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KEYNOTE: DISCOVERER – Making Commercial Satellite Operations in Very Low Earth Orbit a Reality

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Abstract

DISCOVERER is a €5.7M European Commission funded Horizon 2020 project developing technologies to enable commercially-viable sustained-operation of satellites in very low Earth orbits. Why operate closer to the Earth? For communications applications latency is significantly reduced and link budgets improved, and for remote sensing improved link budgets allow higher resolution or smaller instruments, all providing 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. One of the key technologies being developed by DISCOVERER are materials that encourage specular reflection of the residual atmosphere at these altitudes. Combined with appropriate geometric designs these can significantly reduce drag, provide usable lift for aerodynamic attitude and orbit control, and improve the collection efficiency of aerodynamic intakes for atmosphere breathing electric propulsion systems, all of which are being developed as part of DISCOVERER. The paper provides highlights from the developments to date, and the potential for a new class of aerodynamic commercial satellites operating at altitudes below the International Space Station.

Keywords: (maximum 6 keywords)

Nomenclature

Acronyms/Abbreviations

ABEP	Atmosphere-breathing electric propulsion
EO	Earth observation
FMF	Free molecular flow
GSI	Gas-surface interaction
GTO	Geostationary/geosynchronous transfer orbit
SOAR	Satellite for orbital aerodynamics research
VLEO	Very-low Earth orbit

1. Introduction – Why Use Very Low Earth Orbits?

Satellite derived services have become embedded in our interconnected society providing rapid international communications, navigation, and remote sensing data, which in turn facilitate services from television and broadband internet, through to environmental management and disaster monitoring. The changing nature of the space industry that develops these satellites also means it reacts to potential market opportunities rapidly. Technologies or approaches which reduce the cost of providing satellite-based services are likely be quickly adopted.

Operating communications and remote sensing satellites at lower altitudes offers significant technical [1] and cost advantages [2]. The benefits can be broadly categorized as those that improve payload performance, platform benefits, and the opportunity to exploit new technological approaches, which are summarized in Table 1.

Table 1 Benefit of operating remote sensing and communications satellites at lower altitudes.

Category	Benefit
Improved Payload Performance	Optical payloads have: • Increased resolution or reduced aperture size • Improved radiometric performance
	Radar and communications payloads have: • Significantly improved link budgets • Reduced antenna size and transmission power • Reduced latency and improved frequency reuse
Platform Benefits	• More benign radiation environment • Improved launch vehicle payload mass (up-mass) • End-of-life disposal is enabled • Reduced space debris collision risk • Improved geospatial accuracy and relaxed pointing requirements
New Possible Technologies	• Aerodynamic attitude and orbit control • Atmosphere breathing electric propulsion for drag compensation

There are, of course challenges to operating in VLEO, largely to do with the impact of the residual atmosphere.

Typically, remote sensing satellites operate in the 500-800km altitude range whilst the new mega-constellations for global broadband are designed to operate in the 550-1200km altitude range (e.g. SpaceX's Starlink and Oneweb). Operating at lower orbits place satellites in Very Low Earth Orbit (VLEO). VLEO can generally be defined as the altitude range where aerodynamic considerations have a significant impact on the design of a satellite operating there. This can be though geometry changes and/or the need for ongoing drag compensation (e.g. GOCE or the ISS), or accepting short lifetimes (typically CubeSats, e.g. Planet Labs). VLEO can therefore be defined as the range from around 450 km altitude down to the Karman line at around 100km. To realize the goal of commercially viable, sustained operation in VLEO, we need to go back to first principles in a number of areas.

2. Orbital Aerodynamics

Orbital aerodynamics is the study of the interactions of the residual atmosphere in the low Earth orbit altitude range, with the bodies that orbit there.

The aerodynamic flow regime acting around a satellite is defined by the Knudsen number K_n, the ratio of the free mean path of the residual gas λ to the characteristic length of the spacecraft L (typically of the order of a metre). When $K_n > 10$, the flow is usually considered to be free molecular, meaning that the effect of interactions between gas molecules is insignificant, and aerodynamics is driven by the direct interaction of the gas molecules with the spacecraft surfaces exposed to the flow [3]. This is the case for most satellites in orbits above around 140 km altitude at mean solar conditions for satellites with dimensions around 1 metre.

The flow density and composition is affected by a number of factors. The atmospheric density decreases approximately exponentially with altitude, yet the high orbital velocity of satellites makes the dynamic pressure significant over typical orbital lifetimes. Extreme UV from the Sun breaks down molecular oxygen, making atomic oxygen the predominant gas species in the VLEO range (see Figure 1).

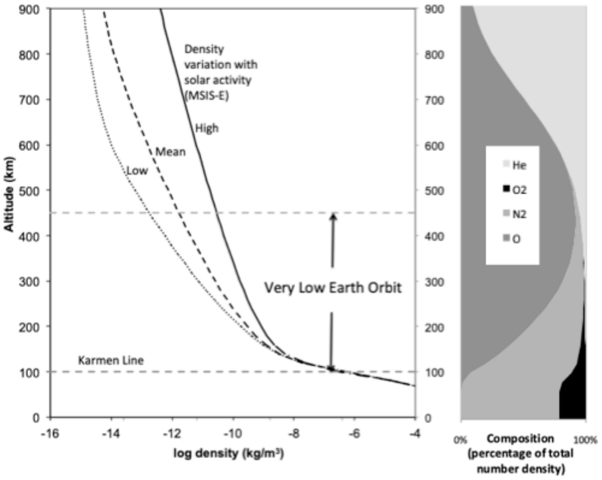


Figure 1 Atmospheric density and composition with altitude using NRLMSISE-00 [4] model and ECSS reference solar and geomagnetic index definitions.

Atomic oxygen is highly reactive species, and empirical data shows that it adsorbs to most spacecraft surface materials. This contaminates the surface and is thought to cause the incoming flow to be accommodated to the surface, being re-emitted at the temperature of the surface [5]. This has the effect of passing the initial momentum of the gas directly to the satellite surface, and as the thermal velocity of the particles is much smaller than the orbital velocity, the momentum exchange due to the reemission is typically a small fraction of the orbital momentum.

This in turn means that aerodynamic shaping of satellites only has an impact if it minimizes the cross-section of the satellite to the flow (ignoring the Maxwellian distribution of gas particle velocities for a moment and thereby treating the flow as a collimated beam). Pointed nose cones for example offer minimal reduction in drag, as the majority of the moment exchange is in the direction of the flow, and any benefit would be outweighed by the increased mass and complexity of adding the cone.

Traditionally this means that as the operational altitude of a satellite decreases into the VLEO range, optimum spacecraft designs limit the cross-section of the satellite, and propulsion systems for drag compensation are required, whether continuous or intermittent. Alternatively, short orbital lifetimes are simply accepted.

But are there other technologies which can make VLEO satellites commercially attractive? DISCOVERER [6] is developing three such technologies: aerodynamic materials, aerodynamic attitude and orbit control, and atmosphere breathing electric propulsion.

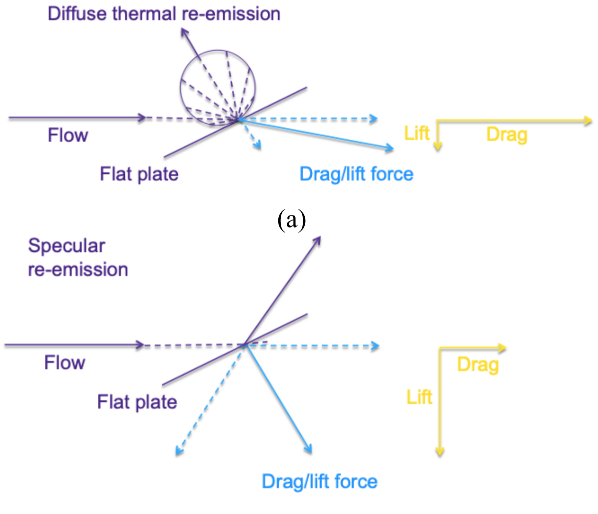
3. Aerodynamic Materials

DISCOVERER as a project goes back to first principles in a number of areas to explore technologies that can minimize drag, or utilize the residual atmosphere as an asset.

The proportion of the incoming gas that is accommodated, and thereby produces predominantly drag forces, is captured in an accommodation coefficient, α. α=0 implies no accommodation and incoming gas is specularly reflected at the incoming velocity. α=1 implies full thermal accommodation, with the gas diffusedly reemitted at the temperature of the surface. Various empirical studies have shown accommodation coefficients in the VLEO range varying from 1 [5] through to 0.82 [7]. This variation is known to be dependent of factors related to the chemistry of the surface material, for example the molecular mass of the material and also on incidence angle [5]. But other than materials selection to ensure surfaces do not excessively erode due the impingement of atomic oxygen, the accommodation coefficient of specific materials has not to date been a consideration in satellite design.

Going back to first principles, what if there were materials which specularly reflect the incoming flow, and which can therefore be used to minimize drag? If such materials existed, how would we know? These are key questions the DISCOVERER project aims to answer.

Why focus on materials which specularly reflect the flow? Figure 2 compares the gas surface interaction, with accommodation coefficients of 1 and 0, with a flat plate at a high angle (>45 degrees) to the flow and the resultant momentum exchange. In the diffuse reemission case, even with a satellite panel at a high angle to the flow, the momentum exchange is largely in the direction of the incoming flow (drag), and little lift is produced (lift to drag ratios are typically of the order of a few percent at best). Whereas in the case of specular reflection, the momentum exchange is now perpendicular to the surface, significantly reducing the drag component, and also raising the possibility of useable lift for attitude and orbit control purposes.



(a)

(b)

Figure 2 Comparison of diffuse thermal reemission (a) and specular reflection (b) and the resulting momentum exchange. Lift to drag ratios shown are representative (not to scale).

DISCOVERER is addressing the question of how we determine the aerodynamic performance of materials through three parallel activities:

1. A ground-based facility to replicate the flow of atomic oxygen in very low Earth orbits, the Rarefied Orbital Aerodynamics Research facility (ROAR), and which will allow the characterisation of the re-emitted flow and thereby determine the nature of the gas-surface interaction and the effective accommodation coefficients of materials [8].
2. An aerodynamics test satellite, the Satellite for Orbital Aerodynamics Research (SOAR), which will assess the generated drag and lift produced by different promising materials in very low Earth orbit [9].

3. Using Alpha Space's "Materials on the International Space Station Experiment Flight Facility" (MISSE-FF) to determine the survivability of the most promising materials when exposed to the full VLEO environment.

3.1. The Rarefied Orbital Aerodynamics Research (ROAR) Facility

ROAR's objective is to replicate the key and predominant reactive gas species in orbital flows, atomic oxygen, at orbital velocities, and in a free molecular flow environment, so that the reemission of the flow from different materials can be characterised. This limits the range of potential atomic oxygen production methods to those that produce fluxes equivalent to those experienced in the VLEO range, and without the use of "carrier gases" to aid the acceleration of the atomic oxygen. ROAR will generate a beam of atomic oxygen using electron stimulated desorption of oxygen atoms from a thin silver membrane (see Figure 3), a method previously demonstrated by Outlaw et al [10].

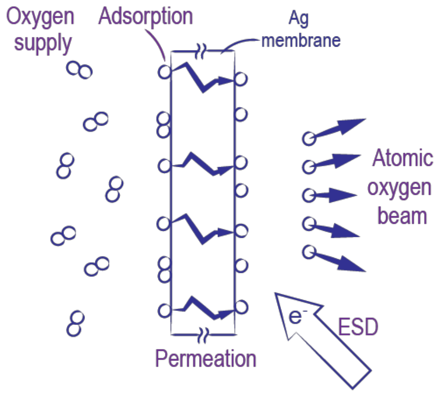


Figure 3 Atomic oxygen production method of Outlaw et al [10].

Maintaining the free molecular flow environment effectively means placing the atomic oxygen source in a high vacuum facility, with sufficient pumping capacity to keep the impingement on a materials sample from residual gas in the chamber to orders of magnitude below the atomic oxygen beam.

Measurement of the beam and the reemission of gas from a materials sample will be carried out using a combination of movable ion-neutral mass spectrometers and residual gas analysers. These have the capacity to measure flux, velocity, composition and angular distribution of the reemitted flow, and thereby characterise the gas surface interactions at the surface, and determine accommodation coefficient of materials.

An overall schematic of the ROAR system is given in Figure 4. Samples will be introduced through a load-lock chamber in an ISO-7 class clean room, and placed on a sample holder which can vary the angle of the sample to the atomic oxygen beam, allowing for variations from grazing angles to normal incidence. The scattered particles are monitored by the detectors surrounding the sample. These detectors are also responsible for characterising the atomic oxygen beam, providing beam shape, energy distribution, ion to neutral ratio and composition.

Nominal characteristics of the facility are operation pressures between 10^{-7} and 10^{-9} mbar, flux of O atoms in the order of $10^{13} – 10^{15}$ atom cm^{-2} s^{-1} with kinetic energies varying from 4–6 eV.

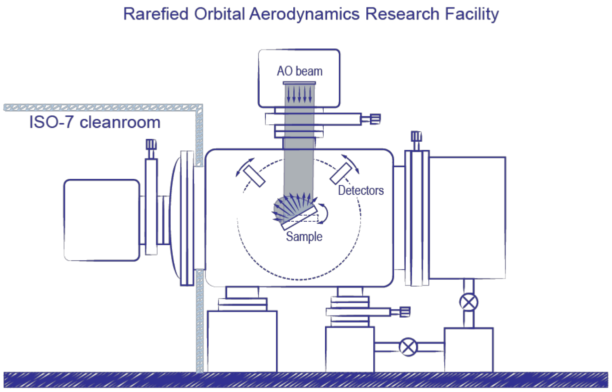


Figure 4 Schematic of ROAR.

The system is currently in the build phase, and is due to be operational by the end of 2019 [11].

3.2. The Satellite for Orbital Aerodynamics Research (SOAR)

Validation of the aerodynamic performance of materials can only be carried out in the VLEO environment. To this end, the Satellite for Orbital Aerodynamics Research (SOAR) was developed [9].

The satellite, shown in Figure 5 has two payloads, a set of deployed fins, coated with different sample materials, and with the ability to vary the angle of the fin to the flow, and an Ion and Neutral Mass Spectrometer (INMS).

Figure 5 CAD model of SOAR

Observations of the satellite dynamics allow the reconstruction of the induced drag and lift from a set of fins exposed to the flow. For example, counter-rotated fins on opposite sides of the satellite, exposing the same material at the same angle to the flow on both fins, will produce a step change in drag along with a roll torque. Induced drag will be determined from the change in orbital elements reconstructed from GPS measurements, whilst the roll torque can be observed using the attitude determination system. The induced drag and lift in turn describe the accommodation coefficient of the material.

The INMS resolves the other key uncertainty in the study of orbital aerodynamics by measuring the characteristics of the residual atmosphere. Capable of measuring the particle flux, velocity and composition of the flow, the density and thereby the dynamic pressure can be determined.

Due for launch in Q3 2020, SOAR will therefore provide validation of the performance of a set of the most promising candidate aerodynamic materials which promote specular reflection of the flow, in the full VLEO environment.

3.3. Materials on the International Space Station Experiment (MISSE)

Whilst ROAR will test the performance and survivability of candidate materials to a beam of atomic oxygen at orbital velocity, it will not demonstrate the capability of the materials to survive the full VLEO environment with other gas species present, extreme UV, and other environmental factors. And whilst SOAR will be able to determine the aerodynamic performance of materials in the VLEO environment, we cannot determine the survivability of the materials on the satellite.

DISCOVERER is therefore placing samples of the five most promising candidate materials on the MISSE Flight Facility on the International Space Station. Alpha Space owns and operates the MISSE facility under agreements with NASA and the Center for the Advancement of Science in Space (CASIS). A model of the inch square sample plate that has already been integrated in the MISSE sample holder can be seen in Figure 6, also showing the Kapton stack which, as it erodes, acts a total atomic oxygen flux measurement.

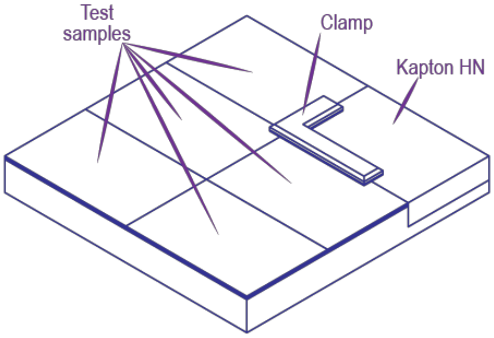


Figure 6 Schematic of the DISCOVERER inch square sample plate, currently mounted in the MISSE sample holder.

Due for launch in October 2019, two pre-flight characterised sets of the materials will be exposed in the ram and wake directions and returned to Manchester after 6 months of exposure for post-flight characterisation. This will allow the determination of erosion rates and any other unexpected environmental processing of the materials.

4. Aerodynamic Attitude Control

In VLEO, aerodynamic interactions with a satellite appear not just as drag but, as atmospheric density and thermospheric winds vary with solar activity, also as out of plane forces and torques. Passive aerostability has been demonstrated on several missions [12–14] and is beneficial in that it presents a minimum drag configuration to the flow without requiring actuation. But for missions requiring high pointing accuracy, or slewing to point sensors, aerostability may not be the best solution as these torques act to disturb attitude. Similarly for missions which require slews for pointing of body mounted instruments, for example for remote sensing, aerostability generates a bias torque, when not in a nominal flow pointing configuration, that must be countered.

At lower altitudes in VLEO, aerodynamic torques will also exceed the capability of traditional attitude actuators, such as reaction wheels and magnetorquers, to compensate these disturbances. The approach taken by DISCOVERER in developing control approaches for different applications still involves traditional actuators due the varying and unpredictable nature of the atmosphere and the implications this has for aerodynamic control. A typical example therefore uses reaction wheels for fine control, with aerodynamics used for trim and momentum management.

The attitude control requirements of VLEO satellites can be broadly grouped into three categories, and appropriate control approaches as described in table 2.

Attitude Concept	Application
Fixed Aerostable	Optical coverage, simple SAR, communications
Aerostable with control (active aerodynamics)	High resolution optical, SAR
Neutrally stable (with or without aerodynamic surfaces)	High agility platforms

Table 2: Aerodynamic control concepts and their typical applications.

Fixed aerostable, platforms which maintain their flow pointing orientation, can be used for some applications where only nadir pointing sensors or antenna are needed, and which have more relaxed constraints on pointing performance. Damping of attitude perturbations is still needed, but these can be provided using passive methods (hysteresis rods or fluid magnetic dampers) or active (e.g. reaction wheels or magnetorquers).

If however, intermittent slews are required to point sensors at targets of interest, the use of active aerodynamics is required, especially at lower altitudes, to avoid saturation of reaction wheels. Aerodynamics can be used to aerodynamically trim the satellite in a slewed position, and also manage the momentum stored in the wheels.

For highly agile platforms requiring very high pointing accuracy, the varying atmosphere in combination with aerostability is likely to unacceptably disturb the pointing. Satellite geometries that are aerodynamically neutrally stable can be envisioned which avoid this.

Aerodynamic control can be provided in a number of ways, but two typical configurations for aerostable satellites are the feathered or shuttlecock configurations, shown in Figure 7. The feathered configuration allows rotation of the angle of each fin about its long axis, whilst the shuttlecock configuration allows rotation of the fins about the hinge with the satellite body.

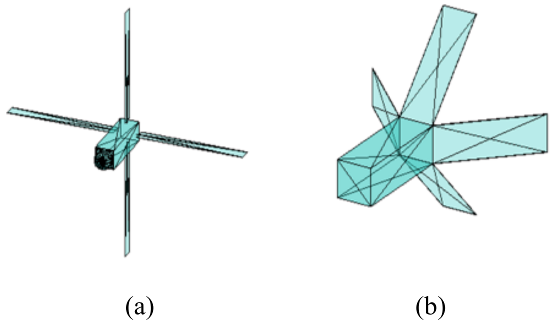

(a) (b)

Figure 7 Two aerostable configurations enabling aerodynamic control with (a) feathered fins and (b) shuttlecock geometry.

Developments to date have involved the development of controllers for these configurations, considering reaction wheels as the primary actuators with varying fin deflections for secondary aerodynamic control. Simulations of these controllers, taking into account all environmental perturbations including dynamic variations of the atmosphere, demonstrate their ability to perform 3 axis control, aerodynamic trimming during slew manoeuvres, and aerodynamic momentum management for the reaction wheels [15].

Its also important to note that aerodynamic materials which, as a by product of reducing drag also produce useable lift, will improve the efficiency and responsiveness of aerodynamic control.

SOAR, whilst the primary aim is to validate the performance of aerodynamics materials, will also demonstrate some of the developed manoeuvres, including aerodynamic trimming and momentum management [16].

5. Atmosphere breathing electric propulsion (ABEP)

Given that drag will limit the lifetime of satellites in VLEO, even if drag is minimized, satellites require a propulsion system to efficiently compensate for it. Conventional propulsion system, including electric propulsion systems, will most likely define the mission lifetime by the amount of propellant carried on-board.

An atmosphere-breathing electric propulsion system (ABEP) aims to solve the two issues at once: it collects the atmospheric particles the satellite encounters in VLEO by means of an intake, and drives them to an electric thruster. The electric thruster will ionize and accelerate them for thrust generation. An ABEP system, see Figure 8, aims to remove the lifetime limit by using the residual atmospheric gas that causes the drag, as the source for the thrust. The system is theoretically applicable to any planet with an atmosphere.

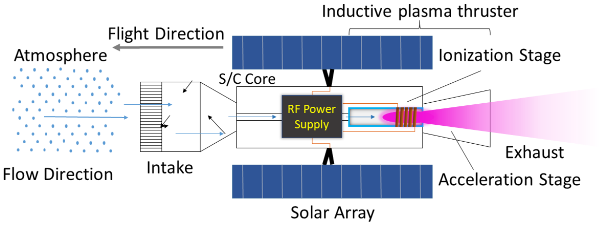


Figure 8 Atmosphere-Breathing Electric Propulsion (ABEP) Concept [17]

In VLEO an ABEP system has to cope with N_2 and atomic oxygen as propellant. Due to the aggressive nature of atomic oxygen, a conventional EP system such as gridded ion thruster (GIT or RIT) or Hall-effect thruster (HET) will suffer rapid performance degradation over time due to erosion of the grids (RIT) and of the discharge channel (HET). The second main issue of conventional EP is the need for a neutralizer. Such a device will either need a supplemental propellant tank, or a special design to be able to operate with atmospheric propellants. Moreover, VLEO is not a homogeneous environment, therefore the system has to cope with variable propellant density and composition. This requires the ABEP system to be throttleable, ignitable at low pressure, and to cope with propellant composition and density variations.

The intake design has been developed within DISCOVERER providing a collection efficiency up to 43%. Currently the intake is being further optimized to increase the efficiency. The current intake design, enhanced funnel design EFD, is shown within Figure 9.

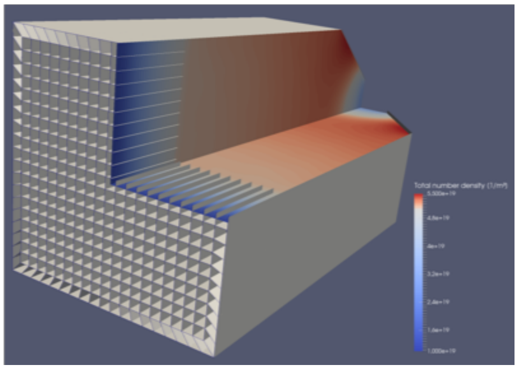


Figure 9 Intake Design EFD

The approach taken for the thruster within DISCOVERER is of an RF-based contactless thruster, thereby removing any issue of performance degradation over time due to operation with atomic oxygen as propellant. Moreover the plasma exhaust is expected to be neutral, removing the need for a neutralizer. Indeed, such contact/electrode-less devices are able to cope with variations in propellant density and composition, are easy to throttle, and the minimum ignition pressure is not a strict limitation unlike for conventional EP. The development of the inductive plasma thruster (IPT) follows on from an extensive heritage of inductively coupled plasma sources at the IRS, University of Stuttgart [18–23]. The IPT is composed of external electromagnets, a quartz discharge channel, an injector, and an RF-fed antenna. The antenna is a birdcage antenna that has been commonly used in Magnetic Resonance Imaging machines. Only in the last few years has it been applied for plasma generation, in particular for fusion research [24–28]. Such an antenna provides a convenient electromagnetic field combination, that ionizes and partially accelerates both ions and electrons in the same direction, while at the same time reducing circuit losses by working at its resonance frequency. The plasma plume is also neutral, which removes the need of using a neutralizer. A properly designed magnetic field will trigger helicon wave formation and enhance the acceleration for thrust generation purposes. The contactless nature of the IPT not only removes any erosion issues, but also enhances the propellant flexibility, making it able to cope with any propellant. A picture of the assembled IPT is shown within Figure 10. First ignition is expected before the end of 2019.

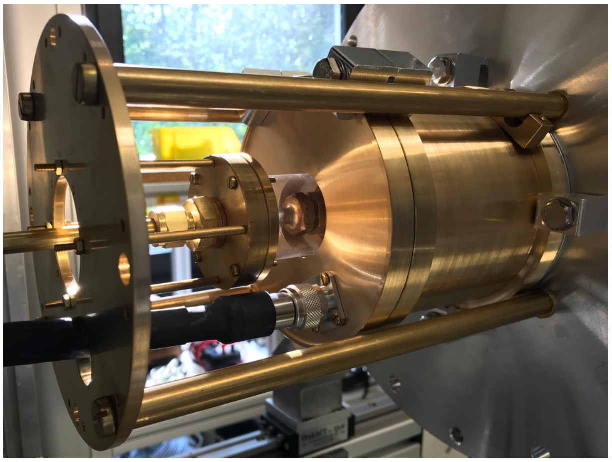


Figure 10 Assembled Inductive Plasma Thruster (IPT) [29]

6. Conclusions

DISCOVERER is developing three inter-related technologies to enable commercially viable use of VLEO orbits: aerodynamic materials which specularly reflect the atmospheric flow, aerodynamic attitude and orbit control, and atmosphere-breathing electric propulsion. All three technologies will be the subject of major demonstration programmes in the next 12 months, and each has the potential to significantly change the optimum design of VLEO satellite platforms. If successful, they have the potential to enable commercially viable, sustained operation of satellites in very low Earth orbits for a variety of applications, whilst achieving all the benefits VLEO operation brings to remote sensing and communications missions.

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References

[1] J. Virgili Llop, P.C.E. Roberts, Z. Hao, L. Ramio Tomas, V. Beauplet, Very Low Earth Orbit mission concepts for Earth Observation: Benefits and challenges, in: 12th Reinventing Sp. Conf., London, UK, 2014.

[2] E.A. Shao, J.R. Koltz, J.R. Wertz, Quantifying the Cost Reduction Potential for Earth Observation Satellites, in: 12th Reinventing Sp. Conf., London, UK, 2014.

[3] D. Mostaza-Prieto, B.P. Graziano, P.C.E. Roberts, Spacecraft drag modelling, Prog. Aerosp. Sci. 64 (2014) 56–65. doi:10.1016/j.paerosci.2013.09.001.

[4] J.M. Picone, A.E. Hedin, D.P. Drob, A.C. Aikin, NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues, J. Geophys. Res. 107 (2002). doi:10.1029/2002JA009430.

[5] K. Moe, M.M. Moe, Gas–Surface Interactions and Satellite Drag Coefficients, Planet. Space Sci. 53 (2005) 793–801. doi:10.1016/j.pss.2005.03.005.

[6] P.C.E. Roberts, N.H. Crisp, S. Edmondson, S.J. Haigh, R.E. Lyons, V.T.A. Oiko, A. Macario-Rojas, K.L. Smith, J. Becedas, G. González, I. Vázquez, Á. Braña, K. Antonini, K. Bay, L. Ghizoni, V. Jungnell, J. Morsbøl, T. Binder, A. Boxberger, G.H. Herdrich, F. Romano, S. Fasoulas, D. Garcia-Almiñana, S. Rodriguez-Donaire, D. Kataria, M. Davidson, R. Outlaw, B. Belkouchi, A. Conte, J.S. Perez, R. Villain, B. Heißerer, A. Schwalber, DISCOVERER – Radical Redesign of Earth Observation Satellites for Sustained Operation at Significantly Lower Altitudes, in: 68th Int. Astronaut. Congr., International Astronautical Federation (IAF), Adelaide, Australia, 2017.

[7] G. March, T. Visser, P.N.A.M. Visser, E.N. Doornbos, CHAMP and GOCE thermospheric wind characterization with improved gas-surface interactions modelling, Adv. Sp. Res. 64 (2019) 1225–1242. doi:10.1016/j.asr.2019.06.023.

[8] V.T.A. Oiko, P.C.E. Roberts, S. Edmondson, S.D. Worrall, D. Kataria, R. Outlaw, S. Haigh, N.H. Crisp, R.E. Lyons, S. Livadiotti, C. Huyton, L.A. Sinpetru, J. Becedas, G. González, R.M. Dominguez, D. González, L. Ghizoni, V. Jungnell, K. Bay, J. Morsbøl, G.H. Herdrich, F. Romano, T. Binder, A. Boxberger, S. Fasoulas, C. Traub, D. Garcia-Almiñana, S. Rodriguez-Donaire, M. Sureda, R. Villain, J.S. Perez, A. Conte, B. Belkouchi, A. Schwalber, B. Heißerer, Design and Development of a Hyper-thermal Atomic Oxygen Wind Tunnel Facility, in: 14th ISMSE 12th ICPMSE, Biarritz, France, 2018. doi:10.1299/jsmemag.121.1198_42.

[9] N.H. Crisp, P.C.E. Roberts, S. Edmondson, S.J. Haigh, C. Huyton, S. Livadiotti, V.T.A. Oiko, K.L. Smith, S.D. Worrall, J. Becedas, D. González, G. González, R.M. Dominguez, K. Bay, L. Ghizoni, V. Jungnell, J. Morsbøl, T. Binder, A. Boxberger, S. Fasoulas, G.H. Herdrich, F. Romano, C. Traub, D. Garcia-Almiñana, S. Rodriguez-Donaire, M. Sureda, D. Kataria, R. Outlaw, B. Belkouchi, A. Conte, J.S. Perez, R. Villain, B. Heißerer, A. Schwalber, SOAR – Satellite for Orbital Aerodynamics Research, in: 69th Int. Astronaut. Congr., International Astronautical Federation (IAF), Bremen, Germany, 2018.

[10] R.A. Outlaw, M.R. Davidson, Small ultrahigh vacuum compatible hyperthermal oxygen atom generator, J. Vac. Sci. Technol. A Vacuum, Surfaces, Film. 12 (1994) 854–860. doi:10.1116/1.579266.

[11] V.T.A. Oiko, P.C.E. Roberts, ROAR – A Ground-Based Experimental Facility for Orbital Aerodynamics Research, in: 70th Int. Astronaut. Congr., International Astronautical Federation (IAF), Washington, DC, 2019.

[12] V.A. Sarychev, S.A. Mirer, A.A. Degtyarev, E.K. Duarte, Investigation of equilibria of a satellite subjected to gravitational and aerodynamic torques, Celest. Mech. Dyn. Astron. 97 (2007) 267–287. doi:10.1007/s10569-006-9064-3.

[13] R.R. Kumar, D.D. Mazanek, M.L. Heck, Simulation and Shuttle Hitchhiker validation of passive satellite aerostabilization, J. Spacecr. Rockets. 32 (1995) 806–811. doi:10.2514/3.26688.

[14] M.R. Drinkwater, R. Haagmans, D. Muzi, A. Popescu, R. Floberghagen, M. Kern, M. Fehringer, The GOCE Gravity Mission: ESA'S

First Core Earth Explorer, in: 3rd Int. GOCE User Work., European Space Agency (ESA), Frascati, Italy, 2007: pp. 1–7. doi:ISBN 92-9092-938-3.

[15] S. Livadiotti, Concepts and Applications of Aerodynamic Attitude and Orbital Control for Spacecraft in Very Low Earth Orbit, in: 70th Int. Astronaut. Congr., International Astronautical Federation (IAF), Washington, DC, 2019.

[16] N.H. Crisp, P.C.E. Roberts, Demonstration of Aerodynamic Control Manoeuvres in Very Low Earth Orbit using SOAR (Satellite for Orbital Aerodynamics Research), in: 70th Int. Astronaut. Congr., International Astronautical Federation (IAF), Washington, DC, 2019.

[17] F. Romano, B. Massuti-Ballester, T. Binder, G.H. Herdrich, S. Fasoulas, T. Schönherr, System analysis and test-bed for an atmosphere-breathing electric propulsion system using an inductive plasma thruster, Acta Astronaut. 147 (2018) 114–126. doi:10.1016/j.actaastro.2018.03.031.

[18] G.H. Herdrich, D. Petkow, High-enthalpy, water-cooled and thin-walled ICP sources characterization and MHD optimization, J. Plasma Phys. 74 (2008) 391–429. doi:10.1017/S0022377807006927.

[19] B. Massuti-Ballester, T. Marynowski, G.H. Herdrich, New Inductively Heated Source IPG7, Front. Appl. Plasma Technol. 7 (2014).

[20] A.R. Chadwick, G.H. Herdrich, M. Kim, B. Dally, Transient electromagnetic behaviour in inductive oxygen and argon–oxygen plasmas, Plasma Sources Sci. Technol. 25 (2016) 065025. doi:10.1088/0963-0252/25/6/065025.

[21] A.R. Chadwick, T. Janocha, G.H. Herdrich, B. Dally, M. Kim, Wall Temperature Measurements Within a High-Power Inductive Plasma Discharge, IEEE Trans. Plasma Sci. 46 (2018) 1040–1046. doi:10.1109/TPS.2018.2805473.

[22] G.H. Herdrich, A. Boxberger, A.R. Chadwick, B. Dally, M. Kim, B. Massuti-Ballester, F. Romano, Progress in Characterization of the Two-staged Hybrid Thruster System TIHTUS, in: ESA Sp. Propuls. Conf., Seville, Spain, 2018.

[23] A.R. Chadwick, B. Dally, M. Kim, G.H. Herdrich, High Power Inductive Electric Propulsion Operation with Alternative Propellants, Aeronaut. J. (2019).

[24] P. Guittienne, E. Chevalier, C. Hollenstein, Towards an optimal antenna for helicon waves excitation, J. Appl. Phys. 98 (2005) 083304. doi:10.1063/1.2081107.

[25] C. Hollenstein, P. Guittienne, A.A. Howling, Resonant RF network antennas for large-area and large-volume inductively coupled plasma sources, Plasma Sources Sci. Technol. 22 (2013) 055021. doi:10.1088/0963-0252/22/5/055021.

[26] I. Furno, R. Agnello, B.P. Duval, C. Marini, A.A. Howling, R. Jacquier, P. Guittienne, U. Fantz, D. Wünderlich, A. Simonin, S. Béchu, A novel helicon plasma source for negative ion beams for fusion, in: 5th Int. Symp. Negat. Ions, Beams Sources - NIBS, Oxford, UK, 2016.

[27] I. Furno, R. Agnello, U. Fantz, A. Howling, R. Jacquier, C. Marini, G. Plyushchev, P. Guittienne, A. Simonin, Helicon wave-generated plasmas for negative ion beams for fusion, EPJ Web Conf. 157 (2017) 03014. doi:10.1051/epjconf/201715703014.

[28] R. Jacquier, R. Agnello, B. Pouradier Duteil, P. Guittienne, A. Howling, G. Plyushchev, C. Marini, A. Simonin, I. Morgal, S. Bechu, I. Furno, First B-dot measurements in the RAID device, an alternative negative ion source for DEMO neutral beams, Fusion Eng. Des. 146 (2019) 1140–1144. doi:10.1016/j.fusengdes.2019.02.025.

[29] F. Romano, G.H. Herdrich, P.C.E. Roberts, A. Boxberger, Y.-A. Chan, C. Traub, S. Fasoulas, K.L. Smith, S. Edmondson, S.J. Haigh, N.H. Crisp, V.T.A. Oiko, R.E. Lyons, S.D. Worrall, S. Livadiotti, C. Huyton, L.A. Sinpetru, R. Outlaw, J. Becedas, R.M. Dominguez, D. González, V. Hanessian, A. Mølgaard, J. Nielsen, M. Bisgaard, D. Garcia-Almiñana, S. Rodriguez-Donaire, M. Sureda, D. Kataria, R. Villain, J.S. Perez, A. Conte, B. Belkouchi, A. Schwalber, B. Heißerer, M. Magarotto, D. Pavarin, Inductive Plasma Thruster (IPT) for an Atmosphere- Breathing Electric Propulsion System: Design and Set in Operation, in: 36th Int. Electr. Propuls. Conf., Vienna, Austria, 2019.