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Early Results from the DISCOVERER Project

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Abstract

The use of very low Earth orbits (VLEO), for communications and remote sensing satellites, offers a number of significant payload and platform benefits. Imaging from these altitudes allows higher resolution or smaller optical payloads, whilst radar also benefits from improved link budgets leading to smaller antennas and lower transmission power. Communications payloads also have improved link budgets, reduced latency, and improved frequency reuse factors. Platform benefits include a more benign radiation environment, lower cost per kilogram to launch satellites, and atmospheric drag makes the environment inherently sustainable, simultaneously removing debris objects and ensuring satellites are quickly removed from orbit at the end of their operational lives. However, the impact of drag on satellite and mission operations must also be addressed.

The DISCOVERER project, which commenced in 2017, is addressing the following key questions about technologies that would enable the commercially viable and sustained operation of satellites in VLEO:

1. Are there materials or processes which reduce the induced drag on spacecraft surfaces?
2. Are there propulsion methods which use the residual atmospheric gas as a propellant, providing drag compensation whilst removing the lifetime limits caused by carrying a limited amount of propellant?
3. How can we improve our understanding of, and make best use of, the orbital aerodynamics of a space platform and its ability to perform attitude control manoeuvres?
4. And what are the new opportunities that these technologies may bring to the market?

This paper provides highlights from the developments made during the DISCOVERER project to date, demonstrating the potential for a new, commercially attractive, class of aerodynamic satellites operating in VLEO.

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

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. The definition of this orbital regime is not universally agreed upon but is generally considered as any altitude below around 450 km in altitude.

Given the significance of these aerodynamic effects, from induced drag to atomic oxygen erosion, the use of VLEO needs to be justified. Crisp et al [1] defines the main benefits in significant detail and so the benefits will not be covered again here.

The challenges of operating in VLEO revolve around satellite interactions with the residual atmosphere, causing increased drag and increased atomic oxygen erosion, atomic oxygen being the predominant gas species in VLEO. Variations in atmospheric parameters, such as density and thermospheric winds, also cause aerodynamic attitude and orbit perturbations. Addressing these challenges involves answering the research questions in the abstract, resulting in the development of a number of new 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

This paper summarises the progress and status of each technology to date and discusses the development of systems and business models to identify potential exploitation routes.

2. Aerodynamic Materials

The atmosphere in VLEO is so rarefied that, over the length scales of a typical satellite, collisions between gas molecules are rare. This means that orbital aerodynamics is dominated by gas particles interacting directly with satellite surfaces [2]. Literature describing experiments to date show that gas particles are typically diffusely reemitted from the spacecraft surfaces, at the temperature of the surface [3, 4], for commonly used spacecraft materials. This lead to drag forces largely proportional to the cross-section of the satellite.

Materials that specularly or quasi-specularly reflect the flow, in combination with surfaces at shallow incidence angles, minimize drag and produce useable lift for control. Candidate materials with these properties are being developed at the University of Manchester.

A key aspect of developing these materials is developing facilities to characterise them. DISCOVERER is carrying out this characterisation in three different ways: a ground-based atomic oxygen beam 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 is an atomic oxygen exposure facility that is designed to characterise the gas-surface interactions (GSIs) that spacecraft experience when in orbit [5]. To ensure that the conditions inside the chamber are representative of those on orbit, special care was taken to guarantee that a clean vacuum was established with an ultrahigh vacuum system that can keep free molecular flow conditions during experiments. Similarly, an atomic oxygen beam with energy and flux values that are near the values found in VLEO was applied, i.e. 4.5 eV and 10^{15} atom cm^{-2} s^{-1}, so that the controlled environment provided by ROAR is not too dissimilar from the real conditions, and so that the observed interactions are representative of those experienced by spacecraft.

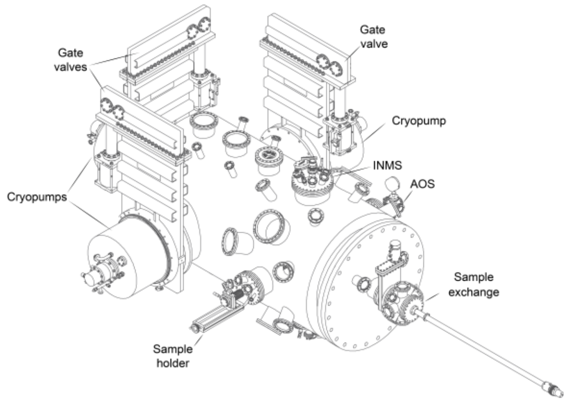

Fig. 1. Schematic of the Rarefied Orbital Aerodynamics Research (ROAR) facility.

The analysis of the interactions is achieved by measuring the outcomes of the scattering of the neutral oxygen atoms with an ion-neutral mass spectrometer (INMS). The INMS measures both the mass and the velocity of the reemitted particles, and therefore their energy. By comparing it with the incoming beam we can experimentally determine the energy accommodation for different materials, possible interactions/reactions between the AO beam and the sample and create a map of the scattering behaviour of the samples with an angular resolution of 2 degrees. The facility is currently being commissioned, with the ultrahigh vacuum, the atomic oxygen source, and the

INMS mounted, and leak tested. Fig. 1 shows the schematics of the facility, highlighting its main systems. A more detailed description of the facility and its commissioning is provided by Oiko at al. [5].

2.2 MISSE – Materials on the International Space Station Experiment

As part of the on-orbit tests for the development of novel materials, two samples containing 4 novel materials, a bare substrate and a reference were launched to the ISS as part of the MISSE-12 mission. These samples were placed on the ram and wake holders of the ISS and exposed to the space environment for nearly 12 months, after which they were retrieved and sent back to Manchester for post-exposure analysis.

The interests in the MISSE experiments are manifold. As already discussed, ROAR is an experiment designed to study the GSIs, which imposes some limitations on the atomic oxygen flux that is used in the experiments. These lower fluxes, whilst guaranteeing the right conditions are kept for studying aerodynamic interactions, limit the ability to assess the sample's resistance to atomic oxygen erosion. This information will instead be acquired from the MISSE samples, along with the combined effects of the full VLEO environment on the materials.

Another purpose of these samples is the information they provide that allow a better interpretation of the data coming from DISCOVERER's other on-orbit test, SOAR. The samples from MISSE will give valuable data about the state of the materials after being exposed to space at altitudes around 400km, before reaching lower altitudes where tests and experiments are expected to be performed with SOAR. Knowing the condition of the coatings after this initial exposure will help us determine a better correlation of the data coming from ROAR and SOAR, improving our analysis, which will influence the design of future experiments in the ground-based facility.

2.3 SOAR – The Satellite for Orbital Aerodynamics Research

The Satellite for Orbital Aerodynamics Research (SOAR) has been developed to validate the aerodynamic performance of materials in orbit, demonstrate aerodynamic control manoeuvres, and provide in-situ measurements of the atmosphere in VLEO.

SOAR is a 3U CubeSat that has two scientific payloads that work in unison to achieve these aims, a forward-facing ion and neutral mass spectrometer (INMS) and a set of four fins, located at the rear of the spacecraft, which are coated with different materials and can be rotated to varying angles with respect to the oncoming flow (see *Fig. 2*).

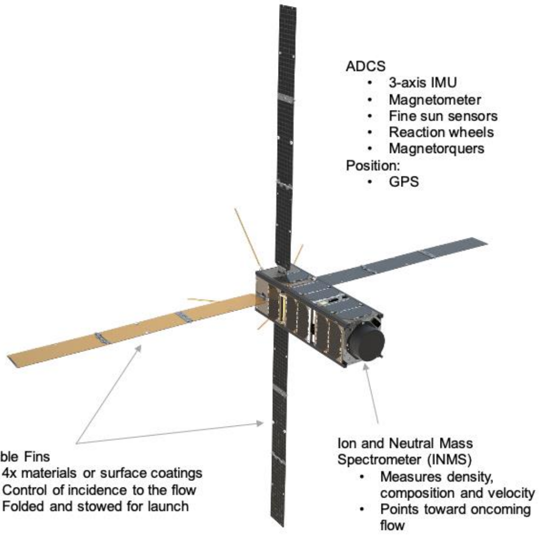

Fig. 2. Visualisation of SOAR with fins deployed highlighting key features.

The spacecraft also features GPS for precise orbital position measurements and a capable ADCS that includes a state-of-the-art MEMS IMU, fine sun sensors, reaction wheels and magnetorquers.

When the steerable fins are all configured to be parallel or perpendicular to the satellite body, known as the minimum and maximum drag configurations respectively, the satellite has an aerostable configuration and will nominally point towards the oncoming flow. Characterisation of the aerodynamic performance of the different materials will be performed by rotating opposing steerable fins to different angles with respect to the flow and subsequently observing the variation in the orbital trajectory or attitude response of the spacecraft. The steerable fins will also be utilised as control surfaces to perform demonstrations of novel aerodynamic attitude control methods in VLEO (see the section on aerodynamic control).

To measure the drag coefficient either co-rotated or counter-rotated configurations of opposing steerable fins can be used. During each experimental period, the reaction wheels can be used to compensate for the aerodynamic torques generated by the fins to maintain the nominal attitude of the spacecraft. The interaction of the rotated fins with the oncoming flow will generate additional drag in comparison to the minimum drag condition and the corresponding variation in the orbital position and velocity can be used to estimate the drag coefficient of the exposed surfaces using a method of least-squares orbit determination with a free parameter fitting process. Comparatively, the lift coefficient of the surface materials will be determined using counter-rotated configurations of opposing steerable fins. The aerodynamic torque generated will principally result in a rolling motion of the spacecraft that, when not counteracted by the on-board attitude actuators, can be measured using the combination of attitude sensors. A similar method of attitude determination and free-parameter fitting can subsequently be used to estimate the effective lift-coefficient of the exposed surfaces [6].

During these experiments, the INMS payload will provide in-situ measurements of the oncoming flow conditions, including density, velocity, and composition. These measurements will provide significant improvements over the use of modelled parameters, reducing the uncertainty associated with the experimentally determined aerodynamic coefficients. The INMS payload will also be used to perform more widespread surveys of the atmospheric properties over the lifetime of the mission as the altitude of the satellite decays.

SOAR was launched to the ISS on the SpaceX CRS-22 mission on 3rd June 2021, and subsequently deployed into orbit on 14th June 2021. The lifetime of the satellite from its initial orbit with a perigee of approximately 415 km is expected to be between 6 and 12 months depending on the true atmospheric density, progression of the solar cycle, and the rate and duration of experiments that will be performed.

3. Aerodynamic Attitude Control

Aerodynamic attitude perturbations, especially for applications with high pointing accuracy requirements such as remote sensing, need to be countered. In VLEO, these perturbations can exceed the control authority of traditional actuators, but aerodynamics itself can be a part of the solution. DISCOVERER has taken the approach that whilst active aerodynamic surfaces can help counter these disturbances, and even be used to facilitate pointing, real-time uncertainties in flow density, velocity and direction will always mean that aerodynamic control torques also carry uncertainty. Furthermore, the use of external aerodynamic control surfaces naturally carries an additional drag penalty. However, combinations of active aerodynamics for coarse corrections or momentum management, combined with traditional actuators for fine pointing control such as reaction wheels, may provide a viable solution even in the lower VLEO range.

New algorithms for aerodynamic attitude control have been developed within the scope of DISCOVERER [7, 8]. Pointing or reorientation manoeuvres with the combined use of aerodynamic control surfaces and on-board reaction wheels have been implemented using a modified PID controller with an intelligent integrator action. This control may enable aerodynamic control in one or more of the body axes of the satellite whilst the reaction wheels are used to stabilise the remaining axes. Such methods may also be used to perform complete three-axis control of spacecraft operating in VLEO but would require well characterised and high-performance materials that have some specular reflection properties. Management and dumping of satellite angular momentum or rejection of external perturbing torques has also been implemented by the means of an infinite-horizon linear quadratic regulator. Such methods may be particularly relevant for lower altitudes in VLEO where the atmospheric density is high and rapid saturation of traditional attitude actuators may occur, especially if off-axis pointing is required or asymmetric satellite geometries or configurations are specified.

To support both manoeuvre sets, a common algorithm to calculate the necessary configuration of a set of control surfaces to provide the desired control torque has also been developed. This algorithm accounts for the current configuration of the control surfaces, the attitude of the satellite, and estimated environmental parameters and has been shown to provide robust performance despite the uncertainties associated with the VLEO environment [9].

These algorithms have also been implemented on SOAR for in-orbit demonstration using the four steerable fins as the required aerodynamic attitude control surfaces. Aerodynamic roll control, combined roll and yaw, combined pitch and yaw, and angular momentum dumping manoeuvres will be tested at altitudes below approximately 300 km. Simplifications to the idealised algorithms have been made to ensure compatibility with the computational capability of the CubeSat on-board computer. More complex models for the atmospheric density and the satellite aerodynamic coefficients have been replaced with look-up tables. Calculation of optimal gains has also been omitted and will instead be performed on the ground and uplinked to the satellite.

Despite the promise of such control, the remaining uncertainty associated with VLEO environment may limit performance of aerodynamic control until suitable flow sensors that can be used in-the-loop can be developed and included in future implementations.

4. Atmosphere-Breathing Electric Propulsion

ABEP system developments within DISCOVERER include multiple intake designs and a plasma thruster [10, 11]. Intakes in VLEO are designed based on free molecular flow conditions and are therefore driven by the GSI properties of the materials. Three intake designs have been developed (see Figure 3) two based on diffuse reflection properties, and one on specular reemission. The diffuse-based intakes are the Enhanced Funnel Design (EFD) and the “diffuse intake”. Such designs have up to ~46% collection efficiency and their performance is highly dependent on the accuracy of the attitude control and determination system (ADCS) to point the intake into the freestream. The design based on specular reflection, on the other hand, is named "specular intake" and reaches up to ~94% collection efficiency while also being much less sensitive to the alignment with the freestream [11].

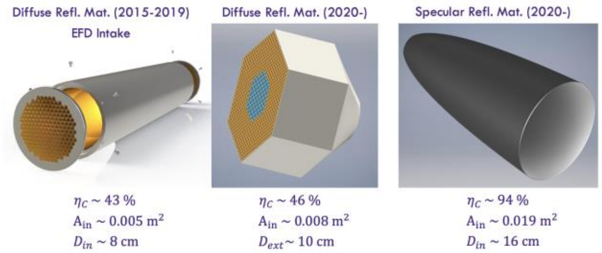

Fig. 3. ABEP Intake Designs (adapted from [11])

The thruster development has focussed on an RF Helicon-based plasma thruster (IPT). This focus is based on the main advantages to be found in the application of contactless technology that removes any issue of thruster's component erosion due to the highly aggressive atomic oxygen predominant in VLEO. Furthermore, such thruster technology produces a quasi-neutral plasma plume that removes the need to employ a neutralizer. The thruster prototype (see Figure 4) has already been successfully operated. It is based on a birdcage antenna with an externally applied magnetic field to enhance the discharge by triggering helicon waves within the plasma. The thruster's bird-cage antenna is matched at the resonance frequency ensuring a maximized power transfer efficiency and, at the same time, producing a linearly polarized magnetic (and electric) field within the discharge channel. The thruster has been operated with Argon, Oxygen and Nitrogen as propellant, see figure 5, and highlights very low power consumption, P~60W [10, 12].

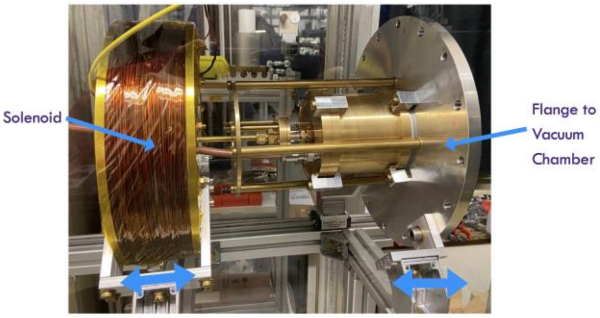

Fig. 4. RF Helicon-based Plasma Thruster Prototype

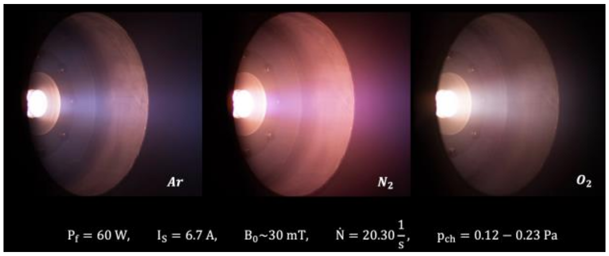

Fig. 5. RF Helicon-based Plasma Thruster in Operation [12]

5. Systems and Business Modelling

VLEO satellites, even for remote sensing are not new. In fact VLEO was used in the Cold War for reconnaissance as early as the late 1950's, for example in the Corona missions. However, commercially viable satellite systems require longer lifetimes to facilitate attractive returns on investment, whilst minimising platform costs, aspects enabled by the DISCOVERER technology developments. The aerodynamic performance of materials and ABEP systems, combined with the geometrical design of satellite concepts, must be wrapped into a systems modelling approach to identify feasible concepts. These in turn must be correlated with cost and business modelling to identify the most promising commercial concepts.

DISCOVERER has developed and published new system relationships for VLEO satellite platfoms for Earth observation in [13]. System models reflecting the different technologies and being developed within the scope of the DISCOVERER project have been used to investigate their impact on EO platform design at reduced orbital altitudes. An integrated systems modelling approach has been developed to capture the key benefits described earlier in this paper, and to reflect the additional challenges faced in the VLEO environment, principally the critical nature of the spacecraft aerodynamic performance and the complex relationships between drag, thrust, and power that are presented for ABEP systems.

Explorations performed using this integrated systems model for VLEO spacecraft design have provided some measure of the reduction in system mass and cost that is afforded by operation at lower orbital altitude and enabled by the prospective technologies. For example, designs for a very-high resolution optical satellite operating at an altitude of 220km, enabled by an ABEP system for drag-compensation and featuring high-performance aerodynamic materials, may see a reduction in mass of up to 75% in comparison to existing spacecraft of this class (e.g. WorldView-4). Even when a less speculative view of the developing technologies is taken, significant savings in mass (>60%) are still presented along with the promise of significant reductions in the associated cost of manufacture.

The Business Model (BM) Canvas of various existing EO companies has been developed to identify both the EO BM pattern and success factors. It leads to the discovery of a new BM pattern in the EO New Space market focused on making more accessible and affordable data to the commercial sector [14] thanks to the reduction of operating costs, the construction of partnership agreements, the use of agile processes in AI&T (Assembly, Integration and Testing), and the automation of intelligent services powered by AI and ML algorithms using cloud-based platforms. Additionally, EO ecosystem trends, including access to space, new ground segment services, and turnkey providers, have become interesting BMs for DISCOVERER. The system modelling of new platforms such as VHR-HP (Very High-Resolution High-Performance satellite), VHR-LC (Very High-Resolution Low-Cost satellite) constellation, and SARoptic satellites also show interesting and promising opportunities to be exploited in VLEO. In addition, new Value Proposition Canvases have been studied for those platforms integrating the technology developments from DISCOVERER such as ABEP, new materials and aerodynamic control, generating to medium-term market opportunities of up to $6.5 billion for the EO market in VLEO in year 2028.

6. Conclusions

DISCOVERER continues to work to address its original research questions with important developments in materials along with methods to characterise their orbital aerodynamic performance, in atmosphere-breathing electric propulsion, in aerodynamic control, and in the development of systems and business models to identify the most promising VLEO concepts. The project has seen significant practical achievements to date, with the ignition of a prototype RF helicon-based plasma thruster, the design, development and launch of the project's Satellite for Orbital Aerodynamics Research (SOAR), the development novel materials with potential aerodynamic properties, and exposure and return of samples of those materials on the exterior of the International Space Station. Significant modelling activities have also been completed including the DSMC modelling and optimisation of aerodynamic intakes for ABEP thrusters, the development of VLEO mission system models, and the development of business models for VLEO mission opportunities and the supporting ecosystem.

As DISCOVERER moves into its final phases, several other key activities about to start producing results. These include the Rarefied Orbital Aerodynamics Research facility (ROAR) for aerodynamic materials characterisation, and SOAR, both of which are the final stages of commissioning. Characterisation of the ABEP thruster also continues along with the development of prototype intakes for tests within ROAR.

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