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DISCOVERER – Radical Redesign of Earth Observation Satellites for Sustained Operation at Significantly Lower Altitudes

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Abstract

DISCOVERER is a €5.7M, 4¼ year Horizon 2020 funded project which aims to radically redesign Earth observation satellites for sustained operation at significantly lower altitudes. The satellite based Earth observation/remote sensing market is one of the success stories of the space industry, having seen significant growth in size and applications in recent times. According to Euroconsult, the EO data market from commercial and government operators, such as from data distributors, is expected to double to $3 billion in 2025 from an estimate of $1.7 billion in 2015. Yet key design parameters for the satellites which provide the data for this market have remained largely unchanged, most noticeably the orbit altitude. Operating satellites at lower altitudes allows them to be smaller, less massive, and less expensive whilst achieving the same or even better resolution and data products than current platforms. However, at reduced orbital altitude the residual atmosphere produces drag which decreases the orbital lifetime. Aerodynamic perturbations also challenge the ability of the platform to remain stable, affecting image quality. DISCOVERER intends to overcome these challenges by carrying out foundational research in the aerodynamic characterisation of materials, in atmosphere-breathing electric propulsion for drag-compensation, and in active aerodynamic control methods. A subset of the technologies developed will also be tested on an in-orbit demonstration CubeSat. In order to put these foundational developments in context, DISCOVERER will also develop advanced engineering, commercial, and economic models of Earth observation systems which include these newly identified technologies. This will allow the optimum satellite designs for return on investment to be identified. DISCOVERER will also develop roadmaps defining the on-going activities needed to commercialise these new technologies and make Earth observation platforms in these very low Earth orbits a reality.

Keywords: orbital aerodynamics; very-low Earth orbit; atmosphere-breathing electric propulsion; low-drag materials; Earth observation concepts; business model canvas.

Acronyms/Abbreviations

ABEP	Atmosphere-Breathing Electric Propulsion	GIT	Gridded Ion Thruster
CGM	Control Moment Gyroscope	HET	Hall Effect Thruster
DSMC	Direct Simulation Monte Carlo	GSI	Gas-Surface Interaction
EO	Earth Observation	SOAR	Satellite for Orbital Aerodynamics Research
INMS	Ion and Neutral Mass Spectrometer	ToF	Time-of-Flight
IPG	Inductively-Heated Plasma Generator	TRL	Technology Readiness Level
IPT	Inductive Plasma Thruster	VLEO	Very Low Earth Orbit

1. Introduction

Very Low Earth Orbit (VLEO) can be defined as an orbit below 450 km where the atmosphere begins to have a significant effect on spacecraft orbit and attitude dynamics, whereas Low Earth Orbit (LEO) typically describes any orbit below 2000 km. These orbits have a number of identified advantages which are particularly applicable to Earth Observation (EO) missions. Given these significant benefits, there is a need to reassess the aerodynamic and propulsive technologies required to operate spacecraft in lower altitude orbits.

The vision of the DISCOVERER project is a radical redesign of EO satellites for sustained operation at significantly lower altitudes than the current state of the art, using a combination of new aerodynamic materials, aerodynamic control and atmosphere-breathing electric propulsion for drag-compensation. These satellites would be smaller, less massive and less expensive to launch, but would still achieve the same or even better resolution and data products than current platforms. This in turn will reduce the downstream cost of programmes for maritime surveillance, intelligence and security, land management, precision agriculture and food security, and disaster monitoring~~.~~

This vision requires foundational research in spacecraft aerodynamic characterisation, in material aerodynamics and atomic oxygen resistance, in electric propulsion, and control methods, all tied together in a systems design framework including business models and EO market analysis. DISCOVERER aims to develop the key technologies from concept (TRL 1-2), through proof-of-concept, and on to validation (TRL 4-5). The long-term next step beyond DISCOVERER would be to fly these technologies together on an EO platform comprehensively demonstrating the viability of these new satellites and their application.

Towards this vision, the proposed work will address the following foundational research questions:

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 the understanding of orbital aerodynamics and its applications be improved and be put to best use on a space platform and its ability to perform attitude (pointing) and orbit control manoeuvres?

In order to put these foundational developments in context, DISCOVERER will also develop advanced commercial and economic models of Earth observation systems which include these newly identified technologies. This will allow the optimum satellite designs for return on investment to be identified. DISCOVERER will also develop roadmaps defining the on-going activities needed to commercialise these new technologies and make very low Earth orbit, Earth observation platforms a reality.

2. Benefits of VLEO for Earth Observation

A number of recent studies [1]–[5] have explored the different benefits of operation in VLEO compared to altitudes of above 500 km. These benefits are summarised in the following subsections.

2.1 Improved Payload Performance

With decreasing altitude, the resolution of optical instruments increases for the same aperture size. Thus, resolution can be increased for the same payload size or the payload size and mass reduced for same resolution by operating at a lower orbital altitude. For radar payloads, reducing the operational altitude can reduce the transmitted power requirements and minimum antenna area whilst maintaining a given resolution.

Furthermore, as the distance to the imaging target is reduced the radiometric performance is improved due to the inverse-square law. This is significant for optical, radar, and communications-based detectors (eg AIS, ADS-B, SIGINT) meaning that the sensitivity of a given instrument can be relaxed whilst achieving similar results. This may correspond to reduced instrument cost, size, and mass.

Finally, with a shorter distance to the target, attitude determination errors and uncertainties have a less significant effect. Thus, either geospatial position accuracy can be increased or attitude determination requirements reduced.

2.2 Aerodynamic attitude and orbit control

Whilst the significant aerodynamic drag experienced in VLEO is typically considered a drawback requiring compensation, the increased magnitude of aerodynamic forces in this orbit range can be used to provide some beneficial attitude and orbit control capabilities.

Due to the nature of the interaction between the rarefied gas flow and spacecraft surfaces in VLEO, achievable aerodynamic lift forces are currently very small and dominated by the drag force. However, with suitable spacecraft geometry and mass-distribution, the drag force can be used to provide aerostability, pointing the spacecraft towards the direction of the incoming flow [6]–[8]. Furthermore, with additional controllable surfaces, aerodynamic torques can be generated to achieve a measure of attitude and pointing control capability, reducing the requirements of other attitude control subsystems [2], [9], [10].

The use of aerodynamic drag for orbit control has historically been considered for a number of different applications including aero-assisted transfer and rendezvous [11]–[16]; atmospheric re-entry interface location [17]–[19]; and formation flight and constellation maintenance [20]–[24].

More recently, utilisation of aerodynamic lift forces have also been proposed for formation/constellation maintenance [25] and to correct the inclination of descending SSOs [26].

2.3 Mission and System Design

Due to the benefits afforded to typical EO payloads by operation at lower altitudes, the total size, mass, and cost of the spacecraft can be reduced whilst maintaining a similar mission performance. The reduction in spacecraft mass and size may also increase the number of available launch opportunities and reduce launch cost.

Launch vehicle performance, in terms of injected orbital mass, is also typically greater to lower altitude orbits. This may be particularly beneficial for the launch of VLEO constellations which can take advantage of this increased launch capability at no additional cost.

Similarly to the improvement to radiometric performance, communications system parameters benefit from reducing altitude as lower transmission power and antenna areas are required. However, the window for communication with any given groundstation is reduced as the duration of each pass is shorter.

Finally, due to the increased atmospheric density and therefore aerodynamic drag experienced in VLEO, end-of-life disposal is ensured through de-orbit. Compliance with IADC regulations therefore presents no additional system requirements. Debris which is present or enters VLEO also decays at a faster rate than higher altitude orbits. The persistence of any debris is therefore limited, meaning that these orbits are resilient to any debris build-up, presenting a lower risk of collision.

2.4 Impact and Applications of VLEO for EO

At present, few vehicles operate in the altitude range between the highest reconnaissance aircraft at 26km (highest sustained SR71 flight) and the lowest space platforms at around 450 km, except for relatively short durations or with frequent resupply. Yet, for remote sensing, very low orbits offer considerable advantages over conventional space platforms whilst maintaining global coverage, and without the inherent constraints of airspace restrictions and limited range and duration. Cost reduction of VLEO platforms will also contribute to the deployment of distributed systems (constellations, swarms and formations), which can increase coverage capabilities including larger swath and reduced revisit times.

In maritime surveillance, higher resolution imagery can facilitate the identification and classification of small boats (between 1 and 8m length). In systems which can achieve intraday revisit time, VLEO platforms could contribute to monitoring areas that are prone to illegal fishing, spills, immigration, and accidents and piracy; and to monitor and control borders, fisheries, protected areas, and marine pollution.

VLEO satellites are also highly applicable to intelligence and homeland security. An increase in resolution and revisit time would contribute to the detection, identification and monitoring of strategic infrastructure and areas associated to suspicious activities such as illegal tunnels and airstrips used for goods and human trafficking, smuggling and illegal crops. They would also contribute to the evaluation of the vulnerability and risk assessment of facilities and critical infrastructure such as pipelines to terrorism attacks.

In land management and precision agriculture current users demand multi-temporal and multispectral satellite imagery products to analyse the land cover dynamics and detect changes. Multi-temporal classification and regression techniques are used to provide products exploiting high revisit time and high spatial resolution. Furthermore, food security is closely related with agriculture. Worldwide 800 million people are exposed to a lack of food for different reasons: floods, soil moisture, geology and lack of rainfall, among others; making cultivation difficult and increasing demand on the existing crops. VLEO satellite systems will contribute to the monitoring of crops and soil cultivation. Used in combination with meteorological models and ground-based information, satellite imagery can be used to create food security early warnings and better manage the agriculture and the food supply.

Several space-based initiatives have been developed to deal with emergency disaster and crisis management involving satellite imagery analysis. For example, the International Charter “Space and Major Disasters” initiated by ESA and CNES, the Center for Satellite-Based Crisis Information (ZKI) at the German Remote Sensing Data Center of DLR, and the Copernicus programme which includes an emergency management service. VLEO satellite systems will have a major impact in crisis management because they can increase the resolution and the revisit time, enabling a more rapid and precise response.

There are also potential technology benefits from developing VLEO systems. In orbit testing, demonstration and validation plays a key role in the space industry, facilitates the development and transfer of innovative technology from the laboratory to the market, ie from a prototype to an operational, qualified product. A cost reduction in the launch of VLEO systems and the use of appropriate interfaces and dispensers will further enable in orbit testing, demonstration and validation of new technology.

3. Orbital Aerodynamics and Spacecraft Drag

Aerodynamics in the orbital environment are driven by gas-surface interactions (GSIs) in the rarefied flow that exists around spacecraft in LEO and VLEO [27].

Whilst the fundamental molecular interactions of the predominant gas species, atomic oxygen, with spacecraft surfaces are poorly understood, its impact on the aerodynamic performance of a surface is significant. The residual atmosphere at altitudes above 200km is so rarefied that the mean free path of the gas molecules greatly exceeds the typical dimensions of a satellite. This means collisions between molecules can be ignored and aerodynamics is driven by GSIs. These in turn are dominated by the material chemistry with atomic oxygen from the atmosphere adsorbing to, and possibly eroding, the surface. The nature of this interaction is known to be dependent on surface roughness/cleanliness [28], surface molecular composition and lattice configuration [29], surface temperature [30], [31], incident gas composition [30], [31], and velocity and angle [32]–[34]. However, the number of past spacecraft that are able to give any insight into the effect of these parameters is very small. Little is known, for example, about how the flow incidence angle, the surface material or the surface roughness affects drag [35].

DISCOVERER aims to address this deficit by identifying and developing materials which encourage specular or quasi-specular reemission of the incident gas particles. Such materials, used in a spacecraft geometry which angles surfaces to the flow, would significantly reduce the drag on the spacecraft (an order of magnitude reduction is possible).

The limiting factor preventing research in this area has been the lack of experimental data. There have not been systematic campaigns to obtain data from on-orbit experiments and a facility capable of reproducing and measuring these interactions on the ground does not exist. Whilst hyperthermal atomic oxygen sources exist for accelerated material erosion testing, these are typically at much higher flow rates, use a carrier gas, or are pulsed, all of which change the flow regime and the fundamental nature of the interaction with the surface for aerodynamics. DISCOVERER proposes a two-pronged approach to the problem. Firstly, an entirely novel hyperthermal atomic oxygen wind tunnel will be developed, built, commissioned and operated allowing the testing of materials in a representative flow environment. Secondly, a small test spacecraft will be developed and flown to provide truth data for the ground-based experimental results.

3.1 Rarefied Orbital Aerodynamics Research (ROAR) Facility

The ROAR facility will comprise a continuous-flow hyperthermal atomic oxygen source and flow field diagnostic equipment in an ultra-high vacuum chamber (see Fig. 1). The oxygen source will use electron stimulated desorption from a supported thin-film silver membrane to generate a pure beam of atomic oxygen at flow velocities equivalent to those around spacecraft in VLEO, and at fluxes equivalent to those on spacecraft in VLEO (at least 10^{19} atoms $m^{-2} \cdot s^{-1}$). The incident flow and the reemitted gas distribution from the test-piece will be directly measured using a variant of mass-spectrometers originally designed to characterise the flow impinging on spacecraft in low Earth orbit. Observing the velocity, composition and distribution of the reemitted gas from the test-piece surface will allow complete characterisation of the GSI and thereby identify materials which promote specular reflections.

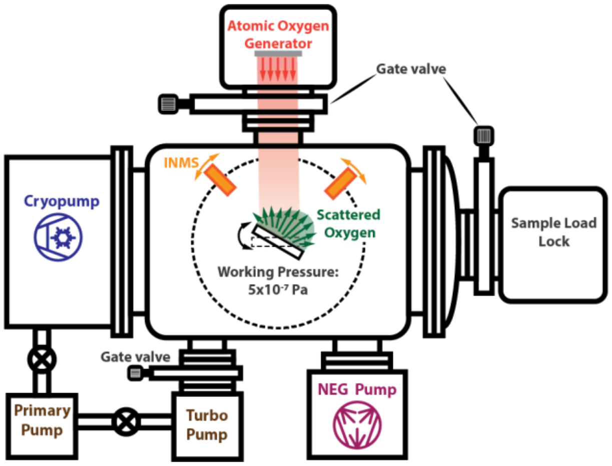

Fig. 1 Schematic representation of the Hyperthermal Atomic Oxygen Wind Tunnel facility.

Several developments are being made to achieve this aim. The ability to perform time of flight mass spectrometry on the incoming gas is being added to the existing mass spectrometers, and the atomic oxygen source is being developed to achieve a larger flow cross-section than previous design iterations (a few centimetres), and higher fluxes. As an ultra-high vacuum is required to achieve the pure atomic oxygen flow, the facility needs a very high pumping capability (of the order of 10's of $m^3 \cdot s^{-1}$) to maintain this pressure whilst the atomic oxygen source is in operation.

The facility will enable the test of different materials and surface finishes in a wide range of environments (flow density, velocity and incidence angle) at significant pace enabling the formulation and validation of GSI theoretical models. Within a few months of operation the facility will provide more data than that accumulated by more than 50 years of spaceflight. Our understanding of the underlying phenomena, and our ability to engineer materials, surface finishes and shapes that exhibit a desired set of aerodynamic properties, will leap forward in a relatively short amount of time. This facility is the most-cost effective way of advancing the GSI field reserving the more expensive and time-consuming on-orbit experiments for validation and demonstration. Whilst highly challenging, it will be the world-leading facility for orbital aerodynamic research.

3.2 SOAR—Satellite for Orbital Aerodynamics Research

The in-orbit test satellite, SOAR, is a 3U CubeSat which will launched in 2020. SOAR will carry two payloads to investigate the interaction between different materials and the atmospheric flow regime in orbit. As a secondary objective, SOAR also seeks to demonstrate aerodynamic attitude and orbit control manoeuvres.

The flow characterisation is achieved with a Time-of-Flight (ToF) Ion and Neutral Mass Spectrometer (INMS) developed at the Mullard Space Science Laboratory, UCL. The INMS enables accurate measurement of the flow composition, density, and wind velocity, all which can vary significantly in VLEO over time.

The aerodynamics characterisation payload developed at The University of Manchester, consists of four deployable test surfaces which can be used to expose different materials to the flow at different angles of incidence (see Fig. 2). These deployable surfaces also provide aerostability, pointing the spacecraft into the oncoming flow and enabling accurate operation of the INMS payload.

Fig. 2 Conceptual impression of the in-orbit test satellite, SOAR.

Using on-board GPS measurements for orbit determination, the drag experienced by the CubeSat can be evaluated, giving a direct measure of the momentum exchange in the real flow environment. Accurate measurements of small attitude oscillations using a small star-tracker also allow the lift generated by the deployable surfaces to be measured, giving information on the gas reemission characteristics. To remove the perturbations caused by thermospheric winds, the satellite will also determine the wind direction and strength so that the angle of the fins relative to flow is always known.

Aerodynamic orbit and attitude control manoeuvres will also be demonstrated by SOAR. By using coordinated deflections of opposing deployable surfaces the ability to achieve modest pointing angles with respect to the oncoming flow will be demonstrated. Aerodynamic damping of natural oscillations will also be explored.

Finally, as the orbital altitude of the satellite decays towards the re-entry interface, the ability of the satellite to control the location of re-entry will be demonstrated. Using the deployable surfaces, the ballistic coefficient of the spacecraft can be modulated and therefore used to target a pre-defined location of atmospheric re-entry [19].

4. Atmosphere-Breathing Electric Propulsion

Aerodynamic drag in LEO reduces the orbital energy and altitude of satellites leading to their re-entry unless the drag is compensated by a propulsion system. Whether this system is chemical or electric, the lifetime of the mission is limited by the amount of propellant carried on board. An Atmosphere-Breathing Electric Propulsion (ABEP) system is a concept (see Fig. 3) in which the residual atmosphere encountered by a satellite orbiting at low altitudes is collected and used as propellant for an electric thruster, theoretically eliminating the requirement of carrying on-board propellant.

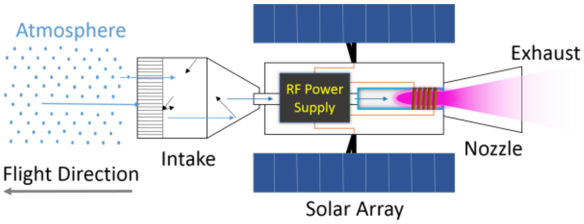

Fig. 3 ABEP system concept.

Some concepts have already been investigated [36] but most of these have not developed beyond paper studies. These studies imply the use of an electric thruster, due to its scalability to small satellites and its high specific impulse, however, at present the focus has been on gridded ion thrusters (GIT) or Hall effect thrusters (HET) which suffer from performance degradation over time due to erosion of the accelerating grids or the discharge channels especially if chemically aggressive propellants are used.

The state-of- the-art at the present time is a study from JAXA [37], where an ABEP concept has been developed in which the intake and thruster are combined into one device. A laboratory model for intake testing purposes has been built and tested with an atomic oxygen flux generator, showing a collection efficiency of more than 40%. This has been verified by a University of Stuttgart Institute of Space Systems (herein IRS) Direct Simulation Monte Carlo (DSMC) modelling tool [38]. Further studies have investigated the use of atmospheric propellant in ion [39] and Hall-effect [40]–[42] thrusters, demonstrating their capability of ignition and operation, however showing limited lifetime due to the effect of atomic oxygen on the thruster's surfaces. Recently this work has been extended within an ESA TRP with the outcome of a RAM-HET system test (intake and HET in one system), that demonstrated the feasibility of collecting and using atmospheric propellant for drag compensation [43].

Further work has been done by IRS on the design of intake based on JAXA [37] and BUSEK [40] concepts, toward an optimised design to be applied to an inductive plasma thruster (IPT) of the size of IPG6-S [44]. Although this thruster concept departs from currently assessed concepts such as HET and GIT, the inductive thruster is strongly justified by several benefits: a) its propellant flexibility (eg as needed for dynamic and/or altitude dependent composition changes within the thermosphere; b) it is electrodeless and gridless, eliminating the lifetime limiting erosion issue; c) it does not need a neutraliser as the plasma leaving the thruster is already neutralised; and d) the electrodeless function of the thruster is already qualified by the extensive application of comparable devices, eg for pure high enthalpy material tests using pure oxygen as the working gas [45].

DISCOVERER proposes to explore and develop this IPT based ABEP concept to establish the feasibility of such a propulsion system with realistic power and mass constraints. Firstly a consolidated system analysis for an ABEP system, the available and verified models for the intake design, and the innovative approach of using an inductively heated plasma thruster will be carried out. The intake must efficiently collect the residual atmosphere and feed it to the electric thruster. DISCOVERER proposes to design, build and test intakes, using DSMC simulation for the design, and scale models in the atomic oxygen wind tunnel for verification. Recent studies provide numerical verification of previous intake studies and a verified tool for analytical intake evaluation [38] and optimisation toward the use of an IPT has been done [44].

DISCOVERER also proposes to design, build, and test an IPT, based on the experience and heritage at IRS on inductively-heated plasma generators (IPG) used for re-entry simulation and propulsion. Such a device is composed of a discharge channel, where the gas propellant flows, surrounded by an RF-fed coil which ionises the gas. Preliminary studies have successfully operated a small inductively-heated plasma generator (IPG6-S) with atmospheric propellant (air, O_2, CO_2) at mass flows derived from an ABEP system analysis [46]. Further work has to be done for the development of a laboratory model of an IPT based on IPG6-S, with a discharge channel diameter < 40 mm, 0.5-5 kW input RF power, with a complete design of the accelerating stage. This prototype device will be tested in a representative orbital environment to evaluate minimum conditions for ignition and measure the respective produced thrust.

5. Aerodynamic Attitude and Orbit Control

In VLEO aerodynamic forces and torques are the main perturbation source. Rather than just using traditional actuators, for example, reaction wheels and control moment gyroscopes (CMGs), DISCOVERER will explore the use of aerodynamic forces and torques as an integral part of the orbit and attitude control systems, with the potential to reduce mass, power, complexity and ultimately cost.

Aerodynamic attitude control has been considered for some satellites, and aerostability has been demonstrated (eg ESA’s GOCE mission), however more complex aerodynamic attitude or orbit control is still to be developed and demonstrated. EO platforms often require rapid and accurate slews for pointing at a target. In VLEO, both aerostability and the ability to slew rapidly whilst rejecting unwanted torques are both desirable for different operational states. These are somewhat conflicting requirements unless active aerodynamic control surfaces are introduced, but the predicted utility of such surfaces ultimately relies upon the imperfect gas surface interaction models.

Combinations of aerodynamic attitude control and propulsion techniques may be suitable for orbit control for applications such as ground-track re-tasking, and constellation maintenance. If suitable surface materials are found which produce specular reflections of gas molecules with the surface, useable lift generation may also be possible allowing cross-track manoeuvring. Additionally, even if a spacecraft does not have any type of propulsion system, the aerodynamic forces can be used to provide collision avoidance manoeuvres against conjunctions with the debris population, augmenting the resilience of the orbit range.

Aerodynamic forces/active surface aerodynamics can be also used to minimise the aerodynamic torques during imaging operations (improving platform stability and data quality), for singularity avoidance of CMGs, and momentum management of control wheels. These applications are of general applicability to both LEO and VLEO spacecraft.

DISCOVERER will determine the requirements for attitude and orbit manoeuvres for EO spacecraft from the applications the satellite is designed to cover, such as 3-axis stabilisation, agility, slew rates, pointing accuracy, position knowledge and relative orbit manoeuvring. The use of aerodynamically induced forces and torques, and associated control methods, will then be considered to optimise the performance of the system in terms of cost and mass. These control methods will be implemented on the SOAR test satellite where possible and the results of this demonstration used as real-world validation.

6. VLEO System Design

The disruptive approach to developing VLEO technologies proposed by DISCOVERER holds the promise of radically changing orbital operations below 450km. In order to achieve this long-term vision of VLEO EO platforms, the opportunities that these new technologies may bring into the market are being analysed using a model-based systems engineering approach and the Business Model Canvas methodology of Osterwalder and Pigneur [47]. Implementation and technology development roadmaps resulting from these models will be produced for Space Agencies and Technology Providers, making the path to full implementation of VLEO platforms for EO applications clear.

In order to identify new and promising system concepts for VLEO platforms, systems models focusing on the effects of reducing orbital height and the implementation of drag-compensation and aerodynamic technologies will be developed. Using system parametrisation methods, these models will enable exploration of the design space for VLEO platforms incorporating the sought technology breakthroughs and expected performance parameters of ABEP, external aerodynamic geometries, and aerodynamic control methods.

A comprehensive analysis of the current EO market and projected future market trends will be used to identify new stakeholders and develop advanced business models for the different EO applications of interest. Through integration with the developed systems engineering models and Business Model Canvas methodology, this will enable identification of the potential commercially viable system concepts in the EO market.

7. Conclusions

DISCOVERER aims to develop radically new technologies and techniques to achieve the long-term vision of VLEO EO platforms. It will identify, develop and characterise materials which enable low drag satellite platforms. It will create and use facilities to determine the aerodynamic properties of these materials in a representative environment, and validate these results on a test spacecraft in very low Earth orbit. It will design, build, and test intakes for atmosphere-breathing electric propulsion, and the electric thrusters themselves. It will design and test active aerodynamic control manoeuvres to exploit the aerodynamic forces and torques available. And it will map out a clear long-term path for the exploitation by identifying the most promising and commercially viable concepts.

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