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DISCOVERER: Developing Technologies to Enable Commercial Satellite Operations in Very Low Earth Orbit

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Abstract

The DISCOVERER project is developing technologies to enable commercially-viable sustained-operation of satellites in very low Earth orbits for communications and remote sensing applications. Operating closer to the surface of the Earth significantly reduces latency for communications applications and improves link budgets, whilst remote sensing also benefits from improved link budgets, the ability to have higher resolution or smaller instruments, all of which provide cost benefits. In addition, all applications benefit from increased launch mass to lower altitudes, whilst end-of-life removal is ensured due to the increased atmospheric drag. However, this drag must also be minimised and compensated for. DISCOVERER is developing several critical technologies to enable commercially-viable operations in at these lower altitudes including aerodynamic materials, aerodynamic attitude and orbit control methods, atmosphere breathing electric propulsion and an in-situ environment monitoring payload. The current status of these developments are summarised, along with the plans for the coming year.

Keywords: Orbital Aerodynamics; Very Low Earth Orbit; Remote Sensing; Earth Observation; Satellite Communications.

Acronyms/Abbreviations

ABEP	Atmosphere-breathing electric propulsion
CRS	Commercial Resupply Service missions to the ISS
EO	Earth observation
INMS	Ion and neutral mass spectrometer
ISS	International space station
ROAR	Rarefied Orbital Aerodynamics Research facility
SOAR	Satellite for Orbital Aerodynamics Research
VLEO	Very low earth orbit

1. Introduction – Why Use VLEO?

Very low Earth orbit, or VLEO, is the altitude range where aerodynamic effects due to the residual atmosphere in these low orbits has a significant impact on the design of satellites which operate there. Typically, this is defined as any altitude below around 450 km in altitude.

Bearing in mind the impact of those aerodynamics effects, the effort in operating a satellite at these altitudes needs to be justified. In a recent paper by Crisp et al [1] the benefits of operating EO satellites in VLEO are laid out more clearly than ever. These benefits can be split into two categories, improved payload performance and platform benefits.

In terms of payload performance, optical payloads have significantly increased resolution or reduced apertures, and also increased radiometric performances, offering smaller payloads and reduced payload cost. Similarly, radar and communications payloads have significantly improved link budgets, reduced antenna size and transmission power, and for communications specifically, reduced latency and improved frequency reuse.

Platform benefits include a much more benign radiation environment, and launch vehicles can place more payload into lower orbits, reducing the cost of launching satellites. The residual atmosphere also means that end-of-life disposal is automatically enabled, drag pulling the satellites out of orbit within a matter of weeks to months. That same drag at these altitudes keeps the debris collision risk low as the atmosphere sweeps out debris objects.

That residual atmosphere also presents the biggest problem to overcome, causing increased drag and increased atomic oxygen erosion, atomic oxygen being the predominant gas species in VLEO. Additionally, variations in density and thermospheric wind direction cause aerodynamic attitude and orbit perturbations. DISCOVERER is addressing these challenges by developing a number of technologies:

- materials that encourage specular reflections of the residual atmosphere in free molecular flows, which can be used in concert with the design of external satellite geometries to minimise drag, and generate lift for aerodynamic attitude and orbit control
- aerodynamic attitude control methods, which are essential at lower altitudes to complement traditional attitude control actuators
- atmosphere-breathing electric propulsion (ABEP), combining an optimised atmospheric intake with an RF helicon-based plasma thruster, to effectively remove the lifetime limits resulting from finite propellant for drag compensation
- environment monitoring payloads with the potential to provide active feedback for aerodynamic attitude and orbit control.

This paper summarises the progress and status of each technology to date, building on the previous keynote paper on DISCOVERER from IAC-19 in Washington D.C. [2].

2. Aerodynamic Materials

Orbital aerodynamics is aerodynamics in the highly rarefied flows experienced in VLEO. The atmosphere at these altitudes is so rarefied that, over the length scales of a typical satellite, collisions between gas molecules are rare. This means aerodynamics driven by gas interacting directly with the satellite surfaces [3]. Experiments to date with commonly used satellite materials show that the gas is typically diffusely reemitted from the spacecraft surfaces, at the temperature of the surface [4, 5], leading largely to drag forces proportional to the cross-section presented to the flow. Aerodynamic control is consequently driven by drag effects.

If materials can be developed which specularly or quasi-specularly reflect that flow, whilst being resistant to atomic oxygen erosion, then angled surfaces to the flow can minimize drag and produce useable lift for control. Such materials are being developed at the University of Manchester which can't be disclosed here due to IP constraints. However, the methods to characterise them can be. These include characterisation in a ground-based facility called ROAR, aerodynamic performance testing in the real environment on a test satellite call SOAR, and erosion testing on the exterior of the International Space Station.

2.1 ROAR – The Rarefied Orbital Aerodynamics Research Facility

ROAR reproduces the most reactive component of the atmospheric flow in VLEO, atomic oxygen, at orbital velocities, and measures the velocity, flux and composition of the gas scattered from materials samples, all in a free molecular flow environment. As such it will be able to characterise the aerodynamic performance of materials, that is the angular distribution and velocity of reemitted gas at different impingement angles. ROAR is currently being commissioned at the University of Manchester and can be seen in Fig. 1. A detailed update on the status of ROAR can be found in [6].

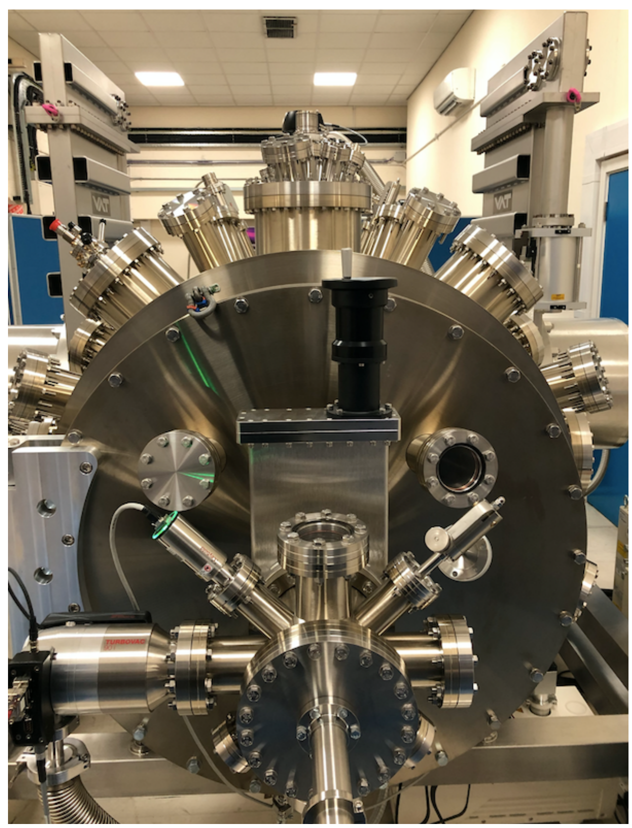

Fig. 1. ROAR – the Rarefied Orbital Aerodynamics Research facility

2.2 SOAR – The Satellite for Orbital Aerodynamics Research

SOAR is DISCOVERER's aerodynamics test satellite, characterising the performance of aerodynamic materials in-situ, demonstrating aerodynamic control, and hosting our in-situ atmospheric characterisation sensor.

Fig. 2 shows the configuration of SOAR including 4 deployable steerable fins. These fins are coated in different candidate aerodynamic materials and can be rotated to induce aerodynamic attitude and orbit perturbations. These perturbations can then be used to determine the aerodynamic properties of the materials.

At the time of writing SOAR is currently in the final stages of qualification and is scheduled for launch in March 2021 on SpaceX's CRS-22 to the ISS, from where it will be deployed directly into VLEO. Information on the test campaign and the current status of satellite can be found in [7].

Fig. 2. The Satellite for Orbital Aerodynamics Research

2.3 MISSE – Materials on the International Space Station Experiment

To ensure the longevity of the materials, samples of the materials developed at the University of Manchester are currently being exposed to the ram direction flow on the Materials on the International Space Station Experiment (MISSE). Alpha Space owns and operates the MISSE facility under agreements with NASA and the Center for the Advancement of Science in Space (CASIS). Launched on 2 November 2019 on the NG-12 CRS mission, the materials will be returning to Earth on SpaceX's CRS-21 in December 2020. They will then be subject to a suite of materials characterisation tests and compared with samples exposed to hyperthermal atomic oxygen flows in ROAR.

2.4 Aerodynamic Materials Summary

The above three experiments will provide DISCOVERER with a unique data set on the aerodynamic performance of the candidate materials, and the ability to survive in the VLEO environment.

3. Aerodynamic Attitude Control

Aerodynamic attitude control methods have also been developed within DISCOVERER, some of which have now been implemented on SOAR in readiness for launch next year. Noting the aerostable nature of the geometry of SOAR, and most VLEO satellite concepts proposed in the literature and in the public domain, perturbations due to atmospheric variations in density and flow direction will affect their stability. Compensation of these perturbations with traditional attitude control actuators, such as reaction wheels and magnetorquers, is possible but as the altitude reduces an increasing amount of control authority is required. Combinations of aerodynamic control for coarse control and traditional actuators for fine control has therefore been the focus of the developments.

Methods implemented on SOAR include:

- Active aerodynamic pointing
- Aerodynamic trim in non-flow pointing orientations
- Aerodynamic momentum management of the on-board reaction wheels

Details of these methods can be found in [8].

4. Atmosphere-Breathing Electric Propulsion

Drag compensation is critical for satellite operations in VLEO as, regardless of how much it is minimised, drag will still act on a satellite. ABEP comprises an aerodynamic intake that collects gas from the residual atmosphere, which is then fed to an electric thruster for drag compensation. The approach taken within the DISCOVERER involves optimised intakes and an RF helicon-based plasma thruster [9]. The intake design is currently being further optimised, to improve the collection efficiency. In addition, sub-scaled intakes are being prepared to be tested inside ROAR to support intake development and verify numerical simulation results. The RF helicon-based plasma thruster is based on a resonant birdcage antenna and was ignited for the first time in March 2020 (see Fig. 3). Its design and the frequency tuning capabilities have been verified experimentally. Currently, it has undergone its first discharge characterization and data are currently being post processed. Preliminary testing has shown low power requirements and easy ignitability with Argon, Nitrogen, and Oxygen for different input flows and applied magnetic fields. More details on the thruster are presented in [10].

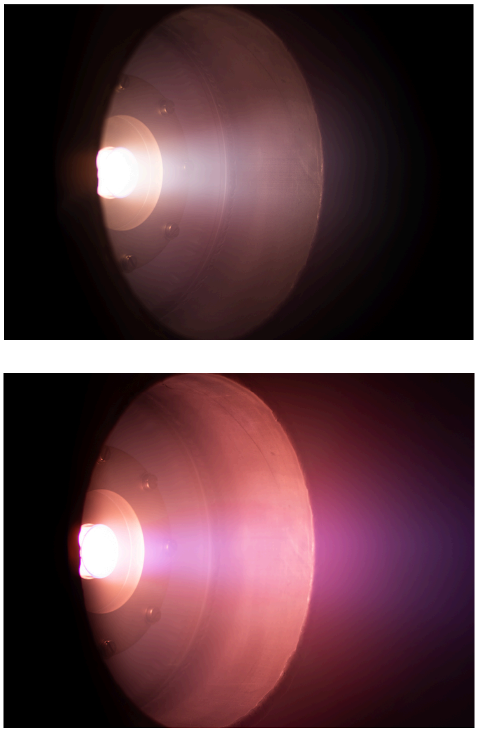

Fig. 3. RF helicon-based plasma thruster operating on oxygen (top) and nitrogen (bottom).

5. Ion and Neutral Mass Spectrometer for In-Situ Environment Characterisation

The materials characterisation experiments on SOAR rely on having a good knowledge of key atmospheric parameters such as density, composition and flow velocity. In addition, in-situ measurements of these parameters have direct scientific interest. As a result, one of the payloads on SOAR is an Ion and Neutral Mass Spectrometer (INMS) which has been developed by the Mullard Space Science Laboratory (see Fig. 4). The INMS is a miniaturised electrostatic analyser with a gated time-of-flight capability, designed for sampling of low mass ionised and neutral particles in the spacecraft ram direction. The instrument resolutions are optimised for resolving the major constituents in the lower thermosphere, i.e., N, O, O2, NO and N2 and the instrument has the capability to measure ram wind velocity to better than 70 m/s.

The SOAR INMS is now integrated on SOAR and awaiting the outcome final environmental tests for the whole satellite.

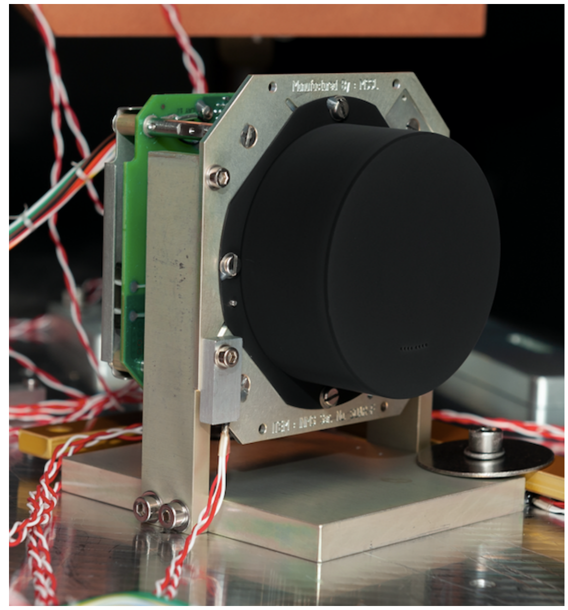

Fig. 4. The Ion and Neutral Mass Spectrometer (INMS) prior to integration into SOAR

6. Conclusions

DISCOVERER is moving into the final and most exciting stage of the project with results imminent from multiple experiments covering ground and space-based tests of aerodynamic materials, demonstrations of aerodynamic attitude control in VLEO, lab-based characterisation of atmosphere breathing electric propulsion, and in-situ measurements of atmospheric parameters in VLEO. These technologies all enable, in different ways, sustained operations of satellites in very low Earth orbits. As such they also support the ultimate goal of commercial EO and communications satellites operating at much lower altitudes, with all the benefits that doing so offers.

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