IAC-20-B4,2,5,x59341

Investigation of Novel Drag-Reducing and Atomic Oxygen Resistant Materials in Very Low Earth Orbit using SOAR (Satellite for Orbital Aerodynamics Research)

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Abstract

Interest in operating spacecraft in very low Earth orbits (VLEO), those below approximately 450 km, is growing due to the numerous benefits offered by reducing altitude. For remote sensing and Earth observation applications, improvements in resolution can be achieved or smaller instruments used with associated benefits in cost or mission value. Similarly, for communications applications, link-budgets and data latency can be improved by reducing the operational altitude. However, a key challenge to sustained operations in lower altitude orbits is to minimise and compensate for the aerodynamic drag that is produced by the interaction with the residual atmosphere. A principal aim of the DISCOVERER project is to identify, develop, and characterise materials that can promote specular reflections of the residual atmosphere in VLEO whilst also remaining resistant to the erosive atomic oxygen that is predominant at these altitudes. In combination with geometric design, such materials would be able to reduce the aerodynamic drag experienced by satellites in orbit and would also be able to generate usable aerodynamic lift enabling novel aerodynamic attitude and orbit control. SOAR (Satellite for Orbital Aerodynamics Research) is a 3U CubeSat that has been designed to investigate the aerodynamic performance of different materials in the VLEO environment and provide validation data for further ground-based experiments. To achieve this, the spacecraft features a set of steerable fins that can expose different materials to the oncoming atmospheric flow. A forward-facing ion and neutral mass spectrometer (INMS) provides in-situ measurements of the atmospheric density and flow composition. SOAR is scheduled for launch to the ISS in March 2021. This paper will present the design of the spacecraft, the experimental method that will be used to investigate the aerodynamic properties of materials in orbit, and will provide an update on the status of the spacecraft as it prepares for launch.

Keywords: Orbital Aerodynamics; Drag and Lift Coefficient; Gas-Surface Interactions; Thermospheric Wind; CubeSat.

Acronyms/Abbreviations

ABEP	Atmosphere-breathing electric propulsion
ADCS	Attitude determination and control system
AO	Atomic oxygen
EO	Earth observation
FMF	Free molecular flow
GSI	Gas-surface interaction
HOAG	Hyperthermal atomic oxygen generator
IMU	Internal measurement unit
INMS	Ion and neutral mass spectrometer
ISS	International space station
RGA	Residual gas analyser
ROAR	Rarefied orbital aerodynamics research (facility)
RWA	Reaction wheel assembly
SOAR	Satellite for orbital aerodynamics research
VLEO	Very low earth orbit

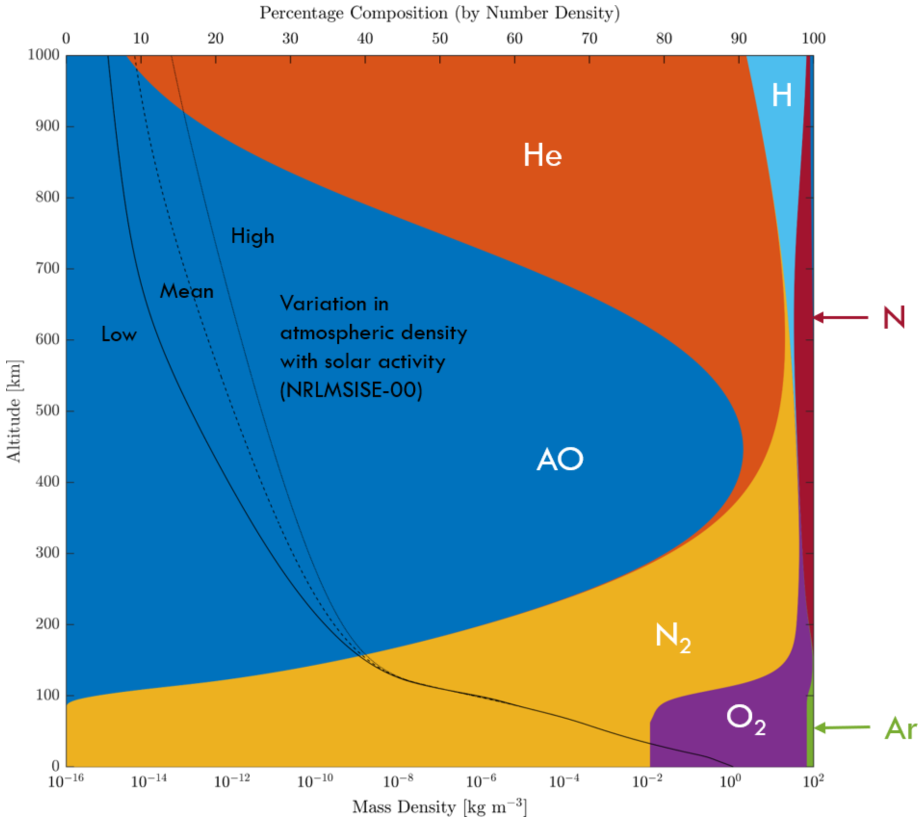

Fig. 1. Atmospheric density and composition with altitude in LEO.

1. Introduction

The use of very low Earth orbits (VLEO), those below approximately 450 km in altitude, has recently been shown to demonstrate a number of benefits for Earth observation [1] and communications applications [2]. These benefits can generally be classified as either mission-related benefits, or those that benefit the design of the spacecraft platform itself.

For Earth observation applications, the benefits of operating at lower orbit altitude principally include increased spatial resolution and radiometric performance for the same sensor Alternatively, smaller and less costly payloads can be used to achieve the same performance as at higher altitudes. For communications applications, the link-budget is improved with reducing distance and the required power consequently reduced.

The more general platform benefits of operating in VLEO include reduced radiation dosing from trapped ionised particles and a reduced risk of on-orbit collision as debris is quickly cleared from low-altitude orbits by atmospheric drag. The orbital insertion capacity of launch vehicles into lower altitudes is also generally improved, leading to potential cost reductions for launch.

However, there are also considerable challenges associated with operating in VLEO. Most critically, atmospheric density increases with decreasing altitude (Fig. 1), and therefore results in increased atmospheric drag. Without drag compensation or mitigation, this drag results in rapid orbital decay and deorbit; the natural lifetime of spacecraft in VLEO is therefore much shorter than at higher altitudes.

The composition of the atmosphere in VLEO is also a challenge. As shown in Fig. 1, the predominant gas species at these altitudes is atomic oxygen (AO), a highly reactive gas species. In combination with the increased density and the energy associated with orbital velocity, this AO can erode and damage the external surfaces of spacecraft with impact for aerodynamic performance, solar-cell efficiency, performance of optics, and effectiveness of thermal protection [3,4].

Modelling of the upper atmosphere is also associated with significant uncertainty [5]. Atmospheric density and composition at a given position and altitude is known to vary considerably on a diurnal and seasonal/annual basis and also with the 11-year solar cycle. However, knowledge of the many environmental mechanisms in the upper atmosphere is incomplete, and there is a lack of consistent, widespread, and long-term experimental data. The impact of smaller temporal and spatial scale variations and thermospheric winds is also less well characterised. Furthermore, the limited knowledge of gas-surface interactions (GSIs) in this upper atmosphere environment, discussed later in Section 2, can result in bias and additional uncertainty in atmospheric models derived from experimentally fitted drag coefficient data [6,7].

DISCOVERER [8–10], a Horizon 2020 funded project, aims to address the challenges of operating in VLEO through the development of fundamental technologies that will enable commercially viable and sustained operations in VLEO:

1. Identification and development of novel materials that can reduce the drag generated by spacecraft in the orbital environment. Improved understanding of the interactions between the oncoming atmospheric flow and the spacecraft surfaces is required.
2. Development of atmosphere-breathing electric propulsion (ABEP) that can eliminate the need to carry on-board propellant by collecting and utilising the residual atmosphere [11]. Such systems are being developed at the Institute of Space Systems at Stuttgart University within the scope of the wider DISCOVERER project [12,13]. Complete drag compensation can be provided by means of such propulsion but must be aided by drag mitigation methods to reduce the requirements on propellant and power.
3. Novel methods of aerodynamic attitude and orbit control that can assist conventional attitude actuators and orbit control methods.
4. Development of systems models and external satellite geometries that incorporate the above technologies to support commercially viable and sustainable operations in VLEO.

2. Gas-Surface Interactions (GSIs) in VLEO

In the highly rarefied VLEO environment, the oncoming flow is considered to be free-molecular, that is, the mean free path of the particles is order of magnitude greater than the characteristic length of the surfaces immersed in the flow. The interactions between the flow particles and the surfaces are therefore of much greater significance than the collisions between the atmospheric particles that can be neglected.

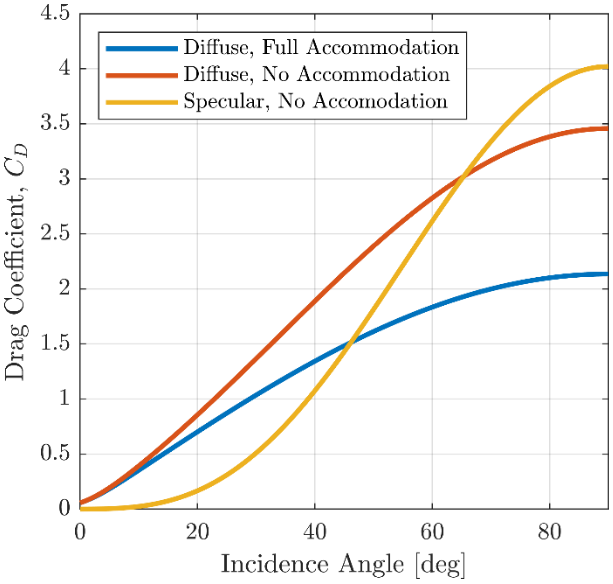

Fig. 2. Variation of the drag coefficient of a flat plate (referenced to a surface area of 1m) with varying surface incidence and GSI assumptions and inputs.

These gas-surface interactions are known to vary with several different factors:

- The angle of the surface with respect to the oncoming flow [14–16].
- The surface roughness, cleanliness, structure, and temperature [17–21].
- The flow composition, particle velocity, molecular mass, and temperature [14,15,20,21].

However, knowledge of the effect and contribution of each of these factors is still largely unknown for many materials, even those that are commonly used in the construction of spacecraft.

The aerodynamic performance of materials in VLEO is dependent on the characteristics of these GSIs and the momentum and energy transfer to the spacecraft from the flow, often captured by the non-dimensional drag and lift coefficients. A variety of models have been developed to estimate these aerodynamic coefficients based on different GSI assumptions and combinations of environmental and physical parameters [22,23].

In VLEO, the abundance of AO contributes to surface contamination through adsorption and surface roughness through erosion. Diffuse reemission characteristics with high thermal accommodation are therefore generally assumed for typical materials at these altitudes [14,24].

However, novel materials that can promote specular or quasi-specular characteristics, when oriented at shallow angles to the flow, may be able to achieve a significantly lower drag coefficient than conventional materials with diffuse reemission properties (see Fig. 2).

Such materials, when combined with appropriate geometric design of satellites, would be able to mitigate the drag experienced in VLEO and provided extended orbital lifetimes or reduced requirements for propulsive drag compensation. These materials would also be able to contribute to the design and development of more efficient intakes for ABEP systems and would enable more effective aerodynamic control surfaces for orbit and attitude manipulation and modification. Materials with specular reflection properties also have promising applications for enhanced deorbit devices due to their ability to generate increased drag when oriented normal to the oncoming flow.

Improved understanding of the fundamental GSI behaviour and the underlying physical mechanisms in the VLEO environment is therefore important for both assessing and modelling the aerodynamic characteristics of current satellites and commonly used materials, but also for the development of novel materials that can provide enhanced on-orbit performance. Knowledge of the interaction of these materials with atomic oxygen is also critical to understand the effects of both surface accommodation and erosion over the lifetime in orbit.

3. The Rarefied Orbital Aerodynamics Research (ROAR) Facility

To investigate the mechanisms for GSIs of different materials in the VLEO environment a new experimental facility has been planned and is currently being commissioned at The University of Manchester. As shown in Fig. 3, the Rarefied Orbital Aerodynamics Research (ROAR) facility is comprised of [25,26]:

- An ultra-high vacuum (UHV) system with pumping capacity to provide FMF conditions, accounting for the incoming flux of AO.
- A hyperthermal oxygen atom generator (HOAG) providing flux and energy of AO at orbital conditions.
- A rotating sample stage and detection system consisting of ion and neutral mass spectrometers (INMS) and residual gas analysers (RGA) to map the 3D particle scattering from the sample surface.

In comparison to other existing facilities that focus on characterising AO exposure and erosion, ROAR has been specifically designed to explore and investigate the fundamental mechanisms behind GSIs of different materials in an environment representative of VLEO. The facility is currently being commissioned and is scheduled to be fully functional in December 2020 [27].

ROAR is also an important component in the search for and identification of novel materials that promote specular reflection characteristics and have resistance to the damaging effects of AO. The facility will also be used to test the design of new rarefied atmospheric intake designs with enhanced collection efficiencies that would contribute to the development of improved ABEP systems.

However, given the uncertainties in atmospheric modelling and knowledge of GSI characteristics (e.g. AO accommodation), validation of the material performance obtained by this facility requires in-situ experimental data from the VLEO environment. This data will be principally provided by the Satellite for The Satellite for Orbital Aerodynamics Research (SOAR).

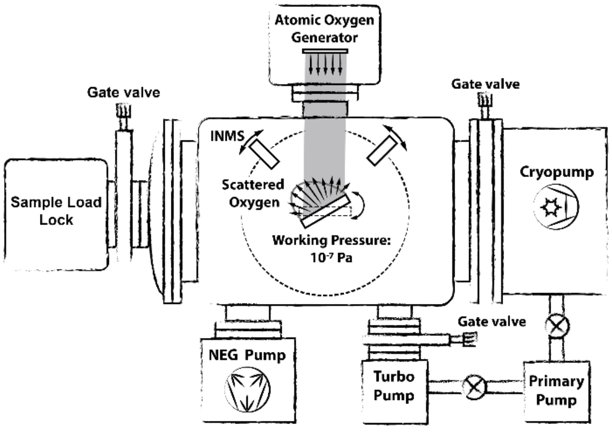

Fig. 3. Schematic representation of the Rarefied Orbital Aerodynamics Research (ROAR) facility [25].

4. The Satellite for Orbital Aerodynamics Research (SOAR)

SOAR is a 3U CubeSat that has been developed within the scope of the DISCOVERER project to specifically investigate the GSIs of different materials in the VLEO environment. SOAR will also perform in-situ measurements of the atmospheric density, composition, and thermospheric winds and will demonstrate novel methods of aerodynamic attitude control [28,29].

The satellite, depicted in Fig. 4, was developed from the original ΔDSat concept [30] and features a unique combination of two payloads to perform these different experiments:

- A set of four steerable fins, developed at The University of Manchester, can be used to expose different materials or surfaces to the oncoming flow at different angles of incidence. The fins are folded and stowed against the body of the satellite for launch and subsequently deployed when in orbit. Each steerable fin is individually motorised to allow independent rotation and therefore allow a wide range of configurations to be achieved.
- A forward facing INMS, developed at the Mullard Space Science Laboratory at University College London, to measure the conditions of the oncoming flow density and composition. A measure of the oncoming flow velocity is also provided by the time-of-flight capability of this instrument.

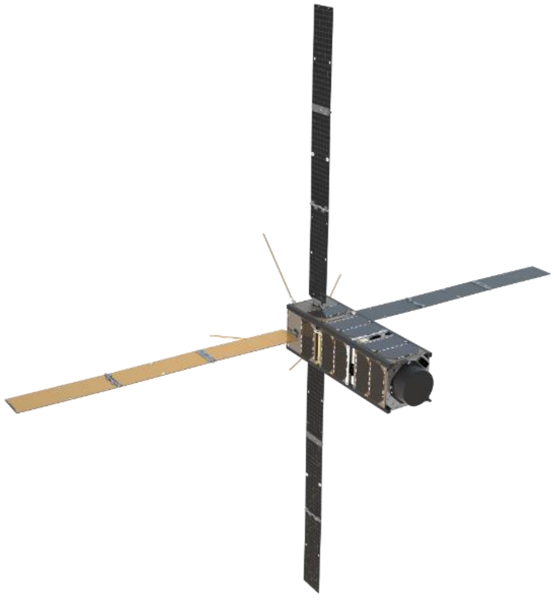

Fig. 4. Satellite for Orbital Aerodynamics (SOAR).

Development of the satellite platform, integration of the payloads, and system-level testing is the remit of GOMspace A/S in Denmark.

The ADCS is comprised of an IMU, magnetometer, and set of fine sun sensors, providing sub-degree attitude knowledge, whilst 3-axis control is provided primarily by a reaction wheel assembly (RWA) with a tetrahedral configuration. Magnetorquers will also be used for momentum management. The position of the satellite during experiments can be provided by an on-board GPS receiver.

When the steerable fins are all rotated either parallel or perpendicular to the satellite body, naturally restoring aerodynamic torques will be generated as the satellite rotates to point away from the oncoming flow. This characteristic is known as aerostability and can assist the attitude control of a nominally flow-pointing satellite. However, due to the lack of aerodynamic damping, the satellite will begin to oscillate if a further source of damping control is not provided. For SOAR, this control will be provided by the RWA or magnetorquers.

Four different surface coatings or materials are applied to the steerable fins. Each material is applied to one side of two opposing fins (either vertical or lateral in the satellite body reference frame) and can therefore be individually co-rotated or counter-rotated into the oncoming flow.

To measure the drag coefficient, an opposing pair of steerable fins is either co-rotated or counter-rotated to a given angle of incidence. If co-rotated, a net yaw or pitch torque (for the vertical or lateral fins respectively) will be produced. If counter-rotated, a roll torque is produced. The RWA can be used to compensate for this torque and associated attitude variation and keep the satellite pointing towards the velocity vector and therefore close to the oncoming flow direction for a period of time. Because this attitude variation is secular and not periodic, the RWA will approach their saturation limit and cannot maintain the attitude of the satellite indefinitely, placing a limit on the duration of a given experimental run.

During such an experimental period, the experienced drag will be modified (increased from the nominal minimum drag condition) and the satellite trajectory and rate of decay, measured GPS position over time, will accordingly change. An orbit determination process can subsequently be used to determine the drag coefficient of the satellite in the set configuration using a free-parameter fitting method. Measurement of the in-situ conditions of the oncoming flow using the INMS helps to reduce the significant uncertainty that would be associated with models of the atmospheric density.

To measure the lift coefficient, counter-rotation of a pair of steerable fins is used, and the satellite is operated in a 2-axis (pitch and yaw) attitude control mode. The roll-axis is left free, allowing the satellite to rotate to a given angle before the configuration is reset to the nominal aerostable configuration. The angular position, rate, and acceleration is measured by the ADCS. A subsequent attitude determination process is used to fit the lift coefficient of the satellite in the set configuration.

The experiments to determine the drag and lift coefficients for the satellite will be performed for different angles of incidence (from parallel to perpendicular to the flow) and at different altitudes as

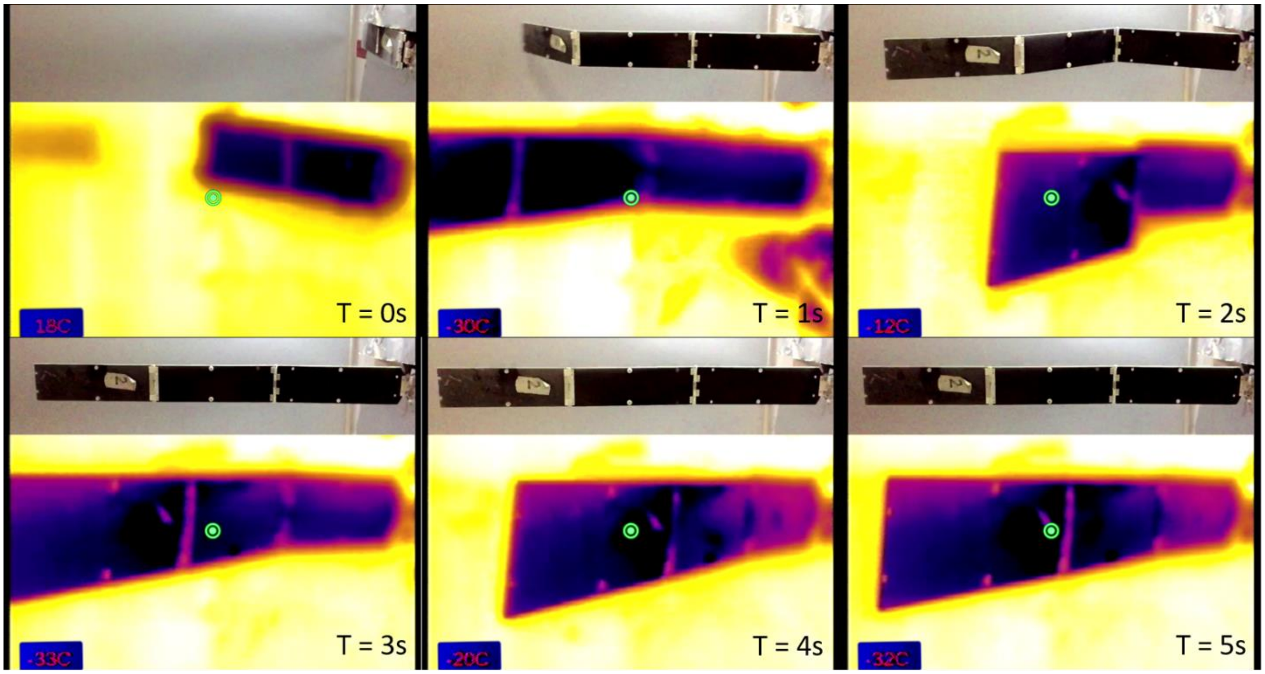

Fig. 5. Thermal testing of the self-sprung deployment of a steerable fin after cooling with dry ice.

SOAR naturally decays. This is intended to reveal any variation in the adsorption of AO to the material surfaces and therefore the associated GSI characteristics as the composition and density of the atmosphere changes with altitude.

Two conventional materials, commonly used on spacecraft, have first been selected for experimentation on SOAR: borosilicate glass and sputter-coated gold. These materials are expected to show characteristically low and high surface adsorption of AO respectively.

Two further novel materials, developed at The University of Manchester (and not named herein for IP protection reasons), have also been selected for in-orbit demonstration on SOAR. These materials have been selected for their expected resistance to AO erosion and adsorption and surface properties that promote more specular reflection GSI behaviour. These materials would therefore experience reduced drag and shallow angles to the flow and increased drag when rotated towards the normal.

5. Current Status

SOAR is currently in the assembly, integration, and test campaign in preparation for launch. The payloads for SOAR have undergone environmental testing. Thermal testing using dry ice has been performed to ensure that the folded and stowed steerable fins will deploy under cold conditions in orbit (see Fig. 5). Thermal vacuum testing using liquid nitrogen cooling and resistive heating has also been performed to confirm the operation of the internal mechanisms under expected orbital conditions (see Fig. 6). The INMS has similarly been tested under thermal vacuum conditions (see Fig. 7).

As of late September 2020, the satellite has been fully integrated (see Fig. 8) and is undergoing system-level environmental, software and functional testing. SOAR is due to be launched to the ISS in early 2021 and shortly afterwards deployed directly into VLEO.

The operational lifetime of SOAR is expected to be between 6-12 months depending on the atmospheric density, progression of the solar cycle (currently departing from a period of solar minimum), and the different experiments that will be performed. These factors significantly affect the experienced drag and therefore rate of decay.

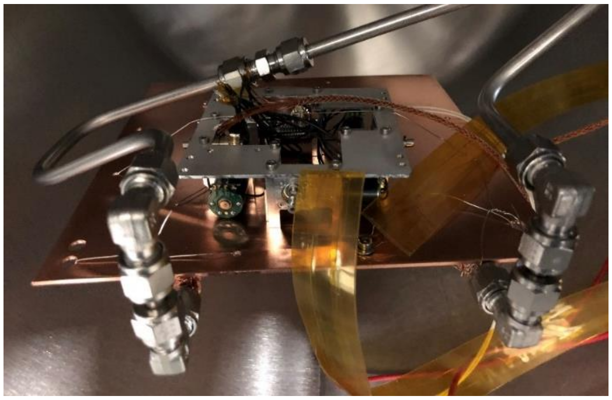

Fig. 6. Thermal vacuum test set-up for the internal assembly of the SOAR aerodynamics payload.

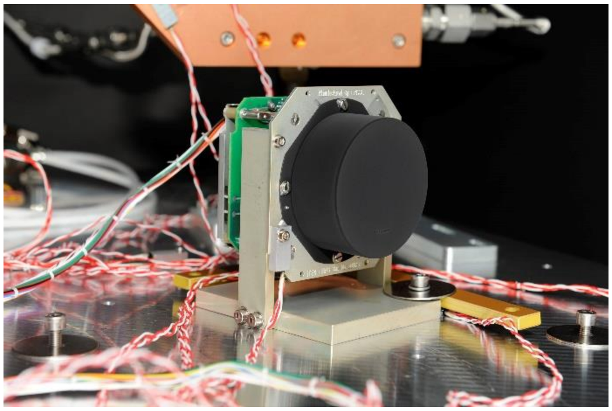

Fig. 7. Ion and neutral mass spectrometer (INMS) unit for SOAR prepared for thermal vacuum testing [image courtesy of UCL/MSSL].

Fig. 8. Fully integrated flight model of SOAR (without steerable fins attached) awaiting system-level environmental testing [image courtesy of GOMspace].

6. Concluding Remarks

SOAR is a scientific satellite that has been designed to support the investigation of GSIs in rarefied flows and to test novel materials with potentially drag reducing properties in the VLEO environment. The satellite has been developed to provide in-situ data to validate ongoing experimentation in a new ground-based facility that simulates the flow conditions in low altitude orbits.

These experiments aim to perform a systematic investigation of the GSI characteristics of different materials under the rarefied flow conditions of VLEO and to search for novel materials that can reduce the drag experienced by spacecraft in orbit whilst also remaining resistant to the effects of AO exposure. Such materials also have applications for improved aerodynamic attitude and orbit control capability, more efficient atmospheric intake design, and enhanced deorbit devices.

SOAR has been developed by The University of Manchester, GOMspace, and the Mullard Space Science Laboratory as part of DISCOVERER, a wider project that is focused on the development of fundamental technologies that will enable the sustained operation of spacecraft in VLEO, principally for EO applications. The satellite is due to be launched in early 2021 to the ISS with deployment into VLEO and operations commencing shortly thereafter.

Acknowledgements

The DISCOVERER project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183. This publication reflects only the view of the authors. The European Commission is not responsible for any use that may be made of the information it contains.

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