords: Very Low Earth Orbit, CubeSat, Earth Observation

Extremely Low Earth Orbit Imaging and Technology Explorer (ELITE) Satellite: Building Capabilities for Very Low Earth Orbit Missions in Singapore with Aerodynamic and Charged Plasma Simulations

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The Extremely Low Earth Orbit Imaging and Technology Explorer (ELITE) is a microsatellite designed to demonstrate flight in very low Earth orbit (VLEO) through an intercollegiate, academia-industry program fully funded by the Singapore government and led by the Satellite Research Center (SaRC) at Nanyang Technological University, Singapore. The spacecraft will be launched at an altitude of 550 km and gradually maneuver its orbit into the VLEO regime (between 300 km to 350 km) to conduct sustained flights at various altitudes for data collection. As an experimental platform, ELITE is equipped with the abilities to (i) capture high-resolution images with onboard cameras that utilize time-dependent integration technology; (ii) characterize the changing atomic oxygen (AO) field in flight region via AO fluence detector; and (iii) measure plasma density and drift velocity on-the-fly through a compact ionosphere probe. Orbit maneuvers and drag compensation are achieved using MUSIC, a low-power Hall effect thrusters capable of operating between 10 W and 100 W. To ensure sufficient margin for the propulsion system to sustain VLEO operations, accurate prediction of the aerodynamic drag is crucial for assessing optimal fuel requirements for the mission. Additionally, due to the thruster's prolonged operation for drag compensation, there is a moderate level of concern regarding the thruster plume impingement. To this end, the ELITE program has built up on simulation capabilities that include: (i) a test particle Monte Carlo method-based reduced-order model that enables varying satellite drag coefficient in VLEO propagator; and (ii) a three-dimensional fully kinetic particle-in-cell solver code to model the thruster plume impingement. The former accounts for surface interactions caused by varying thermospheric gas species along the orbit, as well as varying attitudes along the three axes encountered during satellite operations. The developed model has been linked to the General Mission Analysis Tool to obtain realistic satellite trajectories, thus potentially reducing uncertainties in satellite positioning for conjunction avoidance maneuvers and minimizing antenna errors that may be sensitive to ground track deviations. The latter has successfully generated plume impingement results over an ELITE satellite model, indicating that the distribution and intensity of ion flux on the spacecraft surface depend on the grounding chosen and surface potential. Using these enhanced capabilities for aerodynamics and charged plasma simulations, along with more than 20 years of legacy of SaRC in space and satellite engineering and thorough model testing, the team is cautiously optimistic that ELITE will overcome the challenges of a VLEO mission and return significant insights to both the scientific and commercial communities of space technology and research.

Keywords: Aerodynamics simulations; Thruster plume impingement modeling; VLEO propagation; VLEO satellite program

Technical Session #1:
Science Mission Designs and Concepts

VLEO2025-1-03

Skimsat IOD: A VLEO mission platform demonstrator

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Skimsat is a satellite product platform with aims to provide a platform for low cost operations of key VLEO applications, such as scientific and EO functions. VLEO (<~300km) has several advantages for satellites, including; improved payload performance, reduced radiation constraints, minimal orbital debris risk and low-latency communications. The proposed satellite platform, requires some key technology developments which are to be de-risked to mature the platform product. Hence, the Skimsat In-Orbit Demonstrator (IOD) is designed to validate operational life in VLEO, showcase cost-efficiencies of the VLEO platform concept and demonstrate key platform/payload technologies and their applications.

The Skimsat IOD will include several payload instruments, including a VNIR multispectral imaging instrument aiming to achieve a GSD <0.5m at 260km altitude. Additionally, a radiation monitor will provide in-situ measurements of the radiation environment in VLEO. These IOD payload choices support gathering of VLEO data to prove the value of the VLEO platform.

The propulsion subsystem is vital to demonstrate for a future VLEO platform. The subsystem design utilizes heritage components in combination with key new technology developments to achieve optimal value for the IOD. A small 0.5kW class ring-cusp gridded ion engine is under new development for the Skimsat IOD to be used for the subsystem, offering a beneficial thrust-to-power ratio for this type of mission. The thruster is fed with a combination of qualified and available pressure regulators and flow control units to form the Propellant Management System (PMS) of the subsystem. This PMS is designed to utilize Xenon, fed to the PMS by tanks with extensive flight heritage. Additionally, a PPU is under development to power the GIE and PMS. This development will utilize heritage PPU architecture from other EP subsystems with new adaptations for the new GIE development for the Skimsat IOD. The complete subsystem aims to achieve performance of max EP thrust up to 15mN at >3000s specific impulse.

The Skimsat propulsion subsystem aims to deliver and demonstrate a high-value, capable VLEO subsystem architecture which enables a high-performance VLEO platform suitable for a large range of VLEO use cases.

Keywords: VLEO, Skimsat, Electric Propulsion, Ion Thrusters, Platform

Technical Session #1:
Science Mission Designs and Concepts

VLEO2025-1-04

VLEO Design and development status in SITAEL

Stefan Gregucci (SITAEL)
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and others

Very Low Earth Orbit (VLEO) operations continue to spark great interest among the players of both industry and academia because of their numerous advantages. These range from improved payload performance, with increased resolution for optical applications and lower latency for telecom ones, to the possibility of studying the orbital environment at these altitudes in science-oriented missions. Of course, these advantages come at a cost in terms of technological challenges posed by that same harsh environment surrounding the satellite. In the effort to demonstrate the feasibility of continuous operations at <300km altitudes, it is presented the initial design of an In-Orbit Demonstrator (IOD) mission based on the RAM-EP air-breathing electric thruster, in the frame of the ESA-funded RED project. Building on both SITAEL heritage in the development and testing of air-breathing propulsion and the design of a platform structure specifically built and optimized for the RAM-EP by the Von Karman Institute for Fluid Dynamics (VKI), it is proposed a multi-payload demonstrator satellite embarking two VNIR-TIR Earth observation cameras, a Qv-band antenna and in-situ measurement devices for studying the surrounding plasma environment. The selected orbit is sun-synchronous at 6:00 AM/PM with an altitude ranging between 200 and 271km and a repeat cycle of 17 days, while the target mission duration is 8 years. In parallel with mission definition, the design of the main platform sub-systems is addressed, focusing on Electric Power System (EPS) and Attitude and Orbit Control System (AOCS) dimensioning. Moreover, the results of both preliminary structural and thermal analyses and a plume-satellite interaction investigation are reported, highlighting the way forward for the next design iteration. Overall, the presented IOD mission represents the first step toward the development of the world-first air-breathing VLEO platform, paving the way for prolonged operations at such strategic altitudes.

Keywords: IOD satellite design concept test

Technical Session #2:
System Design

Technical Session #2:
System Design

VLEO2025-2-01

Operational Aspects of an ABEP System for Drag Compensation in VLEO

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Advancements in the development of an Atmosphere-Breathing Electric Propulsion (ABEP) system at the University of Stuttgart's Institute of Space Systems (IRS) highlight the need to focus not only on technical development but also on the operational aspects of ABEP in very low-Earth orbit (VLEO). The present work gives a summary of the analysis performed with the ESA-funded project ram-CLEP on the expected atmospheric conditions and eclipsing times using the ASTOS software and the NRLM-SISE00 atmospheric model, identifying worst-case scenarios—such as maximum atmospheric density and longest eclipse duration—that the satellite system must withstand. This includes the consideration of elliptical Sun-synchronous orbits, which, although unconventional, offer unique advantages such as allowing for lower perigee altitudes and increased system robustness during thruster outages. These analyses establish foundational conditions under which the satellite shall sustain payload operation and use the ABEP system to compensate for altitude loss due to atmospheric drag.

In a proprietary multi-disciplinary design optimization (MDO) approach, which takes into account the drag dependent on geometry and atmospheric conditions as well as performance models of the ABEP system, the most suitable satellite design is identified for further investigations.

This contribution next implements a simulation-based approach to analyze the performance and feasibility of the system in its intended orbit. Beyond single-orbit performance under worst-case conditions, long-term simulations covering the entire eclipse season provide a more comprehensive review of the mission concept's feasibility. This analysis also defines a performance envelope for the ABEP system, outlining operational conditions and power levels for efficient functioning. Moreover, varying the assumed power parameters enables a sensitivity study, which demonstrates the robustness of the proposed solution.

From the simulation-based analysis, certain limiting factors for performance are identified, such as significant fluctuations in mass flow rates, the specific impulse required for the thrusters, and energy availability through solar panels and battery storage. Preliminary mitigation strategies, including adjustments to attitude control and supplemental fuel tanks, are discussed. Finally, this paper outlines key priorities for the future development of ABEP systems, specifically focusing on preparing them for operational feasibility in very low-Earth orbit (VLEO).

Keywords: Very Low-Earth Orbit (VLEO), Multi-Disciplinary Design Optimization (MDO), Mission Analysis, Atmosphere-Breathing Electric Propulsion (ABEP), Feasibility Analysis

Technical Session #2:
System Design

VLEO2025-2-02

Holistic systems modelling of Very Low Earth Orbits (VLEOs) incorporating Atmosphere Breathing Electric Propulsion (ABEP)

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In recent years very low Earth orbits (VLEOs) have been investigated as a way of enhancing Earth observation (EO) and communications missions. VLEO is defined as an orbit with an altitude less than 450km. As optical resolution scales linearly with reduced range to the target and radiometric performance is inversely proportional to the range to the target, these have been considered as obvious candidates in the literature. Similarly, the reduction in latency and free space loss, has made communications missions also good candidates for VLEO. These payloads can be made smaller, resulting in a smaller and cheaper spacecraft. Alternatively, higher performance can be achieved, or some combination of the two.

To enable sustained operation in VLEO, atmosphere breathing electric propulsion (ABEP) has been proposed in the literature. ABEP is a novel form of electric propulsion that avoids the need for pre-stored propellant, by utilising the Earth's residual atmosphere as a source of propellant.

There already exists comprehensive systems modelling techniques for conventional spacecraft design in low Earth orbits (LEO), however, the introduction of ABEP creates additional complexities which current models cannot accurately evaluate. A major gap is the effect of the introduction of ABEP on the stability/manoeuvrability of a spacecraft. To allow the development of novel ABEP carrying spacecraft, a novel, holistic systems model must be developed to rectify this gap. With this systems model, it is possible to undertake early concept design analysis, including preliminary component and platform sizing.

This work constructs a holistic systems model utilising an extended version of the design structure matrix (DSM). This consists of a series of "Blocks" corresponding to the different satellite subsystems, in a specific order related to importance. Subsystem analysis is performed within the blocks whilst the DSM passes and receives key variables. The systems modelling is performed in an iterative manner until the variables converge, yielding a higher performance solution. This solution provides detailed system and subsystem level data, including mass, power and geometric sizing etc.

Within these subsystem analyses, novel methods have been utilised to introduce the complexities of an ABEP system into the systems model, allowing for a more accurate result. This goes beyond the basic parametric type of analysis found in the literature, including factors such as the modified centre of pressure (CoP) and its effect on stability. The systems modelling makes use of novel drag modelling tools with modifications where necessary to allow complexities, such as the intake, to be included in the drag modelling. An automatic mesh generation system is employed using MATLAB toolboxes, linking with open-source CAD programs through a command line prompt. The model is employed for different relevant scenarios, primarily a comparison between ABEP and traditional EP at different altitudes. This will be further extended to different configurations such as the slender and flat body designs and considering concepts such as control surfaces and intake shielding. The different solutions are compared and discussed. By creating a more representative systems model, this work can provide mission planners with greater certainty in designing novel ABEP missions.

Keywords: ABEP, VLEO, Systems Modelling

Technical Session #2:
System Design

VLEO2025-2-03

Exploring Very Low Earth Orbit (VLEO) Spacecraft Design: Challenges and Innovations for Atmospheric Operations and Multi-Role Capabilities

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The rapid expansion of Low Earth Orbit (LEO) operations has intensified industry interest in the underutilised Very Low Earth Orbit (VLEO) range, lying below 450 km above Earth. While conventional LEOs, from 450 km to 2,000 km, are now densely populated, VLEO offers promising opportunities despite its significant technical challenges. Addressing these challenges can unlock potential in the VLEO segment, supporting missions requiring low-latency communication, fuel efficiency, and innovative propulsion approaches.

Recent advancements by key players such as the Japan Aerospace Exploration Agency (JAXA), highlight the potential for sustained VLEO operations. Current research emphasises launch costs, enhanced earth gravity-assisted orbits, end-of-life (EOL) planning, and the novel use of air-breathing electric propulsion. This propulsion method shows promise for maintaining orbital altitude in VLEO while also enabling the spacecraft to serve multiple mission roles.

This study revolves around developing a spacecraft aimed at dual-functionality: operating within the upper atmospheric layers similar to an aircraft while enduring the harsh conditions of space. Key design criteria address the need for materials capable of withstanding high aerodynamic drag, fluctuating pressures/densities, intense thermal cycles, and radiation exposure. Furthermore, structural materials must balance weight efficiency with the rigidity required to endure launch and long-term degradation stresses. The design will incorporate autonomous orbital control for optimised fuel management, resilient solar array configurations for continuous power, and low-latency communication systems optimised for high-speed orbital passes over ground stations.

Initial testing stages will benchmark the proposed spacecraft against current technology, setting a foundation for further refinement. This research aims to advance spacecraft engineering for VLEO applications, contributing insights into achieving durability and operational efficiency in lower-altitude orbits and supporting the development of air-breathing electric propulsion systems tailored to the demands of the challenging environment.

Keywords: Very low Earth orbit, Air-breathing electric propulsion, Spacecraft design, Low-latency communication, Atmospheric operations, Structural durability

Technical Session #2:
System Design

VLEO2025-2-04

AERIS-S: Hybrid Air-Breathing and Refuellable Propulsion for Sustainable, Extended Operations from VLEO to LEO

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AERIS-S represents an innovative hybrid propulsion system designed to significantly extend the range, operational lifespan, and sustainability of satellites navigating between Very Low Earth Orbit (VLEO) and Low Earth Orbit (LEO). As an evolution of the AERIS product line, AERIS-S uniquely integrates air-breathing refuelling capabilities for VLEO (100-200 km) with economical, high-ISP propulsion for orbit-raising manoeuvres to up to 600 km. This ground-breaking approach leverages the atmospheric particles in VLEO to establish a self-sustaining refuelling process, enabling satellite lifespans to extend to an impressive 10-15 years—well beyond the current limitations of onboard propellant storage.

AERIS-S's design allows for one of the incoming air streams to be directed into a compressor, storing atmospheric particles within an onboard propellant tank during low-thrust VLEO operations. This refuelling mode not only extends fuel availability but conserves it for high-ISP manoeuvres such as orbit-raising and lowering. Once refuelled, AERIS-S can efficiently raise its orbit to LEO, where its throttleable design supports a broad range of operations, including precision low-ISP tasks essential for Rendezvous and Proximity Operations (RPO), collision avoidance, and controlled deorbiting. AERIS-S's capabilities for efficient station-keeping across both orbits allow it to alternate seamlessly between VLEO and LEO, aligning with varying mission requirements.

An essential and novel feature of AERIS-S is its avoidance of RF or microwave plasma, which renders it inherently resistant to jamming. Additionally, the propulsion system generates no heat or ionic signature, significantly enhancing its low-detectability profile—an advantage for national security applications and commercial missions where stealth is increasingly prioritised. The engine's modular architecture, shared across the AERIS line, includes nitrogen-fed options for standard LEO operations, a purely VLEO air-breathing variant, and this hybrid refuelling model. This versatility streamlines manufacturing, facilitates scalable deployment, and ensures compatibility across diverse mission profiles.

The propulsion system optimises performance based on mission demands. During refuelling operations in VLEO, AERIS-S operates at low thrust to maximise intake efficiency and gather fuel. For high-thrust requirements, such as orbit-raising, the full incoming air stream is utilized, providing higher ISP output that reduces transit time to LEO. This hybrid refuelling design reduces or even eliminates the need for onboard propellant at launch, lowering both launch mass and cost. The resulting capability enables longer mission lifespans and addresses current limitations of propulsion in VLEO and LEO.

The AERIS-S engine has generated considerable interest within the New Space Economy, especially from sectors focused on On-Orbit Servicing, Assembly, and Manufacturing (OSAM), telecoms, and Earth observation. Its sustainable and scalable propulsion aligns closely with emerging market demands for efficient satellite mobility across multiple orbital altitudes. Testing and commissioning for AERIS-S are

scheduled for 2025/26, with operational launches anticipated in 2026/27. This progressive design, leveraging atmospheric refuelling, flexible orbit capability, and mission-adaptable propulsion modes, positions AERIS-S as a transformative, sustainable solution for extended, agile satellite operations across commercial and national security markets.

Keywords: ABEP; Hybrid-VLEO; New Space; Refuel; Sustainability;

Technical Session #3:
VLEO Application Scenarios

Technical Session #3:
VLEO Application Scenarios

VLEO2025-3-01

Closer to Earth, Faster in Space: The potential of VLEO for Responsive Space

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Very Low Earth Orbit (VLEO) satellites offer significant advantages for enhancing responsive space capabilities, particularly in light of increasing risks from space debris and military threats. Responsive space refers to satellite architecture, infrastructure, and provisions that enable the rapid replacement of critical space-borne capabilities within days. Constellations of satellites play hereby an important role in ensuring redundancy and resilience against single-asset failures. VLEO satellites add value to such constellations due to their ability to deliver equivalent performance on smaller, more cost-effective platforms. Their compact size makes them particularly advantageous for storage as backup satellites and for rapid deployment to restore lost capabilities. Moreover, these smaller platforms can be launched via commercial micro-launchers, providing cost-effective, quick-response launch options. The high-friction environment of VLEO results in faster orbital decay. This can be acceptable in the context of Responsive Space, where priority is given to expanding or restoring space-borne capabilities within a very limited time frame to bridge capability gaps or address short-term conflict scenarios. Additionally, the natural orbital decay helps reduce space debris, which is particularly beneficial when other orbits may be compromised in a denial-of-LEO scenario. We are currently analyzing the scenario-dependent performance of four distinct categories of VLEO systems: air-breathing, EP orbit keeping with Mirco Sats and Medium Sats, LEO-to-VLEO concepts, and suborbital missions. The preferred solution depends in primarily on the survivability limitations due to threats or debris and must be able to maintain or restore key capabilities under any circumstances. In a conflict scenario, the presence of such a responsive fleet would also reduce the benefits for an adversary of using kinetic anti-satellite weapons (ASAT). Consequently, VLEO platforms could play a crucial role in military deterrence, thereby contributing to the preservation of a clean Low Earth Orbit.

Keywords: Responsive Space, Usecase, Missiondesign

Technical Session #3:
VLEO Application Scenarios

VLEO2025-3-02

Very Low Earth Orbit Telecommunications Constellations for Non-Terrestrial Network Connectivity

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This work assesses a range of potential benefits and challenges to the delivery of direct-to-device cellular and other telecommunications services through constellation operation in Very Low Earth Orbits (VLEO) below 450 km. Deploying spacecraft in VLEO presents technical challenges due to interaction with the Earth's upper atmosphere, causing both orbital drag and atomic oxygen erosion. However, developments in erosion resistant and drag reducing materials, along with advances in traditional and atmosphere breathing electric propulsion technologies have begun to open this regime for practical use. Proposed applications have focused on Earth Observation (EO), but reductions in power requirements and latency due to shorter transmission distances, access to higher frequencies and data rates from reduced path loss, eased demands on spacecraft components due to the benign radiation environment, and potential reductions in spacecraft size all present opportunities in the delivery of high-speed global telecommunications. These altitude related benefits may be best realised in the extension of terrestrial cellular connectivity through provision of a direct-to-device non-terrestrial networks (NTN) servicing low power user handsets.

In this work the impact of altitude on telecommunications constellations in VLEO was investigated through the development of a representative analytical constellation model. This was then assessed across a range of network design parameters including constellation size and minimum user elevation angles, satellite coverage, antenna footprint and beam forming, frequency usage, multiple access techniques, channel capacity, and both payload and user power demands.

Early results show that although the overall constellation size expands for lower orbital altitudes, this can improve capacity by allowing an increase in user cells within a footprint. For example, moving from a traditional LEO 600 km orbit to 300 km in VLEO increases the maximum cell capacity by up to 36% dependent on chosen minimum user elevation, however smaller beam-width antenna systems are needed to access the greatest benefits. It is also shown that the higher relative spacecraft motion in VLEO degrades the capabilities of traditional frequency-based duplexing and access techniques by increasing the maximum received frequency Doppler shift by up to 10% for the lowest altitudes and user elevations when compared to a traditional 600 km orbit, but the reduced latency due to shorter propagation distances may instead enable effective application of time domain multiplexing and access. Further analysis shows that the possible number of channels increases linearly with reducing altitude but that the power required per channel decreases quadratically. Therefore, operating in VLEO may enable increased service capacity whilst still realising gains in reduced payload power requirements. These lower channel power demands also ease the burden on user devices and extend single-charge battery life, contributing to a practical application of this technology for commercially available handsets.

Keywords: VLEO, Mega-Constellations, Telecommunications, Direct-to-Device, NTN

Technical Session #3:
VLEO Application Scenarios

VLEO2025-3-03

Optimizing LPWAN-based Satellite Constellations: A Comparative Study of VLEO and LEO Orbits

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This study focuses on the potential effectiveness of AIoT-NTN (AI-enabled IoT-Non-Terrestrial Network) technology in satellite-based IoT communications, aiming to optimize communication efficiency for LPWAN technologies (LoRa, NB-IoT, MIOTY) within VLEO and LEO satellite constellations. Major service points reflecting global IoT demand are selected, and VLEO and LEO satellite constellations are designed to cover these points. Subsequently, the power consumption, data throughput, and signal delay characteristics of each communication technology are compared and analyzed. In particular, in addition to the widely recognized NB-IoT, this study includes a detailed analysis of LoRa and MIOTY, which are expected to be highly effective in AIoT-NTN scenarios.

In an AIoT-NTN-based scenario, this study determines the optimal data transmission amount for Uplink by simulating the data generated by onboard AI chips, measuring Uplink requirements, and deriving efficient data transmission strategies. This approach clarifies the real-world performance differences between VLEO and LEO constellations for each LPWAN technology and proposes optimal satellite configurations suitable for global IoT services.

The study concludes that VLEO satellite constellations offer substantial benefits in AIoT-NTN environments, maximizing the efficiency of LPWAN technologies through stronger signals and lower latency at lower altitudes. These findings, derived from a genetic algorithm-based multi-objective optimization and Pareto front analysis, provide practical guidance for enhancing the flexibility and utility of next-generation global IoT-NTN communication networks and propose an optimal satellite network design strategy based on the unique orbital advantages of each communication technology.

Keywords: VLEO Constellation, LPWAN, IoT-NTN, AIoT, Genetic Algorithm

Technical Session #3:
VLEO Application Scenarios

VLEO2025-3-05

Molecular Beam Investigations of Atomic Oxygen Reactivity and Scattering on Material Surfaces for Satellites in Very Low Earth Orbit

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There is an explosion of interest in the utilization of very low Earth orbit (VLEO, roughly 100 – 350 km altitude) for commercial and military purposes. Despite the obvious proximity advantages of VLEO for Earth observation (e.g., enhanced image resolution, improved data transfer rates, and cost reduction in satellite development and launching), VLEO altitudes have long been avoided because of the high density and harsh oxidizing environment of the residual atmosphere. VLEO environments contain predominantly atomic oxygen (AO) and molecular nitrogen (N₂), which collide with ram surfaces on spacecraft at relative velocities of ~7.5 km s⁻¹. Momentum exchange between these atmospheric atoms/molecules and satellite surfaces result in an aerodynamic drag force on the vehicle. For VLEO operation, the drag is significant enough to require propulsion to counteract drag and maintain orbit, resulting in increased energy and also size (typically from solar panels and propellant storage) to operate the propulsion system. Increased size results in increased drag forces and the need for more energy and propellant, creating a vicious cycle. Beyond the clear necessity of minimizing drag for feasible flight in VLEO, the quantification of drag allows for orbital path determination and collision avoidance. Aside from drag, materials on the external surfaces of VLEO satellites may react chemically with AO, resulting in oxidation, erosion, roughening, and degradation of function. Thus, minimizing and predicting drag, as well as maximizing AO resistance, are crucial for proliferated VLEO operation.

We have used molecular beams of O atoms and O₂ molecules, traveling at orbital velocities of ~8 km s⁻¹, to investigate both the AO resistance and drag potential of various (mostly polymeric) materials that are used on LEO satellites or that might be candidates for use. The pulsed molecular beam, produced from a laser-detonation source, was used to expose selected materials to AO fluences up to ~1 × 10²¹ O atoms cm⁻². Some of these materials were also exposed to the LEO environment on the International Space Station to similar AO fluences. In both cases, the effects of the AO exposure were examined *ex situ* by several surface characterization techniques. Materials that exhibited significant AO resistance were used in molecular beam-surface scattering experiments, and the scattering dynamics were measured as a function of both polar (θ) and azimuthal (ϕ) scattering angles on both pristine and pre-exposed sample surfaces. The velocity and angular distributions of scattered O-atoms depend strongly on the incident angle of the impinging atoms and the roughness of the surface in ways that are not a priori predictable. Nevertheless, trends are emerging that point the way to low-drag and AO-resistant material surfaces that have potential for use on VLEO satellites (some examples will be highlighted). Based on the scattering dynamics data, a new gas-surface scattering model has been formulated, allowing for the determination of overall energy and momentum accommodation and for simulations of satellite drag.

Keywords: Atomic oxygen · Molecular beam-surface scattering · Erosion yield · Satellite drag · Very low Earth orbit

Technical Session #4:
VLEO Orbit Control

Technical Session #4:
VLEO Orbit Control

VLEO2025-4-01

Development of a Novel CubeSat-scale Air-breathing Electric Propulsion System

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It is well known that Very Low Earth Orbit (VLEO) missions would provide significant advantages. First, operating closer to Earth's surface greatly benefits communication missions, thanks to the reduction of latency and transmission power for the same data link performance, and Earth observation missions, thanks to the improvement of reconnaissance conditions. In recent years, air-breathing electric propulsion has emerged as a potential enabling technology for long-duration space missions in Very Low Earth Orbit (VLEO). The concept of air-breathing electric propulsion relies on an intake situated in front of the spacecraft to gather the same atmospheric particles that generate the drag. Utilizing electric power derived from solar arrays or batteries, an electric thruster then ionizes and accelerates these particles to generate thrust. By leveraging these limited yet renewable resources, it becomes possible to decouple the spacecraft's lifetime from the availability of propellant, enabling extended mission durations at low altitudes until other life-limiting factors become dominant (such as ATOX exposure).

Extending the lifetime of VLEO assets to just a few years through air-breathing propulsion would already provide a strong argument for the commercial and scientific exploitation of these orbits. Several concepts have been proposed for air-breathing electric thrusters in the literature; however, ground tests have highlighted difficulties in the efficient ionization of the VLEO atmosphere. Moreover, most, if not all, concepts targeted platform sizes in the range 100-1000kg. Such large platforms would incur in significant cost and development time to perform the In-orbit experiment of a high risk/high reward technology such as air-breathing propulsion.

In this work we present the activities ongoing in the framework of the MISTRAL project, aimed at the development and demonstration of a CubeSat scale air-breathing thruster. The device, denominated VOLTA, is based on novel technological solutions specifically tailored to enable the miniaturization of the system and to improve its efficiency at low chamber pressures, making it particularly suited for air-breathing operation. The presented system is designed to be hosted in a 2U CubeSat form factor ensuring a rapid and cost-effective avenue for the deployment in the real operative environment.

Keywords: Air-breathing electric propulsion, CubeSat, Drag compensation

Technical Session #4:
VLEO Orbit Control

VLEO2025-4-02

Passive Vapor-pressure Driven Propulsion for CubeSats in Very Low Earth Orbit

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Very Low Earth Orbit (VLEO) denotes a much lower orbit for satellites, typically below 400 km altitude. Owing to the lower flight altitude, operating in VLEO provides an improved vantage point to observe the Earth as sensors and communication antennas are operating closer to the ground. In turn, this allows academic and government institutions to launch lower-cost observation and communication equipment. However, because of increased atmospheric drag, satellites in such a low orbit typically have a limited orbital lifetime of 3-5 days at approx. 250 km altitude, which is too short to conduct any missions of substance and justify the launch costs. For this reason, VLEO satellites must include propulsion units to offset the high drag experienced, in order to prolong their orbit life to a usable timeframe. While electric propulsion has been considered a solution to counteract drag, the necessary solar arrays that provide power for the propulsion unit, in turn, induce large amounts of drag, resulting in a quicker orbital decay. Completely passive drag-makeup propulsion systems to offset drag offer a significant advantage as no solar arrays are required. The proposed propulsion system, Orbital Small Propulsion Research using Efficient Yields from methanol Vapor for CubeSat Applications (OSPNEY VAPORSAT), generates thrust from the vapor pressure of the propellant, requires no energy after its initiation, and employs a simple design to reduce costs. The thruster produces approximately 185 μN of thrust to oppose the force of drag on the 3U CubeSat which is sufficient to extend the orbital lifetime of a satellite in VLEO. After considering multiple propellant options such as water and ethanol, it was determined that the optimal propellant would be methanol due to its low freezing point and low vapor pressure. OSPNEY VAPORSAT utilizes a two-chamber propellant tank separated by a film of Gore-tex acting as a liquid-vapor phase separator. To stabilize the attitude of the spacecraft attitude, the OSPNEY VAPORSAT module employs a shuttlecock design, taking advantage of the orbital drag. This presentation will elaborate on the research and design considerations for the propellant choice, nozzle size, propellant tank, and passive Attitude Control System.

Keywords: Passive propulsion, vapor pressure thrust

Technical Session #4:
VLEO Orbit Control

VLEO2025-4-03

A high-fidelity orbit propagator and control strategy for VLEO platforms

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Spacecraft in Very Low Earth Orbit (VLEO) could play an important role in improving daily life through enhanced communication, Earth observation and environmental monitoring. Their proximity to Earth enables higher-resolution imagery for improved weather forecasting and disaster monitoring, faster data transmission with lower latency, quicker natural deorbiting to ensure compliance with space debris mitigation policies. However, operating at such low altitudes introduces significant challenges, particularly because of atmospheric drag, which introduces the need of active propulsion systems to maintain operational orbits over extended periods. Additionally, the proximity to Earth makes VLEO satellites more susceptible to variations in the Earth's gravity field. In this research, a high-fidelity orbital propagator is being developed based on simplified Gas Surface Interaction (GSI) models, atmospheric drag simulations, and orbital perturbations due to the non-spherical gravity field of the Earth and third-body attraction by the Moon and the Sun. The software ADBSat by Sinpetru et al. is adapted and customised to improve computational efficiency of aerodynamic forces while maintaining accuracy. The mesh reader of the software is modified to enable quadrilateral and circular facets, thereby reducing the complexity of the panel representation and the number of facets included in the model. Aerodynamic forces acting on the satellite are computed using a simplified facet model at each iteration of the algorithm, with relative flow velocity calculated comprising contributions from horizontal neutral winds. Atmospheric densities and temperatures were sourced from the NRLMSISE-00 model whereas the GSI model by Schaff-Chambre is implemented into the propagator. The high-fidelity propagator's accuracy is compared against GOCE's data, while using precise CAD models and orbits. The accurate estimation of the aerodynamic coefficients relies on the choice of the GSI accommodation coefficients, which remains a significant challenge in the literature. To address this, the propagator is validated using the accommodation coefficient derived by March et al. Following validation, the propagator is utilised on the feasibility analysis of an air-breathing satellite. The satellite's intake is simplified to a flat plate to adhere to the panel method assumptions required by ADBSat. Furthermore, an altitude control law is implemented to maintain the altitude of the spacecraft within 180-200 km range regardless of orbital perturbations and atmospheric properties fluctuations. A parametric study is also conducted to assess the effect of the accommodation coefficient on the satellite's orbit. Numerical simulations demonstrate the ability of the orbital propagator and control law in supporting the design of air-breathing platforms.

Keywords: VLEO Spaceflight mechanics, High-fidelity propagation, VLEO Orbit Control, Air-Breathing Electric Propulsion

Technical Session #4:
VLEO Orbit Control

VLEO2025-4-04

Design of an Autonomous Formation Flight Control System Using Differential Drag and Electric Propulsion in Very Low Earth Orbits

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The utilization of Very Low Earth Orbits (VLEO) offers several significant benefits, such as improved performance for radar and communication payloads to enhance link budgets and less delays, higher resolution imagery, and reduced lifetime for space debris limitations. These benefits make VLEO increasingly valuable for several satellite missions including scientific purposes, technology demonstrations, and Earth observation. Despite the benefits, there are also several challenges such as the atmosphere causing increased aerodynamic perturbations that reduce platform stability and accelerate the orbital decay of the satellites. The objective of this study is to benefit from atmospheric drag through differential drag concept for a formation flying mission accomplished by two non-identical CubeSats, a 6U and a 12U, equipped with paddle like control surfaces to demonstrate an autonomous formation flying control system in VLEO to maintain their relative orbit. Traditional methods of formation control often rely solely on propulsion systems which consume resources that are limited on small satellites. The aim of our approach is to make use of control surfaces to generate differential drag, thereby optimizing a relative motion control that requires less propellant. Electric propulsion system will be aiding the overall control system design mainly for increasing the velocity. These surfaces can be adjusted to the desired angles, allowing precise control over the projected drag area and, consequently, the drag magnitude, which enables effective formation maintenance. This approach employs a custom-designed controller, based on a Linear Quadratic Regulator (LQR), capable of dynamically adjusting drag surfaces located on the four sides of each CubeSat. This allows for optimizing drag modulation using the natural drag encountered in VLEO, enabling real-time adjustments to the relative positioning of the CubeSats.

Keywords: VLEO; Formation Flying; Differential Drag; LQR

Technical Session #5:
Atmosphere-Breathing Electric Propulsion

Technical Session #5:
Atmosphere-Breathing Electric Propulsion

VLEO2025-5-01

Analysis and prospect of key factors to improve the performance of Air-Breathing Electric Propulsion system in China

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Spacecraft operating in Very Low Earth Orbit (VLEO) enjoy performance advantages, but the operational lifespan is severely limited by the additional propellant requirements due to the rarefied atmospheric drag. The Air-Breathing Electric Propulsion (ABEP) system collects sparse atmospheric particles within the orbit to provide propellant for the thruster. Therefore be able to compensate for air resistance for satellites, and can fundamentally solve the problem of propellant demand. A high-performance intake is crucial for providing a stable working condition for the thruster and is vital for the entire Air-Breathing Electric Propulsion system. This reviews summarizes the research progress of air-breathing electric propulsion systems in China. The research results on the key issues such as Gas Surface Interactions (GSI), material properties and internal flow evolution mechanism faced in the development of the inlet. Furthermore a feasibility and mission analysis of the inspiratory electric propulsion system are carried out according to the current thrust performance of the thruster components. The feasibility analysis of the design idea of pure atmosphere capture as power source is carried out, and some suggestions are presented for the future development direction of air-breathing electric propulsion system.

Keywords: ABEP, VLEO, GSI, Flow derivation mechanism, Mission design and analysis

Technical Session #5:
Atmosphere-Breathing Electric Propulsion

VLEO2025-5-02

Development of AERIS: Low-energy throttleable VLEO Air-breathing electric propulsion (ABEP) technology

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Electric propulsion systems for spacecraft have historically relied on mature technologies such as arcjets, resistojets, gridded ion thrusters, electrospray thrusters, and Hall effect thrusters. While these options have proven performance records, they are associated with high costs, specialised propellant requirements, considerable power demands, and deployment challenges, including charge buildup and short-circuit risks.

With the increasing interest in very low Earth orbit (VLEO) missions, there is a demand for new, efficient propulsion technologies that can provide sustained or intermittent thrust to maintain stable orbits at lower altitudes. This study proposes a high-voltage electrical propulsion system. The technology is independent of the generation of any RF, microwave or magnetism, and no need for any neutraliser in the assembly. The proposed solution is an energy-efficient, compact, and robust alternative for space applications.

This research encompasses comprehensive analytical calculations and numerical simulations of electric fields and fluid flow to optimise the thruster's performance in near-vacuum environments, supported by rigorous experimental testing. Prototyping was conducted on a small-scale thruster, with validation testing in vacuum chambers, on vibration platforms, and under radiation conditions, in collaboration with Surrey Space Centre.

Preliminary results indicate a performance improvement over market-available deployed alternatives such as RF or Microwave plasma thrusters, with the proposed technology generating no heat or ionic signature, high resistance to be jammed, and adaptability for different product configurations. The technology can be rapidly deployed in both space-centric and atmospheric environments. The thruster demonstrates excellent endurance and extended operational lifespan, enabled by an optimised feed-line design that aids in the collection of reserve onboard propellant and efficient use of the VLEO environment with sparse atmospheric density.

The use of low-mass molecular gases such as nitrogen, removing the need for additional heavy and expensive noble gases, avoids the release of charged ions in the exhaust and is abundantly available.

The results from the testing and validation performed for simulating high-altitude atmospheric conditions provide a solid thrust-to-power ratio of about 8 mN/W. The system has been proven to work continuously without any massive requirement of electrical energy or additional feed sources, indicating the system's reliability for long-endurance operations while delivering high-key performance from the very first instant.

Further works include enhancements in transformer design, scalability, material improvements, and flow optimisation to maximise thrust efficiency. Planned in-orbit environmental testing, scheduled for late

2025, aims to achieve Technology Readiness Level (TRL) 7, setting the stage for operational deployment across VLEO, supporting long-duration, low-energy propulsion for a range of spacecraft applications.

Keywords: High-voltage thruster, Thrust-to-power, Low-mass propellant, Non-ionic thruster, Atmospheric adaptability, Air-breathing electric propulsion

Air-breathing Electric Propulsion: Testing Approaches and Simulations

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Air-breathing electric propulsion combines an air intake with an electric thruster to collect and accelerate the atmospheric particles in front of the spacecraft. Collecting the propellant from the atmosphere could enable long-duration space missions at very low altitudes, but the complexities of reproducing on-ground an environment representative of VLEO spaceflight hindered the development and the technological maturation of the concept. In the framework of the BREATHE ERC project and the ARIA FISA project, two different but synergic strategies for the characterization of air-breathing propulsion are being developed, merging experiments with modelling and simulations. In this work, we present the design of the BREATHE facility and the parallel development of a numerical suite to simulate the main physical processes of atmospheric neutral and plasma flows. In parallel, a second testing approach based on a rarefied atmospheric flow source and DSMC simulations is being pursued in a joint effort by the Sant'Anna School of Advanced Studies and the University of Pisa for the verification of air-breathing electric thrusters.

When a thruster is pipe-fed via a mass flow regulator, this typically implies a linear relation between the injected mass flow and the gas pressure, resulting in conditions not representative of thruster operation in air-breathing mode. The BREATHE facility comprises a main chamber (M) and an auxiliary chamber (A), which feature dedicated pumping systems. The equipment under test (i.e., the open-inlet air-breathing thruster) will be placed at the interface between the two chambers. By independently regulating the injected mass flow rate and the pressure difference between the two chambers, it will be possible to fine tune the flow properties (in terms of particle flux and pressure) inside the thruster control volume, and thus achieve a good level of representativeness of thruster operation in air-breathing mode. In parallel, the development of a flow source capable of reproducing rarefied fluxes of neutral particles, to be performed in the framework of the ARIA project, will allow for characterizing the intake collection and the effectiveness of integrated thruster-intake configurations.

Finally, we present the neutral flow and plasma chemistry simulations and the capabilities and limitations of the proposed verification approach. The results presented include the estimation of the flow properties resulting in a reference open-inlet, air-breathing thruster test item. The dependence of the resulting flow conditions on the facility control parameters in terms of injected mass flow rate and auxiliary chamber pumping speed are evaluated quantitatively. In combination with state-of-the-art flow modelling techniques and data analysis implemented in the BREATHE Virtual Lab, the mixed physical-virtual laboratory environment will provide an effective platform for the development of air-breathing propulsion systems, contributing to the realization of next-generation air-breathing satellites.

Keywords: air-breathing electric propulsion, vacuum facility, rarefied gas dynamics, numerical simulations, ground testing

Simulation and Configuration Design of Permanent Magnets applied to an RF Helicon-based Thruster

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Satellites in very low Earth orbit (VLEO) experience drag from Earth's residual atmosphere, causing a slow orbit decay over time. However, lower altitudes benefit of optical instruments and communication devices, improving resolution and/or reducing costs. Long-term missions in very low Earth orbits (VLEOs) of about 100 km to 400 km above Earth's surface are not feasible for long-term missions without providing the required thrust to compensate for drag. In a normal satellite, larger fuel volumes would be needed and therefore increasing the mass of a satellite, or reduce the size of the payload in a dedicated mass budget. In an effort to enable VLEOs the Institute for Space Systems (IRS) is developing an Atmosphere- Breathing Electric Propulsion (ABEP) system. The current developed laboratory model design is an electrodeless RF helicon-based Plasma Thruster (IPT). It has been tested at IRS and it features a solenoid that provides an external magnetic field to the thruster assembly to aid in the plasma creation and confinement. Currently, the work is focused on improving the design of the lab model to a vacuum capable model which can be used later as a flight capable model, applicable to CubeSats and small satellites. For these use-cases, the solenoids prove to be heavy and large, and add additional power as well as thermal management requirements. The present work investigates the implementation of a permanent magnet configuration on the IPT as an alternative to solenoids, in order to aid the advancement of the IPT design towards to a flight capable system and as part of an ABEP platform which incorporates a particle collector (i.e. intake) and a dedicated power processing unit (PPU). Different ring magnet configurations suitable for the use of the vacuum model IPT are investigated, featuring an optimal magnetic field topology and extracting performance and plasma properties using a theoretical model for all different configurations. In addition, a sensitivity analysis is incorporated to check the various factors affecting the magnetic field topology as well as an overall simulation process is established. A simple way is proposed of manipulating the magnetic field strength without impacting the field topology by adjusting the internal diameter of the ring magnets and keeping the remaining geometry constant. As a result, potential changes of the field strength and the resulting performance parameters, required by future developments of the IPT, can be accounted for.

Keywords: ABEP, Helicon Thruster, Permanent magnets, Simulation, OpenFoam

Technical Session #6:
ABEP Plasma Physics

Technical Session #6:
ABEP Plasma Physics

VLEO2025-6-01

Progress in ground testing of intake-collector for Air-Breathing Electric Propulsion

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Operation of satellites in Very Low Earth Orbits (VLEO) offers unique advantages. However, the increased atmospheric drag requires frequent compensation through propulsion. The Air Breathing Electric Propulsion (ABEP) concept offers a potential solution by using particles from the residual atmosphere as propellant for electric thrusters. The thrust produced by ABEP systems relies on the efficient collection of particles through intake-collectors. However, this efficiency depends on the scattering dynamics of impinging atmosphere particles and the internal surfaces of the intake-collector. Currently, there is a lack of experimental data and numerical models capturing the scattering dynamics of atmospheric particles on intake-collector surfaces at varying energies and incident angles. Therefore, ground testing is crucial to move the technology forward. In this work, we present a method for measuring transmission probabilities in ABEP intakes, using VKI's Dual chamber for Rarefied Gases ON ground testing (DRAG-ON) facility. The system includes an injection chamber connected to a settling chamber by a testing chamber where the intake-collector sits. Flow is generated with an inductively coupled RF plasma source, and traditional conductance measurements, normally used for thermalized flow, are adapted to DRAG-ON's collimated flow conditions. Our experiments include calibrating ionization gauges using the dynamic method and a known conductance. The calibration results match the manufacturer values and add insights into their uncertainties. We also measured the effective pumping speed in the settling chamber and backflow transmission probability from the intake outlet. Plasma flow was characterized using electrostatic probes, which measured radial profiles of ion current density and point measurements of ion energy distribution functions. We mapped these plasma flow's characteristics and identified several optimal test conditions that produce uniform ion distributions at orbital velocities (6500-7800 m/s). These conditions were then used to assess the aerodynamic performance of the intake. The plasma transmission probability results show good consistency for the selected plasma conditions. Additionally, we evaluated the effect of biasing the intake with different potentials and found small differences in transmission probability. The uncertainty on the measured transmission probabilities was estimated based on Monte Carlo methods. Our analysis showed that the measurement accuracy improves as the ratio of intake ion flux to total injected flow rate increases. Under optimal conditions, we achieved relative uncertainties of 20% (67% confidence interval) for transmission probability measurements, demonstrating the reliability of the developed method for testing ABEP intake designs.

Keywords: Air Breathing Electric Propulsion, Internal Flow, Rarefied Flow, Gas-Surface Interactions, Plasma

Technical Session #6:
ABEP Plasma Physics

VLEO2025-6-02

Current Progress in the Development of an ECR Plasma Source for Air-Breathing Electric Propulsion System

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This contribution presents the current state of development of a resonant plasma source intended for Air Breathing Electric Propulsion (ABEP) applications. ABEP systems offer a promising solution to extending the lifetime of Very Low Earth Orbit (VLEO) missions by using residual atmospheric particles as a propellant. Such systems would operate in very low-pressure environments where plasma ignition and confinement prove challenging. The proposed altitude of operation at 200 km also introduces considerable drag force, establishing the minimum thrust required for continuous operation.

Previous particle simulation efforts conducted within this research have determined the indicative values of in-orbit pressure and drag force acting on the system. Using a simple parabolic intake geometry, the pressure values in the ionization region after passive compression (estimated at 1-10 mPa) and the drag force enable a comparison with laboratory results, allowing for an assessment of development progress. The resonant plasma source introduced in this work is therefore specifically designed to operate with high extraction efficiency within low-pressure environments by utilizing Electron Cyclotron Resonance (ECR). The nature of resonant power deposition allows for ignition and sustain of plasma discharge at pressures comparable with VLEO environment after compression. This approach is unique, as most plasma sources require a minimum pressure to operate, and contemporary studies rarely report successful ignition and operation in such extremely low-pressure environments.

The device geometry comprises independently designed modules, with the main component being a resonator - a high-frequency antenna enveloping the discharge channel responsible for power deposition. An array of magnets ensures both ECR plasma operation and confinement. The extraction is achieved using a set of grids biased at 1000 V to accelerate the oxygen and nitrogen ions. The use of magnetic nozzle is currently in consideration, although, due to the low mass of the ionized particles, the grid system is expected to offer superior acceleration. A pressure gauge and valve allow for fine adjustments of the pressure in the discharge channel, which most commonly contains dry air.

The modular design of the laboratory device supports scalability in dimensions and input power, currently promising an increase in efficiency with an increase in the respective parameters. The performance is calculated from the extracted ion current, showing high thruster efficiency at 23 % while falling short in total thrust and thrust-to-power-ratio estimation using the current setup. The projections show positive trends with respect to a significant increase in power. Future plans include technical upgrades to the device to support powers up to 100 W and verification of the estimated values through direct thrust measurements. In conclusion, the current design allows for high efficiency plasma ignition and operation in extremely low-pressure environments. Successful translation into operational ABEP system relies on the system's ability to positively scale with respect to higher power and larger dimensions as predicted by numerical simulations.

Keywords: Air Breathing Electric Propulsion; Very Low Earth Orbit; Electron Cyclotron Resonance

Technical Session #6:
ABEP Plasma Physics

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Investigation of low temperature rf-plasmas inside a RIT-10 and rf-neutralizer using oxygen/nitrogen gas mixtures as propellant

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Enabling a sustainable and low cost access for small satellites to the very low earth orbit is currently a hot topic in the commercial space sector. The concept of Air-Breathing Electric Propulsion (ABEP), proposed more than two decades ago, has gradually moved in the focus of research in this context. The fundamental idea of ABEP is the collection of residual atmospheric gas, mainly consisting of atomic oxygen and molecular nitrogen, via a collector or intake system, which may be either passive or active. The gas is then compressed and employed as propellant for the thruster system. Given the low overall density of the gas in VLEO (approximately 10^{16} m^{-3}) the achievable mass flows are rather low. Furthermore, the particles impinging on the satellite possess a relative velocity of approximately 8 km/s, and thus create a non-negligible drag. The combination of these two facts means that a thruster system with a high specific impulse is required for ABEP to be viable. A radiofrequency ion-thruster (RIT) together with an rf-neutralizer fulfills this requirement and is a good candidate system for ABEP applications. The operation of the thruster system must be very well characterized over a wide range of densities and compositions of the residual atmospheric gas to ensure a reliable drag compensation. As the RIT operates with a plasma, the plasma conditions must be studied in order to predict the behavior in orbit for different atmospheric conditions. For this purpose, we study the plasma inside the discharge vessel of the RIT-10 and the rf-neutralizer using a Langmuir double probe, THz-time domain spectroscopy (THz-TDS), and optical emission spectroscopy (OES). The plasma parameters are measured at various operation points of the thruster (or neutralizer), including different mass flow rates, input powers, excitation frequencies, extraction currents, and compositions of the O_2/N_2 gas mixture used as propellant. The variation of the plasma parameters obtained for the different operation points are compared with corresponding results of global models of the RIT and the neutralizer in order to better understand their microscopic origin. Of particular interest in these measurements is the electron temperature, as a high electron temperature is indicative of a high plasma potential, and, consequently, a high Bohm velocity. The resulting impact of ions on the grid or ion catcher may cause significant erosion of the materials. This ion sputtering may ultimately limit the operational lifetime of the thruster system.

Keywords: ABEP, RIT, rf-neutralizer, RAM-EP, rf-plasma

Technical Session #7:
Gas-Surface Interactions and Materials

Characterization of RF plasma degradation of Kapton films

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Satellites operating in Low Earth Orbit (LEO) and Very Low Earth Orbit (VLEO) offer compelling advantages for Earth observation, including enhanced image resolution, improved data transfer rates, and reduced launch costs. The environment encountered by vehicles in these orbits consists of atomic oxygen and molecular nitrogen whose energetic collisions with satellite surfaces lead to oxidation, erosion, and degradation of materials, especially those containing organic polymers. Additionally, VLEO operation requires frequent drag compensation which could be achieved by Air-Breathing Electric Propulsion (ABEP) systems. These systems ionize atmospheric propellant to generate thrust but the impingement of ions from the thruster plume into external satellite surfaces can cause additional degradation. While plume contamination has been extensively studied for thrusters using Argon and Xenon, research on atmospheric plasma-surface interactions remains limited.

In this paper, we present ground-based experiments designed to evaluate the interaction between atomic oxygen (AO) ions and Kapton HN. The experiments were conducted in a newly vacuum facility equipped with a RF inductively coupled plasma source that generates AO ions at translational energies typical of VLEO environments. While the plasma source does not replicate the charge state of O atoms, it offers a broader range of conditions, making it adaptable for studying interactions like plume contamination. We chose Kapton HN as the test material because it has been extensively characterized in flight experiments and ground-based studies, allowing us to benchmark the plasma source as a tool for AO exposure studies.

The plasma beam was characterized using electrostatic probes. These included a planar Faraday probe array and a magnetic retarding field energy analyzer, which provided detailed measurements of the radial distribution of ion flux and ion energy distribution, respectively. After exposure to oxygen plasma, the erosion yields of Kapton are assessed with profilometry, using meshed samples to obtain multiple step-height measurements. Morphology changes are evaluated using Scanning Electron Microscopy images of pristine and exposed samples. The measured erosion yields and surface morphology changes of Kapton samples are compared with existing data from atomic oxygen exposure facilities and space missions.

Keywords: Atomic oxygen, Erosion yield, Very low Earth orbit, plasma

Technical Session #7:
Gas-Surface Interactions and Materials

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FEP erosion in VLEO environments: Comparison of ground data and SLATS observations

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It has been considered that FEP is one of candidates for thermal control material applicable to VLEO due to its high durability in LEO environment. However, effect of hyperthermal N₂ collision on FEP erosion needs to be clarified quantitatively to ensure the survivability of FEP in VLEO environment, because FEP erosion is known to be sensitive to collision energy of neutral atoms. In this presentation, we will report the experimental results of quantitative evaluation of erosion yield of FEP due to atomic oxygen (Ey(AO)) and to argon (Ey(Ar)) in a simulated VLEO environment independently. A series of experiments were done by the laser detonation beam source with gas mixing system at Kobe University. O₂ and Ar gases were used as source gases. Note that Ar was used to simulate N₂ collision energy in VLEO. Two beam conditions (50%Ar+50%AO, 70%Ar+30%AO and 90%Ar+10%AO) were used in the experiment. Because FEP erosions in simultaneous exposure conditions of AO and Ar beams are known to be additive, Ey(AO) and Ey(Ar) were evaluated by solving the simultaneous equations regarding mass loss of FEP in two different conditions. The analytical results indicated that Ey(Ar) was more than 6 times greater than Ey(AO). These experimental data were implied that the erosion of FEP in VLEO was mainly due to N₂ collision, and that by AO was a minor factor. This surprising conclusion was supported by the fact that Ey(AO) obtained in this study was close to that measured in MISSE-2 in LEO where N₂ effect was negligible.

Ground-based data obtained in this study were more directly compared to the SLATS/MDM flight data which is the world first and only FEP erosion data in VLEO. The erosion of FEP aboard SLATS was estimated from the reflectance of LED light. Pixel values detected by CCD device were analyzed as described elsewhere. We observed that FEP erosion was proportional to the fluence of N₂ rather than AO. This in-orbit observation also support the conclusion obtained by the ground-based experiments.

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Keywords: Materials erosion, FEP, Atomic oxygen, Nitrogen, VLEO

Atomic Oxygen Resistance of Silsesquioxane-Coated Polyimide Films Studied by LEO/VLEO and Lab Exposures

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The utilization of very low Earth orbit (VLEO) is advantageous for higher-resolution Earth observation, and lower-cost launch and communication. At VLEO environments, highly dense atmospheric gases, whose dominant component is atomic oxygen (AO), collide with satellites at the relative velocity of $\sim 8 \text{ km s}^{-1}$. AO collision results in erosion, roughening, and degradation of organic materials used for thermal control and structure. Furthermore, highly dense gases would induce satellite drag that impacts on the requirements of propulsion system. Having a satellite design and materials that can reduce satellite drag are required for long-lived VLEO satellites. As a candidate of AO-resistant materials, we have focused on a photocurable-silsesquioxane-based coating, SQ, manufactured by TOAGOSEI Co., Ltd. [1] The coating forms a passivating silica (SiO_x) layer through the reaction with AO, which can protect the underlying organic material from further AO attack.

SQ-coated polyimide film was exposed to an LEO space environment for ~ 1 year at MDM2 mission on the ISS. [2] The mass loss of the SQ-coated polyimide film was $\sim 1\%$ that of a polyimide, Vespel, so its high AO resistance has been demonstrated. [2] However, many cracks were formed on the exposed surface during AO exposure with $1.3\text{--}2.1 \times 10^{21} \text{ atoms cm}^{-2}$, although the surface excluding the crack positions looked smooth. Cross-sectional SEM imaging showed that the formed cracks penetrated both silica and SQ layers, and the depth of a crack was $\sim 6 \text{ }\mu\text{m}$. Crack formation on SQ-coated surface was also seen at MDM mission on SLATS. [3] Ground-based AO exposure using a laser-detonation source from JAXA indicated that small cracks are observed at AO fluence of $\sim 3 \times 10^{20} \text{ atoms cm}^{-2}$ or higher, and some of the cracks penetrate even the underlying polyimide film. In addition, cross-sectional Raman spectroscopy showed that AO exposure leads to the change in polymer orientation at the polyimide surface, suggesting that the reaction between the coating and AO would induce internal stress in the coating and polyimide layers. Such cracks may degrade the thermo-optical and mechanical properties of the material and may enhance the satellite drag, because they might promote energy transfer from incidence gases through multiple scattering. Based on the results of LEO and lab exposures, our future work will study on a new, improved silsesquioxane-based coating that is less prone to forming cracks during high-fluence AO exposure.

[1] Kimoto, Y. et al. *J. Spacecraft Rockets* 2016, 53, 1028-1034.

[2] Goto, A. et al. *CEAS Space J.* 2021, 13, 415-432.

[3] Goto, A. et al. *Acta Astronaut.* 2023, 212, 70-83.

Keywords: silsesquioxane, polyimide, atomic oxygen, space exposure experiment, LEO, VLEO

Technical Session #7:
Gas-surface Interactions and Materials

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Modelling Surface Roughness in Gas-Surface Interaction for Orbital Aerodynamics

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The growing density of space objects within the 400 km to 600 km altitude range is generating an increased number of collision warnings during satellite operations, which highlights the urgent need for enhanced orbit prediction capabilities to decrease the likelihood of operational disruptions. The accuracy of existing orbit prediction algorithms is limited by large errors in estimating the aerodynamic coefficients of these objects, which stem from the challenges in accurately capturing how gas particles interact with the objects' surfaces. Currently, the modelling of gas-surface boundary interactions is performed with empirical models with one or two adjustable parameters, like those proposed by Sentman and Cercignani-Lampis-Lord, which are calibrated using in-orbit acceleration data. However, these models do not accurately represent crucial processes at the gas-solid interface that occur on macroscopically rough surfaces, such as multi-reflections and shadowing. Moreover, relying on empirical approaches restricts their applicability to satellites with accessible acceleration data.

We introduce a new physics-based gas-surface interaction model that harnesses the wave-like nature of gas particles to account for the effects of surface roughness on the reflected particle scattering distribution. This model was tested against a Test Particle Monte Carlo simulation involving various rough surface geometries under different incidence angles, environmental conditions, and local scattering laws. The results showed excellent agreement, with relative aerodynamic force errors below 1% across most of the tested parameter space and a maximum error of 6% at the highest level of roughness considered. In a parallel analysis, the model successfully replicated laboratory experimental results of Argon scattering on smooth and rough Kapton surfaces at different incidence angles. This was achieved by adjusting only the roughness parameter while keeping all other variables constant. Finally, the model was used to generate drag coefficients for simple shapes such as a flat plate and a sphere. For the sphere, drag coefficient–altitude trends were calculated using both Langmuir and Temkin isotherms, and the drag coefficients of various high-altitude spherical satellites such as STELLA and GRIDSPHERE were successfully recovered by modifying the roughness parameter alone.

Keywords: Gas-surface interaction, surface roughness, aerodynamic drag, wave scattering, free-molecular flow

Technical Session #8:
Particle Simulation Methods

Investigation of critical aspects for Atmosphere-breathing electric propulsion systems with the Direct Simulation Monte Carlo method for VLEO and ULEO applications.

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The Atmosphere-breathing electric propulsion (ABEP) systems for VLEO and ULEO can offer theoretical advantages since the propellant for the electric thruster can be collected directly from the atmosphere. However, the capability of collection, compressing and thermalizing the incoming flow of an orbiting satellite equipped with the ABEP system is crucial, along with the accurate estimation of the drag force to compensate. Besides recent developments for on-ground tests which require a complex experimental setup, the simulation tools for the rarefied gas-dynamics offer a helpful strategy for the ABEP early development.

The Direct Simulation Monte Carlo (DSMC) method offers a computational tool for the rarefied gas-dynamics application, such as the Very Low Earth Orbits (VLEO) and Ultra Low Earth Orbits (ULEO). The investigation concluded in this study focuses on the errors on the performance estimation yielded by different physical assumptions at different altitudes (150, 180, and 210 km).

First, the impact of inter-particle collisions is examined, quantifying the error between the free-molecular flow assumption and the Variable Soft Sphere collision model, which is relevant at lower altitudes, given the Knudsen number differences between the free-stream and inside the collection and thermalization stage of the atmosphere-breathing propulsion system.

Second, the impact of the gas-surface interaction model on the drag and other performances is evaluated. The widely adopted Maxwellian reflection model is compared to the Cercignani-Lampis-Lord (CLL) model, whose has been extensively adopted for VLEO satellite drag estimation. Both models for gas surface interaction are applied with partially diffuse reflection, as suggested by many studies for lower VLEO satellite applications, with an accommodation coefficient of 0.9 for the Maxwellian reflection, and the same value for the CLL accommodation coefficients for both the tangential and normal energy accommodation.

Finally, for the altitude of interest of 180 km, the impact of the angle of attack (0-20 degrees) on the collection and compression efficiency is evaluated. This aspect is crucial to identify the limits of the propellant delivery to the electric thruster which can result in the electric thruster ignition failing. The results achieved in this study highlight that the threshold of the collection performance starts to decline (~10%) around an angle of attack of 10 degrees. On the other hand, the drag increases from a null angle of attack to the 20 degrees angle of attack increase up to ~35%. This shows that the DSMC simulation can help shed light on crucial aspects of the potential in-orbit test and development of this technology.

Keywords: Gas-surface interaction, Atmosphere-breathing electric propulsion, Intake performance, VLEO, ULEO

A Numerical Investigation of the Effect of Flow Parameters and Wall Models on Gas-Surface Interactions in ABEP Applications

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The power budget of air-breathing electric propulsion (ABEP) systems is closely tied to their ability to compensate for drag. Intake performance is enhanced by increasing the propellant capture and compression ratio, which reduces the demand on specific impulse and contributes to drag compensation. Although there are few particle collisions in the highly rarefied free stream, the parameters of the highly collimated flow from the intake to condenser modules are strongly influenced by wall interactions. As the flow moves through modules of an ABEP system, the flow regime shifts from free molecular to slip with the compression, and gas-surface interactions vary accordingly through the incoming particle collection and compression process. During our current “ABEP Intake End-To-End Simulation & Design” project, supported by the UK Space Agency, the need for an advanced wall model arose to ensure accurate end-to-end simulations and achieve convergence as close to realistic physics as possible. Due to the complexity of gas-surface interactions, a boundary model in a DSMC tool should be developed to adequately represent the reflection kernel for simultaneously modelling multiple interaction physics for various independent particle mixtures with different species. An open-source DSMC solver within a consistently improved and supported suite, such as *dsmcFoam*, is selected to run the flow simulations through the intake and condenser sections of an ABEP system. As the flow regime varies while traveling through the ABEP system, *dsmcFoam* with new dynamic features for altering flow regime will be employed for end-to-end simulations. This is particularly significant for applications like this, where the velocity and energy of particles need to be updated upon impact based on wall properties such as diffuse fraction and accommodation coefficient, and absorption for atomic oxygen in rarefied gas mixtures, through the modules of an ABEP system. It is planned to implement a new boundary condition with gradual improvements within the *dsmcFoam* solver to better predict gas-surface interactions, optimising inlet geometry and assisting material selections for internal surfaces. To initiate this research, a parametric study is being conducted using an extensive simulation matrix to investigate the effects of flow parameters—such as density, velocity, temperature, atomic/molecular species, and angle of attack—and wall model parameters, such as diffuse fraction, on gas-surface interactions. A simplified test geometry was created to run 2D simulations, where the flow interacts with an adjacent wall positioned at 90 degrees to the one of inlet patches. The changes in the drag and skin friction coefficients, force density, and flow properties in the vicinity of the wall are investigated under varying flow and wall conditions.

Keywords: GSI, ABEP, DSMC, *dsmcFoam*

Technical Session #8:
Particle Simulation Methods

VLEO2025-8-03

Particle-based numerical reproduction of the flow in the VKI DRAG-ON facility

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We present the numerical reproduction of the experiments in the DRAG-ON facility of VKI through Particle-in-Cell simulations. The facility is designed to test the performance of intakes for Air-Breathing Electric Propulsion systems in Very Low Earth Orbit (VLEO). The intake model under consideration has a cylindrical section followed by a conical one. A plasma source is used to generate the stream of particles at approximately 8 km/s that reproduce the atmospheric flow on a satellite. The simulations comprise the expansion of the plasma plume from the outlet of the plasma source and its interaction with the intake model. Since ions and electrons do not recombine in the plume, care must be taken to ensure that ions are a sufficiently good analog for the neutral particles in orbital conditions. Therefore, one of the objectives of this study is to assess the differences between the flow produced on ground and the one encountered in orbit. The effect of boundary conditions for plasma injection, background pressure in the chamber, as well as the gas-surface interaction model are analyzed. In particular, a physics-based “modified-washboard” model will be used to treat gas-surface interactions, and compared to the traditional Maxwell (specular-diffuse) and Cercignani-Lampis model. The final objective of this work is to better understand the observed experimental results, to eventually be able to extract information on the interaction of the flow with the intake, fundamental for the extrapolation of performance parameters to VLEO conditions.

Keywords: Particle-in-Cell, simulation, plasma-surface interaction, intake

Technical Session #8:
Particle Simulation Methods

VLEO2025-8-04

Enhanced gas-surface scattering modeling for VLEO satellites in DSMC simulations

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The Direct Simulation Monte Carlo (DSMC) method is a crucial tool for calculating the aerodynamics of satellites in Very Low Earth Orbit (VLEO). However, DSMC simulations fall short in providing high-precision gas-surface scattering models. Implementing such model could vastly enhance mission planning and fuel requirement calculations, ultimately extending operational lifetimes and reducing costs. Moreover, the ability to utilize aerodynamic lift for altitude and orbit control reduces the need for thrusters and fuel. Existing scattering models can only capture the full complexity of the interactions between gas and surface to a limited extent. Molecular dynamics (MD) simulations are excellent for accurately modeling these interactions on a microscopic scale and provide detailed insights into the physical processes involved. However, due to computational limitations, it is not possible to simulate the entire scale of a satellite with MD. We present an advanced modeling technique that is able to use molecular simulation data to create a scattering kernel. This kernel, which represents a conditional probability density function, can be integrated into DSMC simulations, significantly enhancing their accuracy. By embedding microscopic-level insights into mesoscopic simulations, our hybrid boundary condition model seamlessly connects microscopic interactions with macroscopic behavior.

Keywords: Direct Simulation Monte Carlo (DSMC), Gas-surface scattering, Data-based modeling, Hybrid boundary condition model

Technical Session #9:
Aerodynamic Control

Technical Session #9:
Aerodynamic Control

VLEO2025-9-01

Maximization of Lift-to-Drag Ratio for VLEO Platforms using Free-Form Deformation Techniques

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The present work introduces a novel approach to optimize the shape of platforms operating in Very Low Earth Orbit (VLEO) by maximizing their Lift-to-Drag (L/D) ratio. VLEO platforms encounter significant atmospheric drag due to the residual atmosphere at these altitudes, posing challenges for long-duration missions. However, this residual atmosphere can also be harnessed to generate beneficial aerodynamic forces, offering a potential strategy to reduce the costs of orbital maneuvers. To this end, the presented method leverages Free-Form Deformation (FFD) techniques to simultaneously minimize drag and maximize lift through the use of an aerodynamic evaluation tool tailored for free molecular flow. Central to this approach is a custom-developed shape generator, which converts parametric geometries into 3D meshes, enabling efficient exploration of various configurations. A first test case is conducted on a sphere under volume and bounding box constraints to validate the optimization framework, allowing the algorithm to explore optimal shapes within defined physical limits. The results are analyzed and benchmarked against previous studies, demonstrating notable potential for improving aerodynamic performance. Subsequently, we extend the study to a more complex shape and apply the same FFD-driven optimization. This second test case explores the potential of exploiting non-conventional geometries in VLEO environments, where the trade-offs between lift generation and drag reduction are crucial for mission efficiency. Preliminary results demonstrate the effectiveness of the proposed shape optimization strategy in refining vehicle configurations for enhanced aerodynamic performance. The findings are anticipated to offer valuable insights into the design of future VLEO platforms, potentially increasing mission lifetimes and reducing fuel requirements through more efficient aerodynamic designs.

Keywords: Lift-to-Drag, FFD, VLEO, Optimization, Shape, Aerodynamics

Technical Session #9:
Aerodynamic Control

VLEO2025-9-02

Propellant-less Steering Law for Mitigating Orbital Decay in Small Satellites Using Aerodynamic Forces and Solar Radiation Pressure

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The growing demand for low-cost, versatile small satellites in Low Earth Orbit (LEO) has significantly increased orbital traffic, amplifying the challenge of sustaining satellite missions without onboard propellant. These satellites are often deployed in orbital regimes where atmospheric drag and solar radiation pressure (SRP) constitute the main non-conservative forces, often of comparable magnitudes. In Very Low Earth Orbit (VLEO), aerodynamic lift also becomes a critical factor. Non-propulsive control techniques leveraging aerodynamic forces (both drag and lift) and SRP offer promising alternatives for maintaining and adjusting satellite orbits. This paper introduces a propellant-less steering law that exploits drag, lift, and SRP forces to mitigate orbital decay, optimizing satellite orientation to minimize cumulative deceleration effects.

The proposed approach calculates the optimal cross-sectional area for drag, lift, and SRP influences, effectively reducing orbital decay. Applied in simulations to ongoing small satellite missions under realistic operational constraints, the method demonstrates notable decay reduction compared to historical mission data. Additional preliminary analyses on a generic nadir-pointing satellite show that this steering approach not only mitigate decay but can also enable slight orbit raising, depending on satellite geometry and orbital parameters. A flight envelope detailing the range of achievable orbital decay reduction across different small satellite classes in VLEO based on key parameters such as altitude, orientation, and geometric configuration will be presented. The analysis provides a comprehensive framework for mission and vehicle design in VLEO.

Keywords: VLEO, drag, lift, SRP, orbital decay

Technical Session #9:
Aerodynamic Control

VLEO2025-9-03

Machine Learning-Based Quasi-Optimal Feedback Control for a Propellantless Collision Avoidance in (Very) Low Earth Orbit

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The increasing number of objects in (Very) Low Earth Orbit makes active collision avoidance strategies imperative for the safe operation of satellites within this region. Satellites lacking dedicated propulsion systems can utilize aerodynamic forces as a method for executing active collision avoidance manoeuvres. When applied effectively, this approach enables the adjustment of the in-track separation distance by appropriately varying the ballistic coefficient, thereby reducing the likelihood of collisions.

This study proposes a novel Deep Learning (DL)-based feedback control system to manage the possible uncertainties and fluctuations due to the atmosphere and aerodynamic modelling. A Direct Simulation Monte Carlo (DSMC) approach is used to model the aerodynamics of the satellites, thereby providing a comprehensive understanding of the atmospheric interactions at varying altitudes. The proposed method considers an optimal drag-based collision avoidance algorithm previously developed by the authors to generate the training set. These optimal control solutions are based on a joint cost function involving the maximization of the miss separation distance while concurrently minimizing the orbital decay. By dynamically adjusting the ballistic coefficient through the angle of attack, the system significantly mitigates the risk of collisions with other objects in orbit.

In contrast to conventional approaches, often relying on time-optimal analytical solutions and on restrictive assumptions such as constant atmospheric density or limited control strategies (e.g., bang-bang solutions), the proposed DL-based feedback control system offers a more adaptive and robust mechanism for collision avoidance.

The results demonstrate the effectiveness of the proposed control algorithm in performing feedback control even in the case of perturbances and uncertainties in both the atmospheric and aerodynamic models. The findings underscore the importance of integrating advanced modelling techniques and adaptive control strategies in addressing the challenges posed by increasing space debris and satellite congestion.

Keywords: CubeSat; satellite aerodynamics; propellantless control; collision avoidance; (Very) Low Earth Orbits

Technical Session #9:
Aerodynamic Control

VLEO2025-9-04

Operationalizing Differential Drag Control: A Planning Routine for the S-Net Satellite Formation

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The increasing deployment of nanosatellite constellations / formations in Low Earth Orbit has amplified interest in aerodynamic control methods such as the usage of differential drag to manage satellite formations. These manoeuvres offer a simple methodology for influencing the relative motion of satellites without requiring a traditional propulsion system. From a theoretical point of view, differential drag control manoeuvres can be commanded at any point in time and for the desired duration, as they only require a change in the satellite attitude to vary the residual drag. However, practical challenges encountered during previous in-orbit drag control campaigns using the BEESAT- 4 CubeSat have highlighted the importance of considering the operational constraints during the planning process as they significantly limit the effectiveness of the manoeuvres. This paper, which focusses on the S-Net satellite formation consisting of four 9kg nano satellites based on the TUBiX10 platform and launched in 2018, which builds upon the results of the BEESAT-4 campaign as well as previous differential drag campaigns conducted for S-Net, presents the concept for a more sophisticated planning routine for practical in-orbit aerodynamic drag manoeuvres. The aim is to develop and validate an adaptable methodology for the design of differential drag control manoeuvres incorporating the effect of operational constraints as well as the uncertainties in the environmental parameters into the manoeuvre planning process. The potential manoeuvre scenarios are calculated via linearized relative motion equations using state of the art models for the environment (NRLMSISE-00) as well as satellite aerodynamics (ADBSat). By incorporating the most dominant constraints, i.e. a reduced satellite availability and the limited accuracy of the attitude control system, into the manoeuvre planning process, the effect of these constraints on the manoeuvres can be analysed and valuable conclusions can be drawn for future application. Furthermore, the study includes uncertainties of the aerodynamic parameters to provide a range of possible outcomes for the resulting manoeuvres. By implementing these limitations in the analysis, the resulting tool can be used effectively during the manoeuvre design process to develop manoeuvre sequences that achieve the goal of the mission despite the constraints. The paper concludes by proposing a final manoeuvre design for a future in-orbit demonstration of differential drag control with the S-Net constellation. This design incorporates realistic assumptions for the dominant operational constraints and parameter uncertainties and provide a range of expected outcomes for the chosen manoeuvre sequences. Finally, necessary future steps required for enhancing the scientific output of future in-orbit campaigns are presented and discussed.

Keywords: CubeSat; satellite aerodynamics; propellant-less control; collision avoidance; satellite formation flying; differential drag

Poster Session

VLEO2025-0-02

ROMEO a MEO and VLEO research platform: Design considerations for the VLEO applications

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The University of Stuttgart presents the Research and Observation in Medium Earth Orbit (ROMEO) mission, which aims to demonstrate cost-effective technology in various orbital regimes. While the apogee of the satellite is raised towards the Medium Earth Orbit (MEO) beyond 2500 km altitude, its perigee is simultaneously lowered into Very Low Earth Orbit (VLEO) of less than 300 km by an in-house developed water-electrolysis propulsion system.

While the satellites goal is research in MEO, the VLEO mission phase provides unique opportunities to investigate the specific impacts of the residual atmosphere and orbital characteristics on the innovative technologies, that are part of this research satellite platform. The mission design allows for a comparative study of dynamics between VLEO and MEO, enhancing our understanding of the effects between these regimes and the interaction with satellite systems.

This paper focuses on how VLEO conditions influence key systems, including particle radiation detectors, Langmuir probes, Perovskite solar cells, and various optical systems, while also examining the operational challenges posed to the spacecraft's Attitude and Orbit Control System (AOCS). The higher particle density in VLEO significantly affects manoeuvrability, which necessitates innovative disturbance torque mitigation strategies. This research provides valuable insights into the development of future VLEO satellite technologies and their operational considerations. As a showcase for practical application, the implementation on the ROMEO satellite is presented.

Keywords: Small satellite, VLEO, MEO, operations, water propulsion, COTS systems

Poster Session

VLEO2025-0-03

VLEO optical satellite tracking and satellite laser ranging technology development

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The Institute of Technical Physics (ITP) of the German Aerospace Center (DLR) operates a 1.75 m optical telescope at the observatory in Empfingen (Germany, northern black forest). The telescope is capable to track RSO (resident space object) with a speed of up to 10° per seconds. To determine the telescope tracking performance for VLEO (very low earth orbit) satellites, tests have been conducted using GOCE (gravity field and steady-state ocean circulation explorer) satellite TLE (two line element) and synthetic VLEO TLE. In addition, sCMOS camera observations of LEO (low earth orbit) RSO for zenith passes have used to determine optimized VLEO optical tracking settings. For VLEO satellite operations, ITP develops a novel laser method for satellite laser ranging (SLR) and attitude determination within the collaborative research center (CRC) 1667 of the University of Stuttgart. This SLR method is based on chirped pulse compression of eye-safe laser radiation. We present the initial hardware design layout of the laser system and optical link budget calculations for VLEO RSO.

Keywords: VLEO, optical tracking, laser ranging, attitude determination

Poster Session

VLEO2025-0-04

Atomic oxygen densities in VLEO measured by SLATS/AOFS mission

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Very high density of atomic oxygen (AO) in VLEO region is one of the most important concerns for developing long-life VLEO satellite. Total AO fluence needs to be evaluated for developing VLEO satellite, however, previous measurements suggested that the AO densities predicted by NRLMSISE-00 include fairly large error. One of the purposes of Superlow Altitude Test Satellite (SLATS) / atomic oxygen fluence sensor (AOFS) mission is to evaluate AO density in real time using polyimide-coated QCMs. AO density was measured in every 3 minutes (maximum resolution is 2 s) during selective period of SLATS operation. AOFS components, which consisted of temperature-controlled polyimide-coated quartz crystal microbalance (QCM) and a mechanical shutter system, was used for this measurement. AO densities at 216.8 km in altitude were analyzed by the frequency shifts of QCM sensors. In order to evaluate the AO density, shadowing effect by the SLATS fuselage and accelerated erosion effect of polyimide by simultaneous collision of N₂ were both taken into consideration. AO densities, thus calculated, were compared to those predicted by the NRLMSISE-00 atmospheric model. It was confirmed that the relative AO densities measured and predicted by the model showed similar distribution in geomagnetically quiet condition. However, the absolute densities of AO measured by the SLATS were much lower than those predicted by NRLMSISE-00 atmospheric model (one half to one third, depending on the latitude). A low density of AO was also suggested by the drag data of SLATS. It is concluded from these comparisons that NRLMSISE-00 atmospheric model overestimated AO density in all altitude range measured by SLATS.

A part of this study was supported by KAKENHI from JSPS under contract #22H01682, #22H01681 and #22K18859.

Keywords: Atomic oxygen density, SLATS, NRLMSISE-00, shadowing effect

Poster Session

VLEO2025-0-05

Modeling atmosphere-breathing cathode-less thruster based electric propulsion systems

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This study explores the preliminary propulsive performance of an Air-Breathing Electric Propulsion (ABEP) system, specifically focusing on a cathode-less RF plasma thruster using atmospheric air as propellant. ABEP technology, which utilizes the atmosphere as a propellant source instead of a stored reservoir, shows promise as a clean, efficient, and sustainable solution for Very Low Earth Orbit (VLEO) missions. To support its development, this work employs a Global Model (GM) incorporating 177 chemical reactions among 8 species to simulate plasma chemistry dynamics, including electronegative effects. Subsequently, these properties serve as inputs for a quasi-1D analytical propulsive model, which models the transport of plasma in the expansion cone and magnetic nozzle (MN). From the results obtained employing the MN model, an estimation of the propulsive figures of merit such as thrust, Isp, and thruster efficiency, are provided. The GM estimates thrust and specific impulse at various power levels and compares the performance of air to that of conventional propellants like xenon and iodine. Further, the study assesses the impact of variable air inflow concentrations, analyzing species densities and plasma behavior at altitudes of 200, 300, and 400 km. The findings corroborates the potential of atmosphere-breathing thrusters for VLEO missions, providing guidelines for designing the thruster and assessing the feasibility of ABEP systems for sustained low-altitude operation.

Keywords: ABEP, cathode-less thruster, global model, simulation, performance analysis

Poster Session

VLEO2025-0-06

End-to-end test campaign design and preparation of an ABEP system developed at IRS

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To achieve a feasible lifetime of several years, most satellites are deployed in orbits higher than 400 km. Drag of residual atmosphere causes a slow orbit decay, resulting in the de-orbit of the spacecraft. Optical instruments or communication devices would, on the other hand, greatly benefit from lower altitudes either to gain better resolution or to reduce cost. For an orbit range of 150-250 km, atmosphere-breathing electric propulsion (ABEP), which utilizes the residual atmosphere as propellant, could be a potential solution. In the frame of the ESA-funded project ram-CLEP, the Institute of Space Systems (IRS) is developing a compact design of a vacuum capable electrodeless RF Helicon-based plasma thruster (IPT), based on the heritage of the lab-model thruster developed within the EU Horizon 2020 project DISCOVERER, to cope with the VLEO environment. In this activity, the development of a passive particle collector (i.e. intake) is also undergone, aiming for the development of an ABEP system. The intake concept has already been identified as a specular coated paraboloid, with the principle proven via numerical simulations. This system is aimed to be tested both in sub-system level (i.e. thruster, intake) and in system level (thruster and intake together) in an end-to-end test campaign, where a dedicated power processing unit (PPU) for operating the thruster and a particle flow generator (PFG) to create relevant environment parameters (e.g. particle species in VLEO such as atomic oxygen, relevant orbital velocities). The lab-model IPT will be used as a PFG, a device that was successfully ignited and stable operated at power levels in the range of 50-300 W with propellants argon, nitrogen, and oxygen during DISCOVERER project. Recently developed instruments to measure performance allow for further characterization. The momentum flux probe allows thrust measurement and mapping of the plume and it will be used to firstly characterize the PFG and later in the end-to-end test the whole ABEP system. The intake will be characterized on sub-system level using a proposed Patterson probe design. Additionally, optical emission spectroscopy (OES) methods will be utilized into the end-to-end test campaign, characterizing the plasma plume of the PFG as well as the vacuum-model IPT. In this contribution, the design and preparation of an end-to-end test campaign of an ABEP system will be shown as well as test plan and facility aspects will be discussed. Finally, an assessment of system's foreseen characterization with relevant propellants and diagnostics will be presented.

Keywords: ABEP, Helicon Thruster, Intake, Diagnostics, Particle Flow Generator, End-to-end test

Poster Session

VLEO2025-0-07

Impact of hyperthermal oxygen on alumina surfaces investigated by molecular dynamics simulations

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Atomic oxygen (AO) impinging on satellite surfaces in very low Earth orbit (VLEO) transfers momentum and energy, leading to material degradation and drag forces. To be able to counteract these effects, we investigate the impact mechanisms of AO on both crystalline (0001) and amorphous alumina (Al_2O_3) surfaces, which occur as oxidized surface layers of bulk aluminium, commonly used in satellite design. Al_2O_3 also serves as a protective coating for solar panels, often covering extensive satellite surfaces.

Using Molecular Dynamics (MD) simulations with classical and machine-learned (ML) force fields, we gain insights into material stability, angular distributions of reflected particles, and adsorption rates. Our findings indicate that bare Al_2O_3 does not degrade under AO impacts but accumulates oxygen due to high adsorption rates. Near ab initio accuracy ML-MD simulations reveal that dependent on the incidence angle, between 85% and 93% of AO impacts result in adsorption.

The angular distribution of reflected particles is highly dependent on the surface structure and the angle of incidence, with a higher ratio of specular reflection observed on smoother surfaces and at larger incidence angles.

Keywords: atomic oxygen impingement, adsorption, angular distribution of reflected atomic oxygen, molecular dynamics

Poster Session

VLEO2025-0-08

Thermal affected behavior of Perovskite Solar Cells for Space Applications

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Solution-based metal halide organic-inorganic perovskite solar cells (PSCs) have attracted considerable interest due to their affordable and easy fabrication and their remarkably improved photoconversion efficiency >26%. In addition, the ability to fabricate PSCs on flexible substrates opens up promising manufacturing routes and novel applications, such as lightweight photovoltaic devices for space applications such as VLEO satellites. In these environments, the cells are exposed to harsh conditions such as vacuum and high temperature cycling. The stability behavior in general and for space conditions for these cells is not yet well understood. As a result, PSC research has largely overlooked how these semiconductors with different substrates with different mechanical and electrical properties would behave under operational conditions.

In particular, the PSC, which consists of multiple organic and inorganic charge transport layer cells, must withstand multiple thermal cycling steps, resulting in a high stored thermal stress in the entire device stack due to the different thermal expansion coefficients of the different materials. Other phenomena to be considered are phase transitions into different crystal symmetries of the perovskite structure, which also induce lattice strain and change the electrical and optical properties. This becomes relevant when the perovskite is cooled. Heating the perovskite leads to chemical decomposition. The organic part and the iodide and bromide could leave the crystal lattice, leading to a defective crystal structure and the formation of lead iodide.

We have shown that brittle perovskites are susceptible to mechanical failure (i.e. fracture and delamination) under planar biaxial stress, which accelerates their chemical and structural degradation. In addition, the thermal distortions in the underlying substrates lead to halide migration and crystalline reorganization in the perovskite, resulting in an open circuit voltage penalty due to phase segregation. However, these effects are directly or indirectly dependent on the surrounding atmosphere, supported by the vacuum conditions relevant to space applications.

In addition, current-voltage measurements were carried out to follow the performance of the solar cells through the thermal cycle. The results showed that the thermal stresses and phase transitions that occur at low temperatures lead to a drop in the performance. Interestingly, the efficiency could be improved by cooling and reheating to room temperature.

Thus, our work would be important for predicting solar cell behavior in VLEO and is beneficial for using the knowledge gained from the temperature cycling experiment to explain the different thermal degradation behavior of perovskite solar cells.

Keywords: Solar Cells, Perovskite, Thermal behaviour, Vacuum conditions

Poster Session

VLEO2025-0-09

Simulation of plasma-spacecraft interaction and charging in very low Earth orbit using particle methods

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Satellites operating in Very Low Earth Orbit (VLEO) encounter the ionosphere, a region composed of neutral and charged particles that can significantly influence their performance and ultimately their lifetime. While the impact of neutral gas on satellites, such as aerodynamic drag, is relatively well understood, the interaction between satellites and ionospheric plasma is far more complex, making it difficult to fully predict the effects on satellites. This study focuses on modelling and simulating spacecraft interaction and charging processes using stochastic particle methods, with a particular emphasis on the effects of non-equilibrium velocity distribution functions on charging behaviours, such as the Kappa distribution, commonly used for the description of nearly collisionless space plasmas, including those in auroral zones in VLEO. Understanding these influences is crucial for qualitatively describing resulting mechanisms, such as plasma-induced charged drag, which has been shown to potentially affect the orbital stability of VLEO satellites. The development of accurate satellite charging models for VLEO includes a series of simulations across various satellite geometries, ranging from simple spheres to fully 3D models, with validation through on-ground experiments for spherical cases. These results aim to provide new insights into the complex dynamics and modelling of satellite-plasma interactions and improve understanding of the effects under different plasma states.

Keywords: spacecraft plasma interaction charging particle simulation

Poster Session

VLEO2025-0-10

Scattering of thermal Ar atoms at space-exposed Kapton surface and a GSI model for drag mitigation studies

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To achieve a long-life VLEO satellite, development of air breathing ion engine (ABIE) system is a key technology. ABIE has to compensate atmospheric drag of a VLEO satellite. If ABIE does not produce sufficient thrust, reducing the satellite drag helps achieving a long-life VLEO satellite. Since atmospheric drag of a satellite is originated in momentum transfer of molecules scattered at the satellite surface, scattering pattern and energy accommodation of reflected molecules are quite important. The most widely used gas-surface interaction (GSI) model used in DSMC calculation is Maxwell model. Maxwell model combines diffusive scattering and specular scattering in a certain fraction of gamma. A constant value of gamma has been used regardless the incident angle of molecules. Maxwell model may be valid for well-defined surfaces, however, it might not be suitable for applying engineering surfaces such as surface of thermal control materials.

In this study, we measured the thermal Ar beam scattering pattern at ISS-flight sample. The ISS-exposed Kapton was exposed to real LEO environment for 434 days ($2.6\text{-}3.3\text{E}+20$ atoms/cm²) by the external hand rail attachment mechanism (ExHAM) on ISS. It was clearly observed that (1) the scattering pattern depends strongly on the incident angle of the molecules, and (2) ISS-exposed Kapton showed strong diffusive scattering at surface normal direction due to its surface texture. These scattering patterns are different from that used in Maxwell model in both cases. According to the fact described above, we developed a GSI model for drag mitigation studies and estimated the atmospheric drag of SLATS. Detail of this GSI model as well as the computational results will be presented.

A part of this study was supported by KAKENHI from JSPS under contract #22H01682, #22H01681 and #22K18859.

Keywords: Molecular scattering pattern, space-exposed Kapton, DSMC, GSI model

Poster Session

VLEO2025-0-11

Material Optimisation Strategies for Very Low Earth Orbit (VLEO) Spacecraft: An Analysis Using the AERIS Platform

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This study provides an in-depth analysis of material selection for spacecraft operating within the challenging environment of Very Low Earth orbit (VLEO), where conditions demand highly specialised materials due to unique environmental stresses. The VLEO region introduces distinct challenges characteristic of both space and aerospace environments, including exposure to space radiation, low-pressure conditions, extreme thermal fluctuations in the Thermosphere, significant atmospheric drag, charged particle fields, and the threat of space debris impacts.

Our research uses the AERIS platform, a VLEO-optimised spacecraft developed by Stars Edge Ltd, as the basis for testing robust material solutions suitable for these conditions. Operating in VLEO subjects spacecraft materials to intense atomic oxygen exposure, high-frequency thermal cycling, and concentrated radiation levels, each accelerating material degradation. Materials selected for AERIS must therefore ensure structural resilience and integrity for critical systems, including propulsion units, while also offering advanced insulation to shield against internal electric discharge and electromagnetic interference—thus functioning as a Faraday cage for sensitive electronic systems.

This paper examines degradation mechanisms associated with VLEO and evaluates how various materials, particularly composites, perform under these conditions. Composite materials are investigated extensively for their superior strength-to-weight ratio, manufacturability, and lightweight properties, essential for spacecraft casings that require both high durability and effective electrical insulation to protect proximate components.

Testing was conducted through a rigorous multi-stage program at Surrey Space Centre and Cranfield Eagle Lab, incorporating a life cycle assessment (LCA) framework that spans design, verification, and validation. Tests included thermal cycling, oxidation, and radiation resistance simulations to replicate VLEO operational conditions closely. This iterative approach enabled continuous refinement in material composition, shape, and dimensions to maximise durability and functionality.

The outcomes of this research offer crucial insights into material optimization strategies for VLEO spacecraft, paving the way for innovations in spacecraft design and contributing to the future development of air-breathing electric propulsion systems. This work provides a foundational perspective on enhancing spacecraft performance in lower altitudes, ultimately advancing space mission capabilities in VLEO.

Keywords: Composites; Atomic Oxygen; Drag; EM Control; Space Materials; Life Cycle Assessment;

Poster Session

VLEO2025-0-13

Design Analysis Methodology for Combined Passive and Active Control Systems in VLEO Satellites

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The operation of satellites in very low Earth orbit (VLEO) offers significant advantages for spacecraft platforms and mission design. For Earth observation missions, lower altitudes enable smaller or less powerful payloads to achieve comparable performance, enhancing the overall conceptual design of satellite constellations. RedWire is designing a VLEO platform, under the name Phantom enabling cost-effective solutions for VLEO mission.

Operating in VLEO introduces unique challenges, particularly related to the increased atmospheric density, which affects satellite stability and control. The aerodynamic forces and torques experienced by satellites in VLEO are significantly higher than those in higher orbits, necessitating robust and efficient Attitude and Orbit Control Subsystems (AOCS). These conditions demand innovative design approaches to ensure that satellites can maintain their required attitude and perform their missions effectively.

Despite the benefits, VLEO operations pose several challenges, particularly in the design and implementation of the AOCS. When designing control systems for a VLEO platform, it is important to take into account the environmental perturbances that will define the passive control solution of the system, as well as the active control solutions. Considering both at earlier stages of the design will enhance a more efficient design of the platform in terms of control for VLEO across the different AOCS modes requirements.

One of the primary difficulties is understanding the specific requirements defined by the design, such as the necessary level of aerostability by design or the tuning of the inertia characteristics. The increased atmospheric drag in VLEO affects the satellite's attitude, making it essential to balance passive and active control strategies effectively. There are multiple trade-offs to consider, such as the size and number of control units, the integration of new AOCS components, and the cost-effectiveness of different control methods. These trade-offs impact the overall decision-making process at the design stage, influencing the satellite's stability, performance, and mission success.

The approach involves analyzing the spacecraft design to achieve passive stability for coarse pointing through aerodynamic torque and gravity gradient effects, and having an active control system to improve performance and robustness. The trade-off analysis includes review of the platform design and identifying cost-effective methods to meet coarse pointing requirements while minimizing active control usage. Detailed modeling of aerodynamic torques and stability derivatives is conducted for various geometries, linking the geometrical design with stability and response.

This study aims to define an optimal method for determining control strategies by simplifying the non-linear system problem. By linking different contributions and deriving simple equations for steady-state responses and transient evolution, the study demonstrates how each factor (aerodynamic torques, gravity gradient, magnetorquers, reaction wheels, and sun sensors) contributes to the performance of the system. The findings provide a comprehensive modeling approach to aerodynamic torques and stability derivatives for both simple and complex geometries, offering a robust solution for VLEO satellite control.

Keywords: VLEO; Control System; Phantom

Poster Session

VLEO2025-0-16

Aerodynamic Attitude Control of Very Low Earth Orbit Satellites: Simulative Analysis and Insights into Nonlinear System Properties

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Satellites operating in the Very Low Earth Orbit regime, that is, at altitudes between 250 and 450 km, encounter significant aerodynamic forces which are traditionally considered disturbances in spacecraft attitude control design. Instead, active control methods seek to harness these forces using the torques generated by adjustable aerodynamic surfaces as an additional means of external actuation. In this publication, we examine the nonlinear structure of the control problem for a satellite featuring a reference geometry in a feathered configuration with four rotatable surfaces. We argue that challenges for the control design include uncertainty in aerodynamic and atmospheric models as well as time-varying parameters such as density and thermospheric temperature. Furthermore, our work emphasizes that low lift-to-drag ratios not only negatively impact control authority around the roll axis but also significantly restrict the region of validity of the linearized system, complicating allocation procedures. To highlight the effects on control performance, we introduce a custom simulation tool designed for testing rotatable panel geometries under VLEO conditions and present a case study that illustrates the limitations of linear control design methods. Finally, we formulate these system properties in a systems theoretical framework and discuss potential nonlinear control strategies and the need for stability guarantees to further advance the field of aerodynamic attitude control in VLEO.

Keywords: VLEO, Aerodynamic Attitude Control, Simulation, Nonlinear Dynamics, ATLAS

Poster Session

VLEO2025-0-17

Extremely Low Earth Orbit Imaging and Technology Explorer (ELITE) Satellite Platform System Configuration & Development

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The Extremely Low Earth Orbit Imaging and Technology Explorer (ELITE) is a microsatellite developed to demonstrate sustained flight in very low Earth orbit (VLEO). This initiative is part of an intercollegiate, academia-industry program fully funded by the Singapore government and led by the Satellite Research Centre (SaRC) at Nanyang Technological University, Singapore.

The development of VLEO satellites represents a transformative advancement in satellite technology, offering enhanced capabilities in Earth observation, communication, and space-based sensing. The Singapore team has led pioneering research and development in this field, addressing challenges such as increased atmospheric drag and orbital decay through innovative solutions. Key breakthroughs include the integration of advanced aerodynamic control systems, high-efficiency propulsion mechanisms, and resilient satellite structures engineered for sustained operation in the harsh conditions of VLEO. The mission's first demonstration payload features a locally designed high-resolution imager utilizing time-delay integration (TDI) technology, showcasing the potential of compact and efficient imaging systems.

This multidisciplinary effort draws on expertise from engineering, materials science, and computational modelling to optimize satellite design and operations. These advancements push the boundaries of satellite miniaturization and efficiency, paving the way for sustainable and cost-effective satellite deployment strategies. The qualification model of the satellite platform is ready, and the satellite is currently in the improvement and flight model fabrication stage.

Poster Session

VLEO2025-0-18

Real-time Atomic Oxygen Detection Using Transition Metal Oxide Coated Hydrogen-Terminated Diamond Surface

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Atomic oxygen (AO) is a major cause for the deterioration of spacecraft materials, such as polymers, composites, and optical coatings, in low Earth orbit (LEO). AO exposure can degrade thermal, mechanical, or optical system performance, potentially leading to premature mission failure. Future missions, especially for remote sensing, are designed for very low Earth orbit (VLEO) where the variations of thermospheric density and AO flux are more significant than in higher orbits. Therefore, accurate real-time assessment of AO fluence irradiating spacecraft surfaces becomes a crucial issue for mission success, as well as for improving current thermospheric density models.

We present a compact, solid-state sensor with high sensitivity and fast response to AO. The sensor is based on a hydrogenated diamond substrate and transition-metal oxide (TMO) coating. Tungsten oxide, WO₃, with thickness ranging from 6 nm to 30 nm is used as the TMO coating of choice. The Diamond:H-Transitional Metal Oxide AO sensor (DiMO) was characterized using RF plasma-based and laser detonation AO facilities. The results show a linear increase in electrical resistance as a function of AO fluence of up to 2×10^{20} O-atoms·cm⁻², as tested in a ground-based laser detonation AO beam facility. The sensitivity of the sensor is found to be tunable, ranging from 10^{-14} to 10^{-15} Ω·O-atoms⁻¹·cm⁻², and is inversely dependent on the coating thickness.

This work demonstrates the potential usage of diamond-based devices for VLEO real-time AO flux monitoring. Furthermore, compact dimensions and minimal power consumption of the DiMO sensor make it an ideal low-cost solution for the emerging "new-space" era, including nanosatellite applications.



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