DISCOVERER: Final Results and Outcomes

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Abstract

The DISCOVERER project commenced in 2017 with the aim to advance the development of key technologies to enable the commercially viable, sustained operation of satellites in very low Earth orbits (VLEO). Funded by the European Commission through Horizon 2020, the project ends this month. This paper presents an overview of the key achievements and current status of the project.

The project set out to advance the development of, and demonstrate, several technologies with the long-term aim of enabling the commercial use of VLEO. These technologies include:

1. aerodynamic materials which encourage specular scattering of the incoming flow to minimise drag and increase the performance of aerodynamic surfaces in the highly rarefied flows experienced in VLEO
2. aerodynamic attitude control methods to compensate for the dynamic flow environment, especially lower in the VLEO altitude range
3. atmosphere breathing electric propulsion (ABEP), combining an optimised atmospheric intake with advanced RF Helicon-based plasma thruster, for drag compensation

DISCOVERER's test satellite, the Satellite for Orbital Aerodynamics Research or SOAR, was deployed from the International Space Station in June 2021 and re-entered the atmosphere in March 2022. The primary aim was to measure the induced drag and lift on different aerodynamic materials candidates in VLEO by exposing panels, coated in various novel and control materials, to the flow at different orientations whilst observing the induced attitude and orbit perturbations produced. Early analysis of the results from the mission shows promising results for the novel materials developed as part of the project. Parallel studies on the long-term survivability of these materials to the space environment have been on-going through exposure tests on the exterior of the International Space Station through the MISSE programme.

The project has also been developing a ground-based facility, the Rarefied Orbital Aerodynamics Research facility, to characterise the gas surface interaction properties of materials to atomic oxygen at orbital velocities. Characterisation of the facility itself is on-going.

In support of ABEP technology, the experimental development and characterisation of an RF Helicon-based plasma thruster has been on-going, along with detailed computational modelling of aerodynamic intakes. Whilst the thruster has already been operated, current work focusses on the characterisation of its performance.

Finally, work to place these technological developments into context has also been progressed. On overview of the overall achievements in this area is provided, including business modelling of the VLEO market ecosystem, which identifies the enormous market potential for VLEO missions.

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

Acronyms/Abbreviations

ABEP	Atmosphere-breathing electric propulsion
EO	Earth observation
GSI	Gas surface interaction
INMS	Ion and neutral mass spectrometer
ISS	International space station
MISSE	Materials on the International Space Station Experiment
ROAR	Rarefied Orbital Aerodynamics Research facility
SOAR	Satellite for Orbital Aerodynamics Research
VLEO	Very low earth orbit

1. Introduction

The interest in the use of Very low Earth orbit (VLEO) for remote sensing, communications and science missions has seen significant growth since the DISCOVERER project commenced. This is most graphically shown in the number of documents captured by Google Scholar which use the phrase "Very low Earth orbit" and which shows significant growth in documents since DISCOVERER began (Fig. 1.).

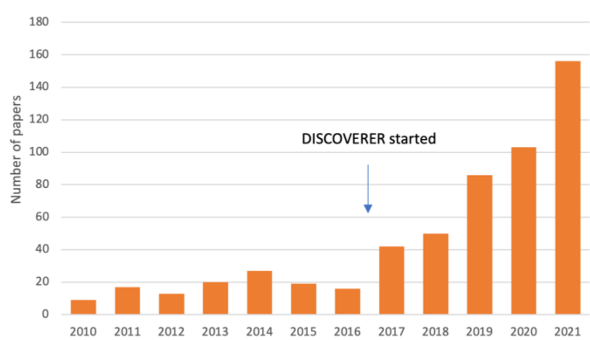

Fig. 1. Google Scholar documents using the phrase "Very low Earth orbit" by year.

The reason for this interest is clear to see from the benefits that operating in VLEO brings, which are well characterised now in a number of papers and technical reports, for example [1] and [2]. However, operating at VLEO altitudes also requires consideration of the aerodynamic effects on a satellite (drag and attitude perturbations) which, by definition, significantly affects the spacecraft design.

Technologies to help overcome the impact of these aerodynamic effects are the key development targets for DISCOVERER. This paper summarises the developments and achievements of DISCOVERER in these technology areas, specifically aerodynamic materials and their characterisation, aerodynamic attitude control, and atmosphere breathing electric propulsion. It also summarises the achievements of DISCOVERER in placing these developments in the context of the space business ecosystem, along with identifying the overall market potential for VLEO missions.

2. Aerodynamic Materials

The highly rarefied nature of the atmosphere in VLEO means that gas-gas collisions are rare, and orbital aerodynamics driven by individual gas particles impinging directly onto satellite surfaces [3]. Prior research shows that these gas particles are typically diffusely reemitted, at the temperature of the surface satellite [4], for typical spacecraft materials. This interaction produces drag, largely proportional to the cross-section to the flow.

In order to minimise drag and produce lift in VLEO, it is necessary for the impinging gas molecules to be reflected specularly or quasi-specularly, in combination with satellite surfaces at shallow angles to the flow. However, such reflection is particularly challenging to obtain and maintain practically, due to the aggressive erosion of most materials in VLEO by reactive hyperthermal atomic oxygen – the most abundant gas species in VLEO.

Based on fundamental research at the University of Manchester into the composition and structure of materials which will best allow for specular reflection, including at the atomic scale, new materials were designed to both promote specular reflection and best resist erosion. The identity of these novel candidate materials can't yet be disclosed due to IP constraints.

Perhaps more difficult than identifying and developing these materials is the process of characterising their aerodynamic and erosion resistant performance. DISCOVERER has taken several independent approaches to this problem to provide both complimentary data sets, but also to maximise the chances of successfully obtaining results. These include the flight of our aerodynamics test satellite (SOAR), the use of the Materials on the International Space Station Experiment (MISSE), and the development of a ground based atomic oxygen beam facility (ROAR). Coatings of the novel materials were applied both to the fins of the SOAR satellite and to substrates for exposure on the MISSE experiment, with appropriate control samples: materials with known specular reflection properties for SOAR, and a material with a known atomic oxygen erosion behaviour for MISSE.

The following sections provide highlights of the developments in these different characterisation activities and their current status.

2.1 SOAR – The Satellite for Orbital Aerodynamics Research

SOAR was designed to investigate the aerodynamic performance of different control and candidate materials in VLEO [5,6]. The satellite was also developed to perform additional experiments to measure the in-situ atmospheric composition and density, the velocity of thermospheric winds, and to demonstrate aerodynamic attitude control manoeuvres.

In order to perform these experiments, the 3U CubeSat platform was equipped with a set of four steerable fins (coated with the different materials) and a ram-facing ion and neutral mass spectrometer (INMS) to measure the properties of the oncoming flow (see Fig. 2).

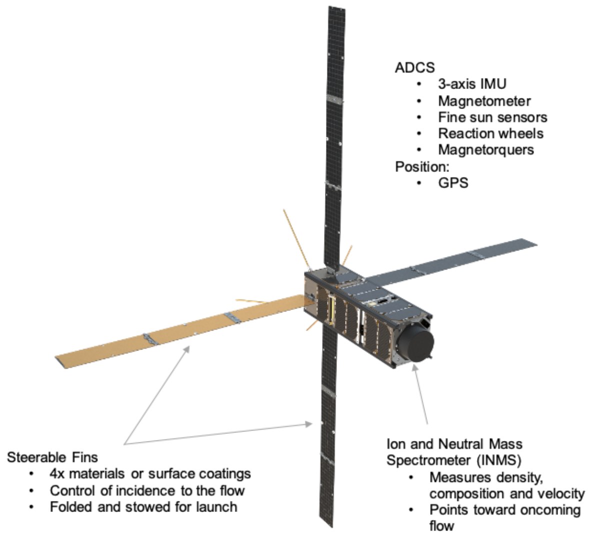

Fig. 2. Visualisation of SOAR with fins deployed highlighting key features.

SOAR was launched on the SpaceX CRS-22 resupply mission to the ISS on 03 June 2021 and deployed on 14 June 2021 into an orbit with apogee and perigee of 421 km and 415 km (see Fig. 3). Operations of the satellite we conducted up until deorbit on 14 March 2022, a lifetime of approximately 9 months after deployment.

Fig. 3. SOAR (right) and Ramsat (left) after deployment from the ISS [image credit: NASA].

During the mission operations, several issues were encountered that required resolution or that affected the overall success of the planned experiments:

- Critically, the INMS suffered an irrecoverable failure on-orbit. Unfortunately, shortly after successful initial commissioning activities, the instrument began to return data packets with zero particle counts. Data from the high-voltage power monitor on the instrument indicated that a SEU may have occurred. Unfortunately, this issue meant that in-situ measurements of the atmospheric density, composition, and velocity could not be gathered during the mission.
- The performance of the steerable fins was found to degrade over the mission lifetime, initially presenting as a “stickiness” that slowed the rate at which the desired rotations would take place. Later in the mission, the fins were observed to get stuck at certain angles of rotation for extended periods of time. Whilst this issue disrupted the experiments to determine the GSI behaviour of the different materials, the rotations could still be performed in most cases. However, the degenerative nature of this issue did prohibit the testing of the aerodynamic control methods that were designed to be performed at lower altitude later in the mission.
- Adjacent channel interference in UHF at the ground station at the University of Manchester was found to significantly affect the downlink of data from the satellite at lower elevation angles. Whilst regular and reliable contact with the satellite could still be made, the available duration and data rate obtainable during each pass was limited, reducing the pace at which operations could be performed. To increase the scientific return from the satellite, the Leaf Space “Leaf Line” ground-station-as-a-service was utilised later in the mission.

As a result of these issues, the volume of data obtained during the lifetime of SOAR was less than desired and the analysis more complicated than anticipated. However, alternative approaches to the experimental analysis that are not dependent on the availability of the in-situ atmospheric measurements from the INMS are being developed and implemented. In particular, to analyse the performance the materials deployed on the steerable fins, modelled density values are being combined with a free-parameter fitting method to determine the surface accommodation coefficient.

This approach is just starting to reveal very promising results for the novel materials developed as part of DISCOVERER compared to the control materials. However, these results need further review, refinement and peer review before being made public, and will the subject of future journal papers.

2.2 MISSE – Materials on the International Space Station Experiment

Use of the MISSE exposure facility on the exterior of the International Space Station has allowed the DISCOVERER project team to directly assess the survivability of the developed novel materials directly in the full VLEO environment – all the relevant hyperthermal gas species, UV, radiation, thermal cycling, vacuum, etc. The MISSE facility allows for samples to exposed on the exterior of the ISS before being returned to Earth for analysis. The generated data is complimentary to that delivered by SOAR and ROAR, providing truth data on erosion and chemical processing for comparison with ROAR data.

Two sets of samples have been flown on MISSE-12 and MISSE-15 (MISSE-15 samples pictured pre-flight in Fig. 4) in both the ram and wake directions, and in each case exposed to the space environment for between 6 and 12 months.

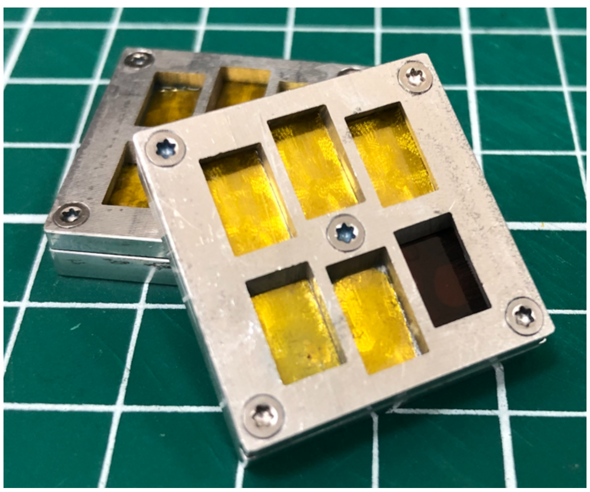

Fig. 4. MISSE-15 sample holders showing the 6 different materials exposed.

Analysis of the returned samples from MISSE-12 is underway, with a particular focus on erosion and chemical changes due to the on-orbit atomic oxygen flux. Materials were first imaged with low vacuum "environmental" scanning electron microscopy (SEM), which allows imaging without destructive metal coating, to assess post-exposure morphology. Low-resolution and high-resolution x-ray photoelectron spectroscopy (XPS) analysis has been applied to determine the elemental composition and oxidation states of the returned materials. Initial results are encouraging, suggesting our novel materials have good resistance to both erosion and oxidation. Further analysis in underway, including high resolution SEM, to best allow for future correlation with atomic oxygen exposure in the ground-based ROAR facility.

A duplicate set of samples was exposed to the space environment for 12 months on MISSE-15. These samples returned from orbit on 20th August 2022 and are currently being de-integrated in preparation for return to Manchester for similar analysis.

2.3 ROAR – The Rarefied Orbital Aerodynamics Research Facility

The aim of the ROAR facility is to perform beam scattering experiments of hyperthermal atomic oxygen from materials samples, in turn allowing the nature of the gas-surface interaction (GSI) to be determined, information critical to understanding the aerodynamic properties of a material [7]. Replicating the flux of atomic oxygen in VLEO, as well as maintaining the flow regime, requires an ultrahigh vacuum system. The system also needs to detect the velocity, composition and angular distribution of the gas being scattered from the sample to form a full GSI characterisation.

ROAR therefore has a number of unique features compared to atomic oxygen exposure facilities. The atomic oxygen source utilises the electron stimulated desorption of oxygen from a thin silver membrane to produce a continuous beam of neutral hyperthermal atomic oxygen at, or near, orbital velocities and densities, an approach first detailed in the mid-1990s by Outlaw [8], one of the DISCOVERER researchers. ROAR also utilises an ion and neutral mass spectrometer (INMS), a variant of a unit with previous spaceflight heritage for characterising atmospheric flows in VLEO [9], and therefore particularly well suited for use within a UHV system to characterise the specular or quasi-specular scattered flow.

A number of technical problems, exacerbated by COVID related delays, has delayed the complete commissioning of the facility, however all the key components are now in place and characterisation of the facility is taking place at the time of writing. Fig. 5. shows the external configuration of the facility, whilst Fig. 6. shows the current test configuration for combined tests of both the INMS and atomic oxygen source, with the materials sample holder in a retracted position, just visible on the left.

The facility will continue to be commissioned and optimised after the end of DISCOVERER project, with the aim of completing the originally intended GSI characterisations, and adding in further enhancements to the facility.

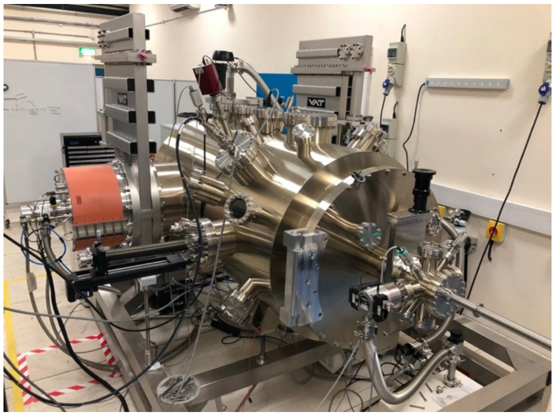
Fig. 5. The Rarefied Orbital Aerodynamics Research (ROAR) facility – external configuration.

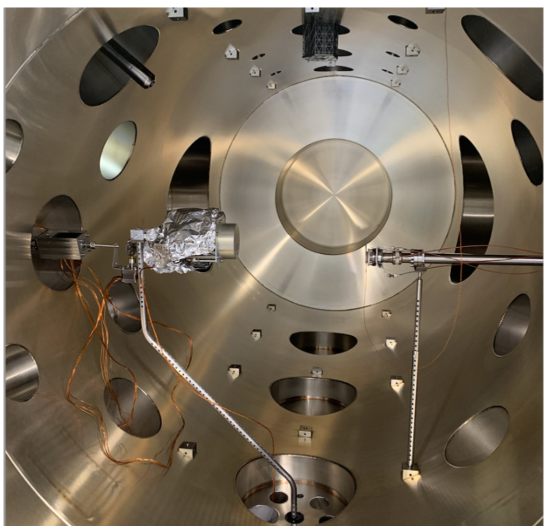
Fig. 6. The current internal configuration of ROAR with the atomic oxygen source (right), and the INMS (left) in position for direct characterisation of the atomic oxygen beam.

3. Aerodynamic Attitude Control

Minimising drag in VLEO is typically achieved by minimising the cross-sectional area to the flow, leading to long and slender designs. This can have the unfortunate side-effect of making the satellite aerostable, which in turn makes it very sensitive to aerodynamic attitude perturbations which can become significant in the lower VLEO altitude range. One solution to overcoming these perturbations is to implement active aerodynamics to minimise or trim these perturbations.

Within DISCOVERER, new algorithms for aerodynamic attitude control were developed. These were implemented on SOAR [10], using the steerable fins as aerodynamic surfaces, to demonstrate active aerodynamics in VLEO including aerodynamic trimming and active attitude adjustment combined with reaction wheels for fine control. These methods used an algorithm to identify the closest set of fin deflection angles which produced the required aerodynamic torques to meet the control requirement at any point in time.

Active aerodynamic control was always planned for later in the satellite mission when the altitude had decayed to below 200 km, where the aerodynamic control authority had increased. Unfortunately, during the scientific operations at higher altitudes, the observed degradation in the ability to turn two of the fins described in section 2.1 made the demonstration of the closed-loop active aerodynamic manoeuvring impossible. Nevertheless, several experiments were successfully performed of the roll control of the platform using a single (non-sticky) fin. As part of them, several open-loop configurations of the control surfaces were set achieving different angular rates to characterise the toque introduced by the fins at different orbital states.

Due to the uncertainties introduced by the dynamic pressure of the rarefied flow, as well as its interaction with the control surfaces, data extracted during the in-orbit experiments is being used in data-driven algorithms to analyse those aerodynamically induced torques, whilst separating out the effects of atmospheric variations and different gas-surface interaction models. These results will be the subject of future publications.

4. Atmosphere-Breathing Electric Propulsion

Within DISCOVERER two major parts of an ABEP system were designed, the intake and advanced thruster, with the latter being already successfully operated [11,12]. The research focus is now put on characterizing the performance of the thruster and the plasma's magnetic field. For this purpose, two instruments were designed, manufactured and calibrated, a thrust balance to measure the momentum flux, and a B-dot probe [13,14].

The momentum flux probe is a miniaturised baffle-plate thrust pendulum in an L-shaped torsional configuration (Fig. 7). Its target, made of graphite for low sputter yield, is brought into the plasma and deflects the pendulum by momentum transfer of the plume's kinetic energy. An LED distance sensor measures the resulting displacement. With a size of 20 mm in diameter, the target allows mapping the momentum of the plume and hence the thrust centre can be localised. The target is furthermore electrically isolated from the rest of the pendulum, to quickly reach the same potential as the plume. This measure reduces influence on the pendulum dynamics by differences in potential. The materials of the probe are carefully selected to mitigate influence on the thruster's magnetic field. The L-shape design furthermore allows the target to be brought closer to the thruster's exit plane. The whole probe is covered by a shield to prevent unwanted motion and interaction with the plasma [15].

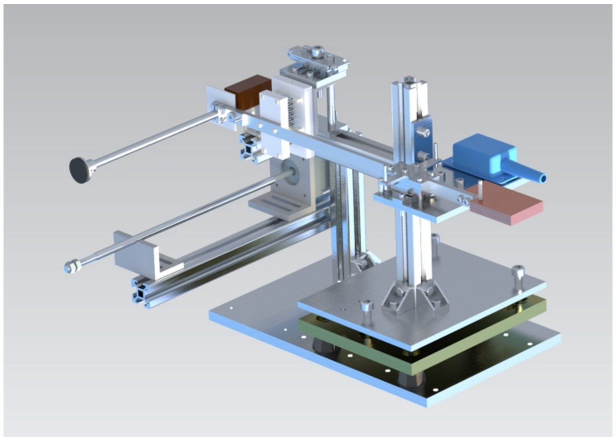

Fig. 7. CAD model of the momentum flux probe without shield

Correlation of the pendulum displacement with a known force is done via an electrostatic comb calibration setup. By applying up to 1 kV, the two halves of the comb attract each other, generating an electrostatic force. This force was calibrated by using a precision laboratory scale [10]. An exemplary calibration curve is displayed in Fig. 8.

First measurements were conducted with the thruster operating and it was possible to record and differentiate the cold gas thrust resulting of 0.6 mg/s of Argon and the plasma thrust at 250 W. Mapping of the whole plume is currently ongoing to derive a thrust level and will be published soon.

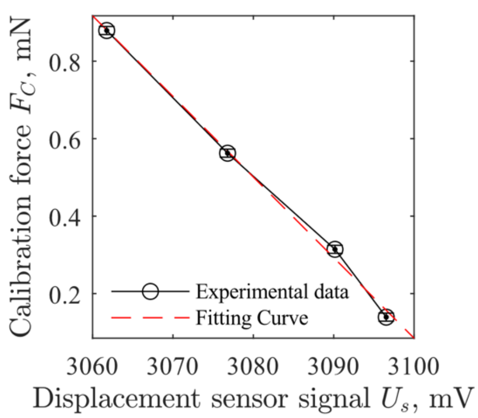

Fig. 8. Exemplary calibration curve of the MFP [16].

The B-dot probe, depicted in Fig. 9., features three identical coils at different angles. Via Faraday's law of induction, magnetic fields can be detected with spatial resolution. The main purpose is to confirm the rotating magnetic field of Helicon waves, to demonstrate the thruster's principle.

Fig. 9. Tip of the B-dot probe showing the three coils.

The probe was designed and built as an elongated PEEK carrier structure for the coil wire, with the coils placed at the tip. The whole setup is sealed with a borosilicate glass tube to prevent interaction with the plasma.

Currently, calibration of the probe with a Helmholtz coil and the thruster's electromagnet itself are ongoing.

Furthermore, work on the intake part of the ABEP system is being continued in the ESA project RAM-CLEP. The specular intake design previously described is being adapted and numerically simulated in the design process of an ABEP platform. The project is thoroughly described in IAC-22-C4.9.1 [12].

5. Systems and Business Modelling

Commercially viable VLEO satellite systems will require lifetimes comparable to typical satellites to produce attractive returns on investment, whilst also minimising system costs. A clear understanding of the market ecosystem is also required to know how VLEO systems fit in.

In part thanks to the DISCOVERER technology developments, VLEO has been demonstrated to be feasibly exploitable for new markets in imaging and telecommunications, estimated at $6.5 Billion in a 10-year horizon just in EO activities in the upstream and midstream sectors. This has been evidenced in a number of DISCOVERER public deliverables and publications. Focussing on the journal publications these include papers on:

- A new framework for VLEO concept-level satellite design and this approach to explore the system-level trade-offs for future EO spacecraft enabled by the DISCOVERER technologies [17].
- The key challenges associated with our understanding of the lower thermosphere, aerodynamic drag, the requirement to provide a

meaningful orbital lifetime whilst minimising spacecraft mass and complexity, and atomic oxygen erosion [18].

- The similarities between the development of the low cost airlines, and the small satellites industry, in order to find the success criteria that can be extrapolated in the development of the VLEO market [19].
- One specific roadmap related to the opportunities that the access to space is offering to the VLEO market [20].

In addition, a book chapter was produced which analyses how disruptive small satellite innovations in VLEO are within the EO market [21]. A set of hypotheses based on established standards for disruptive innovation has been analysed finding that small satellites technologies in VLEO represent a low-end-market disruption innovation, since they don't drastically change satellite EO business. Rather they provide accessible and affordable data that opens new market opportunities for commercial and non-commercial business models and improves the performance of the space market.

Overall, the main conclusion of the project in business terms is twofold. Firstly, the VLEO market provides an enormous potential for exploitation that may allow newcomers to create new products and services. Secondly, even if some technological development is still required, a combination of public and private financing may overcome those challenges.

6. Conclusions

DISCOVERER, as a project, aimed to break new ground in a number of technological areas linked to enabling the commercial exploitation of VLEO orbits. An originally unwritten aim was also to promote the use of VLEO as an attractive alternative to operating satellites at a higher LEO altitudes, an aim we have achieved and which is evidenced by the significant increase in interest in the use of VLEO. The project has also demonstrated the large market potential for VLEO remote sensing and communications systems.

In the development and characterisation of aerodynamic materials, new materials have been developed and tested in two different ways, through in-orbit testing on SOAR and in parallel on the MISSE facility. Both show promising early results in initial data analysis and will be further detailed in future journal papers.

Whilst DISCOVERER's original aim to demonstrate active aerodynamic attitude control on SOAR was impacted by the degraded ability to turn two of the steerable fins, open loop roll manoeuvres were demonstrated, the full characterisation of which is on-going.

In atmosphere breathing electric propulsion, significant progress has been made in the modelling of atmospheric intakes, and the practical demonstration of an RF helicon-based plasma thruster. Full characterisation of the thruster performance is currently underway.

Whilst progress in all areas of the project has not progressed as quickly as originally planned, this is in large part due to the impact of the COVID pandemic, and the highly experimental and ambitious nature of the project. Nevertheless, DISCOVERER has made significant progress towards its intended goals and given the demonstrated value and potential of VLEO, further development in these areas will continued beyond the end of the project.

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References

[1] Crisp, N., Roberts, P., Livadiotti, S., Abrao Oiko, V. T., Edmondson, S., Haigh, S., Huyton, C., Sinpetru, L., Smith, K., Worrall, S., Becedas, J., Dominiguez, R. M., Gonzalez, D., Hanessian, V., Molgaard, A., Nielsen, J., Bisgaard, M., Chan, Y. A., Fasoulas, S., ... Schwalber, A. The Benefits of Very Low Earth Orbit for Earth Observation Missions. Progress in Aerospace Sciences, 117, (2020).

[2] Hills, R., Berthoud, L., Havouzaris-Waller, M. and Gayrard, J., Very Low Earth Orbits (VLEO) for Satellite Communications – D11 VLEO Final Report, ESA Contract No 4000127889/19/NL/FGL, (2020).

[3] Mostaza-Prieto, D., Graziano, B.P., Roberts, P. C. E. Spacecraft drag modelling, Prog. Aerosp. Sci. 64, 56–65, (2014).

[4] Moe, K. & Moe, M. M. Gas–Surface Interactions and Satellite Drag Coefficients, Planet. Space Sci. 53, 793–801, (2005) .

[5] Crisp, N. H., Roberts, P., Livadiotti, S., Macario Rojas, A., Abrao Oiko, V. T., Edmondson, S., Haigh, S., Holmes, B., Sinpetru, L., Smith, K., & et al. In-Orbit Aerodynamic Coefficient Measurements using SOAR (Satellite for Orbital Aerodynamics Research). Acta Astronautica, 180, 85-99, (2021).

[6] Crisp, N. H., Hanessian, V., Sulliotti-Linner, V., Herdrich, G. H., Garcia-Alminana, D., Kataria, D., Seminari, S., & Roberts, P. C. E.. A Method for

the Experimental Characterisation of Novel Drag-Reducing Materials for Very Low Earth Orbits using the Satellite for Orbital Aerodynamics Research (SOAR) Mission. CEAS Space Journal, (2022).

[7] Abrao Oiko, V. T., Roberts, P., Macario Rojas, A., Edmondson, S., Haigh, S., Holmes, B., Livadiotti, S., Crisp, N., Smith, K., Sinpetru, L., Becedas, J., Domínguez, R. M., Sulliotti-Linne, V., Christensen, S., Kauffman Jensen, T., Nielsen, J., Bisgaard, M., Chan, Y-A., Herdrich, G. H., ... Villain, R. (Accepted/In press). Ground-based xperimental facility for orbital aerodynamics research: design, construction and characterisation. In 71st International Astronautical Congress (IAC) – The CyberSpace Edition, 12-14 October 2020

[8] Outlaw, R. A., & Davidson, M. R. Small ultrahigh vacuum compatible hyperthermal oxygen atom generator, J. Vac. Sci. Technol., Vol. 12, No. 3, (1994).

[9] Kataria, D. Mass spectrometry for VLEO and DISCOVERER. https://discoverer.space/wp-content/uploads/2019/12/Session-3_Mass-spectrometry-for-VLEO-and-DISCOVERER_Dhiren-Kataria.pdf Accessed 2 Sept (2022).

[10] Livadiotti, S., Crisp, N.H., Roberts, P.C.E., Oiko, V.T.A., Christensen, S., Dominguez, R.M, Herdrich, G.H., Uncertainties and Design of Active Aerodynamic Attitude Control in Very Low Earth Orbit, J. Guid. Control. Dyn., Vol 45, No. 5, (2021).

[11] F. Romano, Y.-A. Chan, G. Herdrich, C. Traub, S. Fasoulas, P. Roberts, K. Smith, S. Edmondson, S. Haigh, N. Crisp, V. Oiko, S. Worrall, S. Livadiotti, C. Huyton, L. Sinpetru, A. Straker, J. Becedas, R. Dom ́ınguez, D. Gonz ́alez, V. Can ̃as, V. Sulliotti-Linner, V. Hanessian, A. Mølgaard, J. Nielsen, M. Bisgaard, D. Garcia-Almin ̃ana, S. Rodriguez-Donaire, M. Sureda, D. Kataria, R. Outlaw, R. Villain, J. Perez, A. Conte, B. Belkouchi, A. Schwalber, B. Heißerer, RF Helicon-based Inductive Plasma Thruster (IPT) Design for an Atmosphere-Breathing Electric Propulsion system (ABEP), Acta Astronautica 176, 476-483, (2020).

[12] F. Romano, J. Espinosa-Orozco, M. Pfeiffer, G. Herdrich, N. Crisp, P. Roberts, B. E. Holmes, S. Edmondson, S. Haigh, S. Livadiotti, A. Macario-Rojas, V. A. Oiko, L. Sinpetru, K. Smith, J. Becedas, V. Sulliotti-Linner, M. Bisgaard, S. Christensen, V. Hanessian, T. K. Jensen, J. Nielsen, Y.-A. Chan, S. Fasoulas, C. Traub, D. Garcia-Almin ̃ana, S. Rodriguez-Donaire, M. Sureda, D. Kataria, B. Belkouchi, A. Conte, S. Seminari, R. Villain, Intake Design for an Atmosphere-Breathing Electric Propulsion System (ABEP), Acta Astronautica, 187, 225-235, (2021).

[13] Romano, F., Herdrich, G., Chan, Y.-A., Crisp, N. H., Roberts, P. C. E., Holmes, B. E. A., Edmondson, S., Haigh, S., Macario-Rojas, A., Oiko, V. T. A., Sinpetru, L. A., Smith, K., Becedas, J., Sulliotti-Linner, V., Bisgaard, M., Christensen, S., Hanessian, V., Jensen, T. K., Nielsen, J., Fasoulas, S., Traub, C., García-Almiñana, D., Rodríguez-Donaire, S., Sureda, M., Kataria, D., Belkouchi, B., Conte, A., Seminari, S., and Villain, R., Design of an intake and a thruster for an atmosphere-breathing electric propulsion system, CEAS Space Journal, (2022).

[14] Papavramidis, K, Skalden, J., Souhair, N., Herdrich, G., Maier, P., Klinkner, S., Fugmann, M., Traub, C., Fasoulas, S., Romano, F., Chan, Y.-A., Roberts, P.C.E., Smith, K.L., Edmondson, S., Haigh, S.J., Crisp, N.H., Oiko, V.T.A., Sinpetru, L.A., Macario-Rojas, A., Holmes, B.E.A., Becedas, J., Arcos, A., Christensen, S., Hanessian, V., Jensen, T. K., Nielsen, J., Bisgaard, M., Garcia-Almiñana, D., Rodriguez-Donaire, S., Sureda, M., Kataria, D., Villain, R., Seminari, S., Conte, A., Belkouchi, B., Development Activities for the RF Helicon-based Plasma Thruster: Thrust Measurement and B-dot Probe Set-up, 37th International Electric Propulsion Conference, Vol. IEPC-2022, No. 167, Massachusetts Institute of Technology, Cambridge, MA USA, (2022).

[15] Schafft, M., Design and Test of a Baffle Plate to Perfom First Thrust Measurement of the IPT, Master Thesis, University of Stuttgart, Institute of Space Systems, (2022).

[16] Herdrich, G., Papavramidis, K., Maier, P., Skalden, J., Hild, F., Pfeiffer, M., Fugmann, M., Klinkner, S., Fasoulas, S., Souhair, N., Ponti, F., Weikert, S., Tatay Sanguesa, J., Schäff, S., Wiegand, A., Manente, M., Paulon, D., Trezzolani, F., Le Quang, D., Magin, T., Parodi, P., Walpot, L., and Duesmann, B., Platform and system design study of a VLEO satellite platform using the IRS RF Helicon-based Plasma Thruster, IAC-22-C4.9.1, 73rd International Astronautical Congress, Paris, France, 2022.

[17] Crisp, N., Roberts, P., Livadiotti, S., Abrao Oiko, V. T., Edmondson, S., Haigh, S., Huyton, C., Sinpetru, L., Smith, K., Worrall, S., Becedas, J., Dominiguez, R. M., Gonzalez, D., Hanessian, V., Molgaard, A., Nielsen, J., Bisgaard, M., Chan, Y. A., Fasoulas, S., ... Schwalber, A. The Benefits of Very Low Earth Orbit for Earth Observation Missions. Progress in Aerospace Sciences, 117, (2020).

[18] Crisp, N. H., Roberts, P. C. E., Romano, F., Smith, K. L., Oiko, V. T. A., Sulliotti-Linner, V.,

Hanessian, V., Herdrich, G. H., García-Almiñana, D., Kataria, D., & Seminari, S. System modelling of very low Earth orbit satellites for Earth observation. Acta Astronautica, 187, 475-491, (2021).

[19] Rodriguez-Donaire, S., Garcia-Almiñana, D., Garcia-Berenguer, M, Roberts, P.C.E., Crisp, N. H., Herdrich, G. H., Kataria, D., Hanessian, V., Becedas, J., & Seminari, S. Strategic similarities between Earth Observation small satellite constellations in very low Earth orbit and low-cost carriers by means of strategy canvas. CEAS Space Journal, (2022).

[20] Rodriguez-Donaire, S., Gil, P., Garcia-Almiñana, D., Crisp, N. H., Herdrich, G. H., Roberts, P. C. E., Kataria, D., Hanessian, V., Becedas, J., & Seminari, S. Business roadmap for the European Union in the NewSpace ecosystem: a case study for access to space. CEAS Space Journal, (2022).

[21] Rodriguez-Donaire, S., Sureda, M., Garcia-Almiñana, D., Sierra, E., Perez, J. S., Roberts, P., Becedas, J., Herdrich, G. H., Kataria, D., Outlaw, R., Ghizoni, L., Villain, R., Conte, A., Belkouchi, B., Smith, K., Edmondson, S., Haigh, S., Crisp, N., Abrao Oiko, V. T., ... Heißerer, B. (Accepted/In press). Earth Observation Technologies: Low-End-Market Disruptive Innovation. In Satellite Missions and Technologies for Geosciences, IntechOpen, (2020).