AEROVEL: Aerodrag Estimation for Very Low Earth Orbits

Executive Summary

Study

Related OSIP Campaign : VLEO - New ideas for the nearest of outer space

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Activity summary:
Aerodrag is a dominant force acting on spacecraft operating in Very Low Earth orbit (VLEO). Accurately measuring aerodrag is essential for precise orbit determination and orbit control, consequently, precise attitude determination, better collision avoidance, and longer life missions. Conventional methods for aerodrag estimation rely on GPS measurements with simplified onboard models, which can be unreliable or inaccurate due to environmental factors, such as atmospheric disturbances or ionospheric scintillation. This study employs Pressure / Force sensors, Temperature Sensors, and mass spectrometers to estimate density / aerodrag. The activity will perform simulation of the suitability of these sensors and make a proposal for future work.

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1. Introduction

The AEROVEL (Aerodrag Estimation for Very Low Earth Orbits) project addresses a critical challenge in spacecraft operations at very low Earth orbits (VLEO). Aerodrag is a dominant force acting on spacecraft in VLEO, and accurately measuring it is essential for precise orbit determination and control, which consequently enables precise attitude determination, better collision avoidance, and longer mission lifetimes.

The purpose of this activity is to investigate and evaluate different sensor technologies that can directly measure atmospheric density or closely related parameters in VLEO. This approach aims to provide a more robust method for aerodrag estimation compared to conventional methods that rely on GPS measurements with simplified onboard models, which can be unreliable or inaccurate due to environmental factors such as atmospheric disturbances or ionospheric scintillation.

The scope of work encompasses a comprehensive assessment of various sensor technologies suitable for VLEO applications, including pressure/force sensors, temperature sensors, and mass spectrometers that can analyze the mass and abundance of gas atoms and molecules. Each of these technologies offers unique advantages and disadvantages, making the selection of the most appropriate sensor dependent on specific mission requirements.

The objectives of this report are to:

- Evaluate different sensor technologies suitable for VLEO applications and perform down-selection
- Develop and integrate sensor models for different sensor options into an aerodrag estimation framework
- Develop a simulation environment incorporating mission parameters and spacecraft characteristics
- Evaluate the performance and trade-off between different sensor technologies
- Assess the overall feasibility of using the chosen sensor technology and provide recommendations for future work

This report presents the findings from our comprehensive study, which included literature review, sensor modeling, simulation, and performance evaluation. The results provide valuable insights for future VLEO missions seeking to implement robust aerodrag estimation systems for improved spacecraft operations.

2. Project Background

Operating satellites in Very Low Earth Orbit (VLEO), typically defined as altitudes below 450 km and most common range being 250-350 km, presents unique opportunities, such as improved spatial resolution for Earth observation and reduced communication latency. However, the dynamic and variable atmospheric conditions at these altitudes make precise drag estimation challenging.

The atmospheric density in VLEO is highly dynamic and variable, strongly influenced by factors including solar activity cycles, geomagnetic storms, geographic location (latitude, longitude, altitude), and time (diurnal variations). Accurate estimation of the resulting drag force is therefore crucial for effective mission planning, precise orbit determination and control, collision avoidance strategies, and predicting satellite operational lifetimes.

Conventional methods for drag estimation often rely on GPS-based measurements with simplified onboard models, which are often limited by inaccuracies due to environmental disturbances like ionospheric scintillation or solar activity. The inadequacy of these conventional methods necessitates the investigation and evaluation of sensors capable of providing *direct* or *near-direct* measurements of relevant atmospheric properties. The AEROVEL initiative aims to address this need by systematically evaluating a range of potential technologies.

Current technologies for atmospheric density and drag estimation include:

- **Mass Spectrometers**: These instruments provide detailed atmospheric composition data but are constrained by size, power consumption, and complexity.
- **Pressure Sensors:** Compact and low-power solutions that directly measure ambient pressure but require careful calibration.
- **Temperature Sensors**: Useful for estimating density through temperature profiles but sensitive to environmental factors.

3. Methodology

The AEROVEL project adopted a structured, multi-phase methodology to evaluate and select optimal sensor technologies for aerodynamic drag estimation in Very Low Earth Orbit (VLEO) missions. The approach combined literature review, requirements consolidation, sensor and model evaluation, simulation, and trade-off analysis, as outlined below:

❖ **Requirements Definition and State-of-the-Art Review**
- The project began by defining the operational and technical requirements for VLEO drag estimation sensors, considering mission objectives and spacecraft constraints.
- A comprehensive review of the state-of-the-art was conducted, focusing on both direct measurement sensors and atmospheric models .
- Key performance metrics such as measurement accuracy, sensitivity, size, weight, power consumption, durability, complexity, heritage, and cost were identified to guide the evaluation.

❖ **Sensor and Model Down-Selection**
- A comparison matrix was developed to assess each sensor technology and atmospheric model against the defined criteria.
- The suitability of each sensor for VLEO applications was assessed, considering their advantages, limitations, and integration challenges.
- The most promising sensors and models were shortlisted for further analysis based on their performance, feasibility, and mission compatibility.

❖ **Sensor Modelling and Simulation Framework Development**
- Mathematical and behavioural models were created for each shortlisted sensor, capturing their operating principles, limitations (e.g., noise, calibration errors), and expected performance in the VLEO environment.
- An adaptable simulation framework was developed, integrating spacecraft dynamics, atmospheric models, and sensor models.
- The simulation environment allowed for the specification of mission scenarios (e.g., orbit parameters, spacecraft geometry, drag coefficients) and the generation of realistic atmospheric density profiles using established models.

❖ **Performance Evaluation and Trade-Off Analysis**
- Simulations were conducted for various mission scenarios and sensor configurations, incorporating real-world uncertainties such as sensor noise and environmental variations.
- The accuracy and reliability of drag estimates from each sensor type were evaluated by comparing simulated sensor outputs to true aerodynamic model values.
- A trade-off analysis was performed to balance performance, cost, size, weight, power consumption, and integration complexity, identifying the optimal sensor configuration for the mission.

❖ **Feasibility Assessment and Recommendations**

- The overall feasibility of the selected sensor technologies was assessed, including technical, operational, and economic considerations.
- Recommendations for future research, technology development, and potential in-orbit demonstration opportunities were formulated based on the study findings.

4. Key Findings

The project delivered a comprehensive evaluation of sensor technologies for aerodynamic drag estimation in Very Low Earth Orbit (VLEO), focusing on accuracy, robustness, and feasibility under varying orbital and environmental conditions. The most significant findings are summarized below:

❖ **Direct Measurement Sensors Outperform Indirect Methods**
- Pressure sensors (especially piezoelectric types) and mass spectrometers consistently provided the most accurate and robust estimates of atmospheric density and drag force across all tested altitudes (250–350 km) and solar activity levels (F10.7 index 70–300).
- These sensors directly measure atmospheric properties, making their performance largely insensitive to solar and geomagnetic variability, which is a major limitation for model-based approaches.

❖ **GNSS-Based Onboard Methods Are Limited by Model Accuracy**
- GNSS (Global Navigation Satellite System) sensors, while effective for position and velocity determination (1–3 m RMS error for position, <0.02 m/s for velocity in best cases), performed poorly in atmospheric density and drag estimation when used with simplified onboard atmospheric models.
- The primary source of error was not GNSS measurement itself, but the inability of the simplified exponential density models to capture real atmospheric variability, especially under changing solar activity.
- Errors in GNSS-based drag estimation were one to two orders of magnitude larger than those from pressure sensors or mass spectrometers.

❖ **Temperature Sensors Provide Supplementary Value**
- Temperature sensors (e.g., thermocouples) offered moderate performance for density and drag estimation. Their accuracy was better than GNSS-based onboard model methods but inferior to direct measurement sensors.
- Their performance was highly dependent on environmental conditions, particularly solar activity, and they are best suited for supplementary data or calibration roles rather than as primary sensors for high-precision drag estimation.

❖ **Quantitative Results**
- Root Mean Square (RMS) errors (O stands for order) for drag force estimation:
  - Mass Spectrometer: $O(10^{-5})$ to $O(10^{-4})$ N
  - Pressure Sensor: $O(10^{-5})$ to $O(10^{-4})$ N
  - Temperature Sensor: $O(10^{-4})$ to $O(10^{-3})$ N
  - GNSS (with model): $O(10^{-4})$ to $O(10^{-3})$ N, often an order of magnitude higher than direct measurement sensors.

❖ **Environmental Sensitivity and Operational Implications**
- Pressure sensors and mass spectrometers maintained high accuracy across all tested conditions, making them suitable for long-duration and variable-environment missions.
- GNSS-based onboard model methods were highly sensitive to the accuracy of the onboard atmospheric model and solar activity, limiting their reliability for precise drag estimation.
- Temperature sensor-based methods showed increased error under high solar activity due to their inability to track rapid atmospheric changes

The following table summarizes the relative performance of each sensor type for drag estimation:

Sensor Type	Drag Estimation Accuracy	Robustness to Space Weather	Suitability for Small Satellites	Primary Limitation
Pressure Sensor	High	High	High	Requires careful calibration & placement
Mass Spectrometer	Highest	High	Moderate/Low	Size, power, integration complexity
Temperature Sensor	Moderate	Moderate	High	Limited accuracy, sensitive to environment
GNSS (with Onboard model)	Low	Low	Highest	Model dependency, large errors under variability

5. Conclusion

This study provides a comprehensive assessment of sensor technologies for aerodynamic drag estimation in Very Low Earth Orbit (VLEO), addressing a critical need for more accurate and robust orbit control in this challenging environment. The main outcomes and key takeaways are as follows:

- **Direct Measurement Sensors Are Superior:** The evaluation clearly demonstrates that direct measurement sensor, specifically piezoelectric pressure sensors and mass spectrometers, consistently outperform indirect methods such as GNSS-based model approaches and temperature sensors for both atmospheric density and drag force estimation. These sensors offer high accuracy and are minimally affected by environmental variability, making them highly reliable for VLEO missions.

- **Pressure Sensors Are Practically Feasible:** Piezoelectric pressure sensors stand out as the most practical solution for many VLEO missions, balancing accuracy, resource efficiency, and ease of integration. Their compact size and low power requirements make them especially suitable for small satellites, while their direct measurement capability ensures robust performance across varying solar and geomagnetic conditions.

- **Mass Spectrometers for High-Precision Applications:** Mass spectrometers provide the highest accuracy and detailed atmospheric composition data, making them ideal for scientific missions where resource constraints are less stringent. However, their higher complexity, size, and power consumption limit their practicality for smaller or cost-sensitive platforms.

- **GNSS and Temperature Sensors as Supporting Technologies:** GNSS remains highly valuable for orbit determination and navigation but is limited as a standalone solution for precise drag estimation (in this configuration set) due to its reliance on indirect atmospheric models. Temperature sensors are simple and robust, offering supplementary environmental data, but lack the accuracy required for primary drag estimation.

- **Simulation-Based Validation and Limitations:** The findings are based on detailed simulations, which, while insightful, underscore the need for further validation through in-situ VLEO flight data. The study also identifies integration, calibration, and long-term durability as areas requiring additional research and development.

- **Actionable Recommendations:** For most VLEO missions, prioritizing pressure sensors is advised due to their strong performance and operational advantages. Mass spectrometers should be considered for missions with high scientific return. GNSS and temperature sensors should be included for navigation and supplementary data, respectively. Redundancy, careful calibration, and thermal management are also recommended to ensure mission success.

- **Impact:** By providing a robust trade-off analysis and clear guidance on sensor selection, this study lays the groundwork for more accurate and reliable drag estimation in VLEO. These advancements will directly contribute to improved orbit control, longer mission lifetimes, and enhanced scientific and commercial outcomes for future satellite missions in this increasingly important orbital regime.

6. Future Work

Building on the outcomes of the AEROVEL project, several key areas for further research and development have been identified to advance aerodynamic drag estimation in Very Low Earth Orbit (VLEO) missions. The following recommendations are actionable and address both technical challenges and strategic opportunities highlighted by the study:

❖ **Miniaturisation and Power Optimisation of High-Accuracy Sensors**
- Develop smaller, lighter, and more energy-efficient versions of high-accuracy sensors, particularly mass spectrometers, to enable their use on resource-constrained platforms such as CubeSats.
- Invest in R&D collaborations with sensor manufacturers and academic partners to prototype and test miniaturised sensor designs. Prioritise low-power electronics and advanced materials to reduce mass and energy requirements.

❖ **Long-Term Sensor Performance and Degradation Studies**
- Assess the durability and performance drift of sensor technologies over extended periods in the VLEO environment, focusing on effects such as atomic oxygen erosion, radiation damage, and contamination.
- Design long-duration laboratory and in-orbit experiments to systematically monitor sensor performance. Use results to inform material selection, protective coatings, and redundancy strategies for future missions.

❖ **In-Orbit Demonstration and Validation**
- **T**ransition from simulation-based assessments to real-world validation through in-orbit demonstration missions.
- Integrate selected sensor technologies into upcoming VLEO demonstration satellites, such as those planned for the Skimsat platform or similar ESA initiatives. Collect and analyse flight data to refine models, calibration, and operational protocols.

❖ **Enhanced Calibration Techniques for VLEO Conditions**
- Establish robust, in-situ calibration protocols tailored to the unique VLEO environment.
- Design calibration routines that can be executed autonomously during flight, such as periodic calibration during eclipse phases or using onboard reference standards. Validate these techniques with ground-based VLEO simulators and, where possible, suborbital test flights

By addressing these areas, future research will enable more accurate, reliable, and cost-effective aerodynamic drag estimation, supporting longer mission lifetimes, improved orbit control, and expanded scientific and commercial applications in VLEO.