# D5.6 – TECHNOLOGY DEVELOPMENT ROADMAP FOR FUTURE VLEO PLATFORMS

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| WP Leader: | Daniel Garcia-Almiñana (UPC) |
| Authors: | Nicholas H. Crisp, Vitor T.A. Oiko, Peter C.E. Roberts (UNIMAN)<br>Francesco Romano, Georg Herdrich (USTUTT) |
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## 1. Executive Summary

The DISCOVERER project, a Horizon 2020 project that commenced in April 2017, aimed to develop foundational technologies to enable the sustained and commercially viable use of very low Earth orbits (VLEO), principally for Earth observation (EO) applications. However, to support the realisation of this vision, ongoing development of enabling technologies is required beyond the conclusion of this program.

This report outlines the major technologies that require development to support the future exploitation of VLEO. These technologies have been categorised into four principal areas, namely drag compensation, drag reduction, aerodynamic control, and other supporting technologies. For each technology, a brief description of the state of the art is provided and the primary technical challenges are outlined. A guide to the critical developmental milestones prior to operational use is also provided.

This deliverable is principally aimed towards space agencies, policymakers, and industry stakeholders as a guide to the technology areas that require prioritisation and investment to support the necessary developments. This document should also provide inspiration for business and research entities through the identification of novel and rewarding opportunities for study and commercial development, growth, and impact.

## 2. Introduction

This deliverable has been produced for the European Commission Horizon 2020-funded DISCOVERER project that aims to revolutionise satellite Earth observation (EO) through the foundational development of technologies to enable commercially viable and sustained operations in very low Earth orbits (VLEO). However, ongoing development of the technologies explored within the scope of DISCOVERER is needed beyond the end of the project to realise their implementation and enable future VLEO platforms.

### 2.1. Purpose

This report presents a roadmap for the development of different technologies that are necessary for, associated with, and may support the commercially viable and sustained operation of future spacecraft in VLEO. A brief description of the state of the art for each considered technology area is provided and the major technical challenges to their development considered. Milestones associated with the development of each technology are also outlined. The application of these technologies to known mission opportunities ("mission-pull") is also noted where appropriate. This roadmap is principally aimed towards space agencies, policymakers, and industry stakeholders and presents the key technological developments that require prioritisation and investment to enable the future utilisation and exploitation of VLEO.

### 2.2. Development and Feedback

This document is intended to be periodically updated as the different technologies continue to develop, new mission opportunities become available, and the utilisation of VLEO changes. Feedback from the wider community will also be sought to further understand the different technical challenges and important developmental milestones that are associated with the different technologies and to iteratively update and improve this roadmap.

### 2.3. Organisation

This deliverable is organised into four principal sections. In **Section 3** the benefits, challenges, and opportunities of operating satellites in VLEO are summarised providing context for the different technologies considered to support the development of future VLEO platforms. A vision for the future use and exploitation of VLEO is presented in **Section 4**, providing context and foundation for the portfolio of relevant technologies subsequently presented in **Section 5**. For each technology, a summary of the state-of-the-art is provided, the main developmental challenges identified, and key milestones towards implementation and validation outlined. The application of these technologies to known mission opportunities is discussed in **Section 6**.

## 3. Benefits, Challenges, and Opportunities of VLEO

Very low Earth orbits are typically classified as those below 450 km in altitude and are therefore significantly lower than those traditionally used for LEO satellites [1–3]. This reduction of orbital altitude presents a range of benefits that have been identified and discussed [4–6]. However, there are also key challenges that are presented by operating in these lower altitude orbits that explains why VLEO has thus far seen limited exploitation. Recent developments in foundational technologies present opportunities to overcome these challenges and enable the commercially viable, sustained operation of spacecraft in VLEO. These benefits, challenges, and opportunities are briefly summarised in the following sections.

### 3.1. Platform Benefits

Radiation Environment

The radiation environment, characterised by the flux of energetic charged particles, is more benign in lower altitude orbits in LEO. This will result in a reduction of radiation exposure and a lower likelihood of single-event effects (SEEs). Requirements for radiation-hardening of components may therefore be relaxed and the use of commercial-off-the-shelf components may be enabled with benefits to the cost of development and manufacture.

Launch Vehicle Capability

The total payload mass that can be delivered to orbit by a launch vehicle generally increases as the altitude is reduced. For current launch vehicles, the improvement in launch capability to an altitude of 300 km compared to 600 km is between 10% to 50% [6]. The specific cost (per unit mass) is also correspondingly reduced. For a given payload, the number of vehicles available or capable of providing access to orbit may also be increased, providing greater competition, flexibility, and resilience to delays or failures.

End-of-Life Disposal

The increased density of the residual atmosphere at lower orbital altitudes causes rapid decay and deorbit of spacecraft. In the VLEO altitude range, the lifetime of objects with typical ballistic coefficients (accounting for the area to mass ratio and drag coefficient) is less than 25 years for all expected solar activity conditions. Compliance with international guidelines on post-mission lifetime is therefore generally ensured and can be achieved without the use of any additional hardware, subsystems, or propulsion that can increase complexity, cost, and mass.

Debris Collision Risk

The decay of objects from VLEO altitudes also ensures that any debris that is generated in or enters this orbital range will also be naturally deorbited within a relatively short time. These altitudes will therefore remain resilient to any build-up in debris population and the probability of on-orbit collisions will remain low.

### 3.2. Mission/Application Benefits

Spatial Resolution

The spatial resolution of an optical payload with a given aperture diameter increases as the orbital altitude is reduced. Alternatively, as altitude is reduced the aperture diameter and therefore payload size and mass can be reduced whilst the spatial resolution is kept constant.

Radiometric Performance

As altitude is reduced the power from a ground-based source received by a sensor or payload increases. For a given collection area (aperture), the signal-to-noise ratio (SNR) will therefore be increased, allowing for a greater radiometric resolution. Alternatively, less sensitive sensors and smaller collection areas may be used whilst maintaining a given SNR.

For active payloads, for example radar SAR, the transmitted power may be significantly reduced whilst maintaining the radiometric performance. For communications subsystems and payloads, the improvement in SNR increases link-budgets or allows for a reduction in transmission power.

Geospatial Position Accuracy

Mapping errors that result from attitude determination and control accuracy are reduced at lower altitudes, improving the geospatial accuracy of ground imagery and location-based services.

Latency

A reduction in altitude generally reduces the path-length to a ground-target and therefore reduces the propagation time of communications.

Frequency Reuse

At lower altitudes, the footprint of a communications antenna with a given beamwidth is naturally smaller. A greater number of channels per unit area can therefore be utilised increasing the frequency reuse factor and making better use of the available spectrum.

### 3.3. Challenges

Increased Atmospheric Density

The increased atmospheric density in VLEO is the greatest challenge to sustainable operations at these altitudes. The increased density results in increased drag forces and therefore orbital decay and eventual deorbit. Whilst a benefit in terms of debris removal and end-of-life disposal, this also causes operating spacecraft to descend more rapidly than those at higher altitudes and imposes a limited lifetime unless drag reduction or compensation is implemented.

The increase in atmospheric density also increases the magnitude of experienced aerodynamic torques. The requirements on the ADCS may therefore increase, for example requiring more capable attitude actuators to support platform stability and pointing.

Atomic Oxygen Exposure

At VLEO altitudes the residual atmosphere is largely composed of atomic oxygen (AO) that is highly reactive and can adsorb to and erode exposed surfaces. The atmospheric density and orbital velocity also increase with reducing altitude resulting in increased flux of AO and collision energy. These effects of AO adsorption and erosion generally increase the momentum accommodation between the spacecraft and the atmospheric flow and therefore the drag experienced by the orbiting spacecraft. This in turn increases the rate of decay and reduces the useful lifetime (without propulsive compensation). Sensitive surfaces, for example optical apertures and solar-cell cover glass, can also be damaged, compromising mission performance.

Coverage, Revisit, and Access

At reduced orbital altitudes, the total area accessible by a sensor or antenna for a given beamwidth and pointing constraints is smaller. The area coverage rate and duration of communications windows are therefore reduced with impact on the total coverage and uplink/downlink capability. The revisit time is similarly adversely affected with fewer low maximum revisit time windows available at lower altitudes.

### 3.4. Opportunities

Novel Aerodynamic Materials

Materials that are resistant to adsorption and erosive effects of AO and can promote specular or quasi-specular scattering characteristics would improve gas-surface interactions (GSI) and enable greater aerodynamic performance in VLEO. When combined appropriately with satellite geometric design (i.e. with surfaces that have a shallow angle with respect to the flow), these materials would significantly mitigate the drag experienced in VLEO.

Contrastingly, when coated surfaces are oriented close to normal to the flow, these materials could also be used to develop enhanced deorbit devices that can assist with faster spacecraft disposal from higher altitudes.

### Aerodynamic Control

The increased atmospheric density present in VLEO can enable the production of useful forces and torques that can be used to perform attitude and orbital control. Possible applications of orbital control include constellation deployment and maintenance and targeted re-entry. Aerodynamic attitude control can be used to provide coarse-pointing control, aerodynamic trim, and momentum management.

### Atmosphere-Breathing Electric Propulsion

The residual atmosphere in VLEO can also be collected and utilised to provide an amount of drag compensation by using an atmosphere-breathing propulsion (ABEP) system. Spacecraft with such propulsion systems can be launched without the need to carry on-board propellant and tanks with potentially significant reductions in mass. Operational limits based on the amount of propellant launched with the spacecraft are also removed and lifetime may therefore be extended to limits imposed by component degradation.

### In-Situ Rarefied Atmospheric Sensors

Sensors that can improve the measurement and characterisation of the thermospheric density, composition, and velocity of thermospheric winds, amongst other parameters, would help to extend our understanding of the processes in that occur in the upper atmosphere and would support the development of improved empirical models used in spacecraft mission design and operations. Long-duration and distributed sensing is ideally required to provide measurement of both the spatial and temporal variations in the thermosphere.

Sensors that can be used in-situ on spacecraft platforms to obtain accurate and real-time measurements also have application in improving the effectiveness and efficiency of drag-compensation systems (particularly ABEP) and aerodynamic control technologies.

# 4. A Vision for VLEO

The benefits of operating satellites at lower orbital altitudes, described above in Section 3, support a new vision for the utilisation of near-Earth orbits with advantages to the sustainability and resilience of future satellite operations.

The principal risk to the future of space operations in LEO is the presence and accumulation of orbital debris. With the recent and forthcoming proliferation of satellite constellations in LEO, primarily for communications applications, the probability of collisions in these orbits is increasing. In combination with accumulating orbital debris, the risk that certain orbital altitude ranges may become inaccessible in the future cannot be ignored [7].

However, in VLEO the density of the residual atmosphere ensures the rapid orbital decay and deorbit of spacecraft without active drag compensation. This “self-cleaning” characteristic means that VLEO will remain resilient to an accumulation of debris and the associated risk of on-orbit collision will remain low.

If sustained operations in VLEO can be enabled, principally through the development of new technologies and platform concepts, many satellite operations in LEO could be reduced into the VLEO altitude range. For applications such as Earth observation and communications, this reduction in altitude may also simultaneously enable a reduction in spacecraft size, mass, and cost whilst maintaining or improving imaging or communications capability [8].

The transition of the bulk of such operations to VLEO in coordination with the removal of residual debris and greater adherence to de-orbit guidelines, would protect the higher LEO environment and the long-term and safe operation of missions such as crewed spaceflight and orbital stations at these altitudes.

## 4.1. Supporting the Exploitation of VLEO

Beyond the technologies involved in enabling operations in VLEO itself, development of further technologies, ground infrastructure, and businesses are necessary to support and exploit this vision for VLEO. This wider ecosystem includes providing access to VLEO (both launch vehicles and launch brokers or turnkey solution providers), ground segments used to facilitate communications with the in-space assets, and new platform providers. Business models for these areas and roadmaps detailing the required support and necessary steps towards their development are described in the companion DISCOVERER Deliverable D5.7 [RD-5.7].

## 5. Technology Portfolio

The technology roadmap for VLEO is principally divided into four basic technology areas, described in Figure 5-2:

(1) Drag Compensation: the development of novel and improved methods of propulsion that can be used by VLEO platforms to compensate for orbital drag, leading to longer orbital lifetimes or sustained orbits. These propulsion systems are categorised as either traditional EP thrusters or ABEP concepts that require the development of novel thrusters, atmospheric intakes, and associated control systems.

(2) Drag Reduction: technologies that can contribute to the mitigation or reduction of the drag experienced in orbit and includes the development of novel materials with favourable aerodynamic properties and the design of satellite geometric configurations that can incorporate and make best use of these materials. In combination, these technologies can increase the lifetime of VLEO platforms in orbit and reduce the requirements on drag compensation propulsion systems.

(3) Aerodynamic Control: technologies that are associated with the use of the residual atmospheric environment to perform or assist attitude and orbit control, reducing the requirements on traditional attitude and orbit control actuators.

(4) Supporting Technologies: further supporting technologies that contribute to the successful development of VLEO platforms or improvements to mission design and implementation.

### Technology Readiness Levels (TRL)

For each technology, the current state of the art has been associated with an estimated TRL based on the most advanced system or technology presently available. The TRLs used are those adopted by ESA from ISO 16290:2013 [7] and given in Figure 5-1. For the purpose of colour coding the roadmap, the ranges given in below have been applied. However, it should be noted that within each technology area there may be several different specific technologies, concepts, or approaches at varying different stages of development that may have a lower TRL.

| | | |
|---|---|---|
| TRL 1-3: Research | TRL 3-6: Development | TRL 7-9: Implementation |

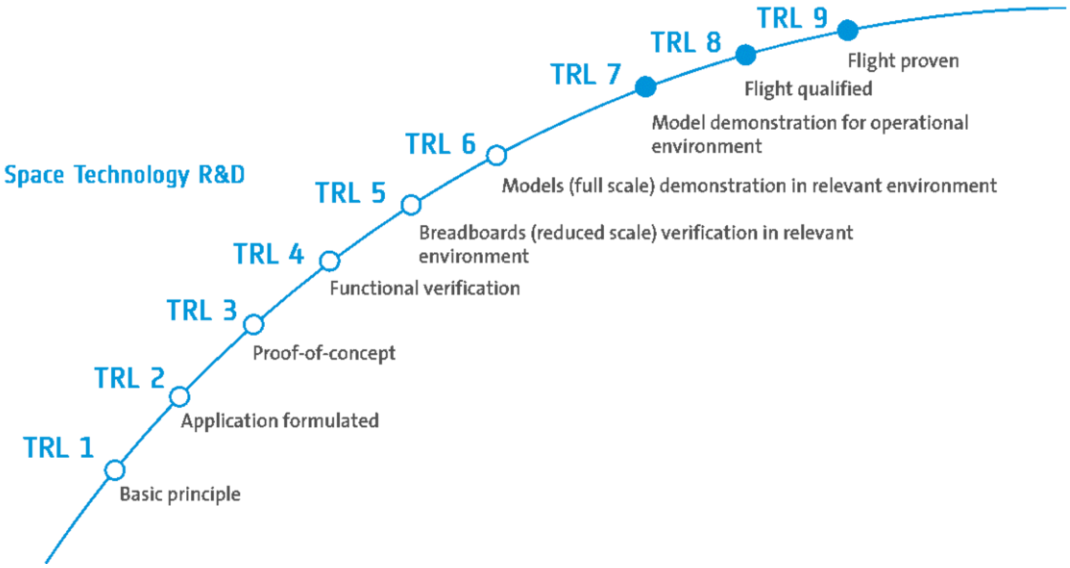

*Figure 5-1 European Space Agency (ESA) technology readiness levels scale [image credit: ESA].*

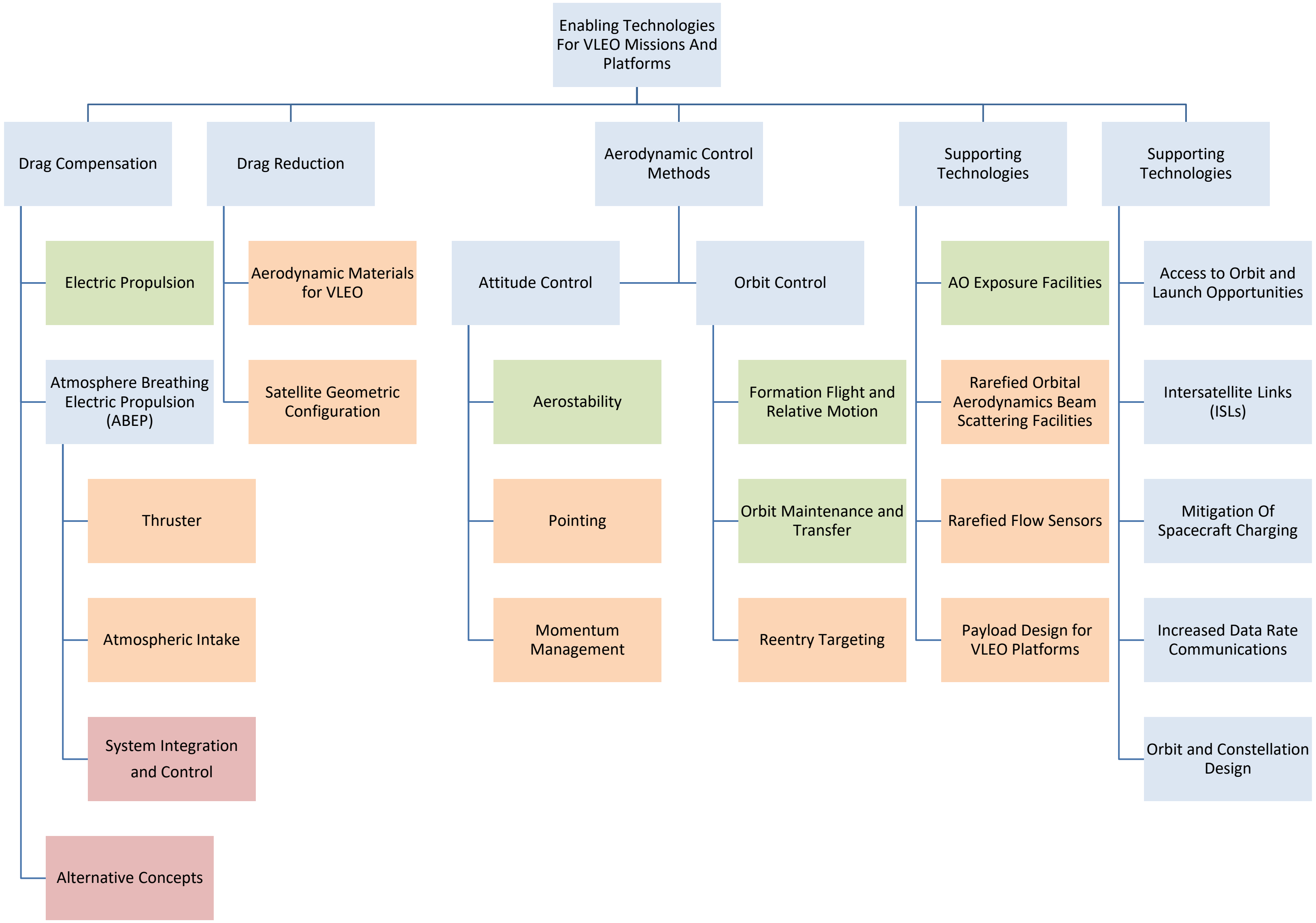

*Figure 5-2 Technology breakdown for VLEO platforms and missions.*

## 5.1. Drag Compensation

Technologies for drag compensation use propulsion systems to produce thrust to directly counteract the effects of drag on spacecraft in orbit and to provide extended orbital lifetimes. Drag compensation can either be complete, providing an approximately stable orbital altitude, or partial, whereby the rate of orbit decay is reduced. Both continuous or phased thrusting strategies can also be considered with different requirements on thruster operation, power collection, and storage. Finally, such a propulsion system may also be able to produce more thrust than required for drag compensation, enabling additional attitude and orbit manoeuvres.

| **Description and State of the Art** | **Technical Challenges** | **Developmental Milestones** |
|---|---|---|
| **5.1.1. Electric Propulsion** | | |
| A wide range of electric propulsion systems have been developed for in-space use and are available at TRL 9.<br>For long-term operation in VLEO, two electrostatic thrusters have currently been demonstrated: QinetiQ T5 ion thrusters on GOCE [8] and an ion thruster system on SLATS [9].<br>Xenon is predominantly used in thrusters of these types, though other propellants can be used [10].<br>Several further electric thrusters are in development for use in VLEO and are proceeding to in-orbit demonstration, for example REGULUS (T4i), Maxwell (PhaseFour), and NPT30-I2 (ThrustMe). | General increases of thrust level, thruster efficiency, and specific impulse to enable versatile operation for spacecraft of different sizes and at lower orbital altitudes.<br>Improve throttling capability and start-stop/restart performance to ensure long-term sustained operation using non-continuous and variable thrust profiles.<br>Ensure long-lifetime operation through selection of appropriate materials for both propellant choice and external effects (e.g. AO erosion).<br>**Community Feedback** | *Community feedback will be sought going forward to identify milestones related to the future development of EP for VLEO applications.* |
| **5.1.2. Atmosphere Breathing Electric Propulsion (ABEP)** | | |
| **ABEP Thruster**<br>Concepts for thrusters compatible with atmospheric propellants include RF-ion thrusters (RITs), Hall-effect thrusters (HETs), RF-plasma thrusters, pulsed-plasma thrusters (PPTs), and magnetoplasmadynamic thrusters (MPDTs).<br>Conventional HETs and RITs were successfully tested with atmospheric propellant ($N_2$-$O_2$ mix) but demonstrated significantly lower performance in comparison to Xe [11]. The RAM-HET was subsequently tested using a similar mixture of atmospheric gases [12].<br>The MABHET was tested using $CO_2$ propellant for use in the Martian atmosphere [13].<br>The RF helicon-based inductive plasma thruster (IPT) [14] aims to employ contactless technology and a quasi-neutral plasma to solve issues of operating with atmospheric propellant. This thruster has been tested with different individual propellants (Ar, $N_2$ and $O_2$). | Ability for the thruster to operate with variable input mass flow rate and composition of gases.<br>Measurement of produced thrust in experimental facilities.<br>Ability for the thruster to generate a variable thrust level, with reduced dependency on the inlet conditions, and to perform start-stop/restarts as required for the desired thrust profile.<br>Ensure an appropriate operational lifetime of all components due to erosion by collected atmospheric propellant (principally AO and $N_2$).<br>Increase in thrust efficiency (N/W) to enable reduction in the required system power for drag compensation purposes.<br>Increase thruster specific impulse to enable drag compensation (dependent on intake performance).<br>Reduction of component masses for operational systems. | Demonstration of prototype thruster operation under representative atmospheric flow conditions.<br>Measurement of thrust while operating under representative flow conditions.<br>Demonstration of an ABEP thruster with thrust performance that matches operational mission requirements in VLEO.<br>Demonstration of system lifetime in relevant environment and under representative propellant usage.<br>Development of contactless technologies and appropriate materials to avoid component erosion issues. |

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| **Atmospheric Intake**<br>Numerous intake designs for an orbital ABEP system have been developed [15].<br>Designs assuming diffuse material characteristics have indicated intake efficiencies to a maximum of 46% [16]<br>Intakes based on specular reflecting materials have been shown through simulation to have efficiencies up to 94%, whilst hybrid designs can have efficiencies up to 70% [17].<br>Sub-scaled intake designs based on different GSI behaviours [17] are due to be tested in the ROAR facility at the University of Manchester. | Surface properties are not likely to be nominal as characterised and may change with long exposure to N2 and AO.<br>Manufacturing complex geometries with high precision and subsequently coating these geometries with the appropriate surface materials.<br>Design of lightweight but rigid constructions to withstand launch loadings.<br>Design of adaptive or variable inlet geometries to adjust for pointing, wind, and density variations and provide enhanced off-nominal performance.<br>Ground-based testing and validation of intake performance under representative atmospheric conditions. | Demonstration and performance characterisation of intake designs in a representative flow environment.<br>Development of prototype intake(s) for flight testing on a relevant platform design. |
| **System Integration and Control**<br>A number of integrated concepts for ABEP systems have been proposed, for example ABIE [16,18] and RAM-EP [19].<br>Studies of the operational use of these integrated systems have also considered different thrusting strategies [19] and off-nominal performance (e.g. misalignments of the intake to the flow and thruster to the desired thrust vector).<br>ABIE, composed of an annular intake and an ECR-based thruster, has been demonstrated in a vacuum environment [18,20]. The RAM-HET has also been demonstrated with an intake and representative atmospheric propellant ($N_2$-$O_2$ mix), though Xe was added to the discharge [12].<br>Operational algorithms for the in-orbit control of an ABEP system are yet to be developed. | Implementation of a power processing unit (PPU) at fixed or variable frequency that can supply the thruster with variable input power as well as restart capability.<br>Implementation of sensors and control algorithms that can dynamically change the ABEP power input depending on the aerodynamic drag and incoming flow conditions to produce the required thrust for the specific mission phase.<br>Enable operation and restart capability with variable input mass flow rate and composition.<br>Design of mechanical structure for holding intake and thruster together and with precise alignment.<br>Ensure that the ADCS maintains the satellite orientation with the flight direction during ABEP operation to ensure efficiency of drag compensation. | End-to-end test of ABEP system components in a relevant environment demonstrating compensation of aerodynamic drag.<br>Demonstration of control algorithms to handle variation of oncoming atmospheric flow conditions and different mission requirements (e.g. thruster throttling for descent).<br>Demonstration of a fully operational ABEP system in the VLEO environment. |
| **5.1.3. Alternative Drag Compensation Concepts** | | |
| **Tether-based Propulsion**<br>Electrodynamic tethers can generate a force from the interaction between a current carrying wire and the Earth's magnetic field. Tethers have been proposed as thrust generating devices to provide propellant-less drag compensation [21]. | Development of a tether that produces thrust forces that can also overcome the additional experienced drag.<br>Development of suitable materials for long-term tether use in the VLEO environment. Materials need to be conductive (low resistivity), low density, strong, have AO erosion resistance, and have a suitable melting point.<br>Tethers of necessary length are challenging to deploy and maintain at the necessary orientation and also interact with the satellite stability. Tether | *Community feedback will be sought going forward to identify milestones related to the future development of alternative drag compensation concepts for VLEO applications.* |

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| | dynamics in VLEO will also be affected by the aerodynamic interactions.<br>Deployed tether may obscure imaging operations. | |

## 5.2. Drag Reduction

Drag reduction technologies aim to reduce the magnitude of the drag force experienced by a body in the residual atmospheric environment present at VLEO altitudes. Drag reduction alone can increase the lifetime of an unpropelled spacecraft in orbit or can help to reduce the propulsive and power requirements of satellites that are equipped with drag compensation propulsion systems.

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| **5.2.1. Aerodynamic Materials** | | |
| Materials for use in VLEO with enhanced gas-surface interaction (GSI) performance (i.e. specular or quasi-specular reflection properties) typically focus on the scattering behaviour of atomic oxygen (AO), the most abundant species present in the atmosphere at these altitudes.<br>AO is highly reactive and adsorbs to spacecraft surfaces and causes erosive damage. These effects change the GSI properties of the surface (e.g. increased accommodation).<br>Silicon dioxide ($SiO_2$) highly oriented pyrolytic graphite (HOPG), and Pyrex have shown superior reflection properties to gold (Au) under experimental conditions [22,23]. Hexagonal boron nitride (h-BN) has also demonstrated to be an interesting candidate [24].<br>Further exploration of 2D materials is ongoing, including in ground-based facilities and on-orbit testing [25,26]. | Identification and development of new materials with enhanced aerodynamic properties for different applications to VLEO spacecraft (e.g. thermo-optical properties, surface conductivity).<br>Surface materials also need to be resistant to the effects of AO. Resilience against thermal cycling, $N_2$ exposure [27], UV and other radiation exposure is also necessary for long-term use in VLEO.<br>Testing of candidate materials under representative flow conditions to demonstrate and characterise aerodynamic properties. See Section 5.4.1 for further information on environmental testing facilities for VLEO.<br>Space qualification and production upscaling of new materials and processes.<br>Overhead of additional processing and handling activities associated with integration of materials onto spacecraft external surfaces. | Improved understanding of GSIs in rarefied flows leading to better modelling of aerodynamic performance in VLEO.<br>Demonstration of materials with enhanced aerodynamic properties under relevant environmental conditions.<br>Verification of use of aerodynamic materials enabling drag-reduction and enhanced lift-production in orbit.<br>Development and testing of suitable material systems (i.e. surface coatings and substrates) that can be used for entire spacecraft surfaces and for long-term operation in an orbital environment. |
| **5.2.2. Platform Geometry and Configuration** | | |
| For conventional materials (diffuse reemission with approximately complete energy accommodation), a reduction in drag can generally be achieved by reducing the cross-sectional area. Shapes with tapered forward and aft facing surfaces (i.e., biconic profiles) are found to be optimal [28].<br>With advanced aerodynamic materials, the angle of the spacecraft surfaces with respect to the flow plays a more significant role in the reduction of drag. Production of lift forces that may be | Wedged or pointed profiles may have a loss of usable internal volume.<br>Stability and controllability of the platforms must be ensured. Impact of external control surfaces and flexible body dynamics (or aeroelasticity) require modelling with suitable environmental inputs.<br>Aerodynamic shape optimization for novel materials may have more degrees of freedom (due to usable lift production) and therefore greater design complexity. | Simulated performance of spacecraft geometries with novel materials demonstrating reduced drag.<br>In-orbit demonstration of drag reduction through combined design of external geometry and specification of surface materials. Possibly by comparison of orbital decay to a similar control object. |

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| useful for control purposes may also be desirable. | | |

## 5.3. Aerodynamic Control

Aerodynamic control methods seek to exploit the external atmospheric perturbations in VLEO to provide control forces and torques that can be used to perform a variety of attitude and orbit stabilisation and control manoeuvres. These aerodynamic control manoeuvres can be considered independently or can be used synergistically with conventional attitude and orbit control actuators to reduce the requirements on these devices and extend their effective use into the lower altitude range.

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| **5.3.1. Aerodynamic Attitude Control** | | |
| **Aerostability**<br>Passive and semi-passive aerodynamic attitude stability (i.e. flow-pointing) has been demonstrated in orbit on several spacecraft using a variety of different geometric configurations and damping devices: (1) aerodynamic skirt and viscous-spring damping system [29]; (2) simple mass distribution and magnetic damping, enabling flow-tracking within ±20° [30]; and (3) a stabilising shuttlecock configuration and active b-dot magnetic damping, providing flow-pointing performance of better than 5° [31].<br>Several further studies of passive aerodynamic stabilisation have also been presented in literature, including shuttlecock and feathered configurations [32].<br>Use of centre-of-mass shifting has been proposed to enable variable aerodynamic-based stability [33–35].<br>Neutrally stable platform designs for use in VLEO may be possible, supporting platform agility [RD-2.2]. | Flow-defined attitude may conflict with agility and pointing requirements of different platforms and mission/payload applications.<br>Uncertainty in knowledge and modelling of aerodynamic and other disturbing environmental torques (e.g. solar radiation pressure, residual magnetic dipole).<br>Development of robust and flexible control algorithms to support aerostable modes using conventional and non-conventional attitude actuators.<br>Integrating attitude control actuators (e.g. conventional actuators, aerodynamic control surfaces, and shifting centre-of-mass) to achieve aerostability requirements.<br>Development of suitable platform concepts to enable neutral stability characteristics without incurring significant drag (i.e. not spherical). | Demonstration of platform configurations for dynamically controlled aerostability characteristics.<br>Development and demonstration of platform stability suitable for different platform designs and mission applications.<br>On-orbit demonstration of platforms with advanced aerodynamic stability. |
| **Aerodynamic Pointing**<br>Aerodynamic pointing control utilises aerodynamic control surfaces to actively generate and modulate aerodynamic torques to provide pointing towards a given (typically non-flow-pointing) vector.<br>The control authority and pointing performance is dependent on the spacecraft geometry and configuration and external environmental conditions.<br>Different pointing modes have been conceived, combining aerodynamic control in one or more axes (roll, pitch, and yaw) with further active and passive attitude actuators to assist with control | Uncertainties associated with the knowledge of the flow environment (density and velocity) and the material GSI performance suggests that only coarse pointing performance is possible with aerodynamic actuation alone.<br>Uncertainty in knowledge and modelling of other disturbing environmental torques (e.g. solar radiation pressure, residual magnetic dipole) must be considered in control algorithms and robustness ensured for relevant mission operating conditions.<br>Minimisation of the drag increment associated with use of aerodynamic control surfaces, both through algorithm | Refined understanding of the interaction of material surfaces with atmospheric flow in VLEO leading to improved knowledge of torques generated by geometries and aerodynamic surfaces.<br>Improvement and demonstration of control algorithms to perform aerodynamic pointing manoeuvres in VLEO, incorporating material performance, external environmental effects, and on-board computational capability.<br>See also Section 5.4.3 regarding flow sensors for improvement of aerodynamic control. |

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| and damping [36–39]. However, only coarse pointing performance is expected due to present uncertainties in estimation of aerodynamic torques.<br>Demonstration of active aerodynamic pointing control has not yet performed in-orbit. | design and incorporation of aerodynamic materials.<br>Implementation of more complex control methods (e.g. adaptive, model predictive) may require additional on-platform computational hardware. | See also Section 5.2.1 for development of materials with enhanced aerodynamic properties. |
| **Aerodynamic Momentum Control**<br>Aerodynamic trim and momentum management methods use control surfaces to vary the experienced aerodynamic torques to reject or balance external disturbances or to dump internal momentum from active attitude actuators (e.g., momentum/reaction wheels and control-momentum gyroscopes).<br>Only a few studies of aerodynamic trim and momentum management have been presented in literature [32]. Momentum dumping during low-perigee passes of orbit raising manoeuvres for geostationary satellites has also been proposed [40].<br>MagSat [41,42] used an adjustable trim boom to balance aerodynamic and gravity gradient torques minimising disturbing yaw torques and the use of the on-board magnetic coils. | Uncertainties associated with both the knowledge of the flow environment (density and velocity) and the material GSI performance restrict the control performance.<br>Uncertainty in knowledge and modelling of other disturbing environmental torques (e.g. solar radiation pressure, residual magnetic dipole).<br>Minimisation of the drag increment associated with use of aerodynamic control surfaces, both through algorithm design and incorporation of aerodynamic materials. | Demonstration of spacecraft momentum control using aerodynamic control surfaces.<br>See also Section 5.4.3 regarding flow sensors for improvement of aerodynamic control.<br>See also Section 5.2.1 for development of materials with enhanced aerodynamic properties. |
| **5.3.2. Orbit Control** | | |
| **Relative Motion**<br>Deployment, formation control, and rendezvous of two or more spacecraft can be performed using differential aerodynamic forces.<br>Differential drag manoeuvres have been performed in-orbit by several missions and systems [43–45].<br>Differential lift manoeuvres have received less attention. However combined with differential drag, these methods have the potential to improve the manoeuvre performance whilst reducing the associated drag losses [46–48]. | Uncertainties associated with the knowledge of the flow environment (density and velocity) and the material GSI performance restrict the possible control performance.<br>Implementation of more complex control methods (e.g. adaptive, model predictive) may require additional on-platform computational hardware.<br>Design of synergetic coordination between aerodynamic manoeuvres and drag-compensating propulsion systems. Development of optimal combined control implementations.<br>Minimisation of the drag increment associated with use of aerodynamic control surfaces, both through algorithm design and incorporation of aerodynamic materials. | Development of differential drag and lift control methods that are robust to the uncertainties and variations in aerodynamic and other environmental effects.<br>Development of autonomous aerodynamics-based relative motion manoeuvres (e.g. formation keeping, collision avoidance, reconfiguration, and rendezvous).<br>See also Section 5.2.1 for development of materials with enhanced aerodynamic properties. |
| **Orbit Maintenance and Transfer**<br>Use of aerodynamic forces to perform the correction of inclination for descending SSOs has been studied, | Increase of usable spacecraft lift-to-drag ratio through platform configuration and use of novel aerodynamic materials.<br>Design of synergetic coordination between aerodynamic manoeuvres and | Development of control algorithms to perform combined orbit transfer using aerodynamic and propulsive input. |

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| requiring a platform lift-to-drag ratio of between 1:1 and 1:1.6 [49].<br>Possible further applications include re-tasking of observation satellites (e.g. inclination or nodal changes) to modify overflight times of targets of interest. | drag-compensating propulsion systems. Development of optimal combined control implementations. | See also Section 5.2.1 for development of materials with enhanced aerodynamic properties. |
| **Re-Entry Targeting**<br>Targeting of the atmospheric re-entry interface using aerodynamic drag modulation based control has been considered in a number of studies [50–52].<br>Applications include the delivery of re-entry capsules over target geographic locations or disposal of large spacecraft over unpopulated areas of the Earth. | Knowledge and uncertainty of the true ballistic coefficient of the platform in the different configurations and uncertainties associated with the knowledge of the flow environment may reduce possible targeting accuracy.<br>Implementation of appropriate drag modulating surfaces to enable targeting of the necessary range of latitudes and longitudes from a chosen transition altitude.<br>Availability of desired re-entry latitude and longitude may be restricted for very low transition altitudes.<br>Implementation of attitude stability and control methods and hardware to ensure nominal drag modulation performance. | Development and demonstration of control algorithms to perform successful re-entry targeting to desired location using variation in aerodynamic forces.<br>Development of on-board closed-loop control algorithms requiring little to no ground-based guidance or computation to achieve re-entry requirements. |

## 5.4. Supporting Technologies

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| **5.4.1. Atomic Oxygen Exposure Facilities** | | |
| AO exposure facilities are a key tool in supporting the study and development of new technologies and materials for VLEO applications.<br>Most existing experiments use a pulsed beam based on laser detonation sources. These sources can produce beams with flux between $10^{14}$–$10^{17}$ atoms/cm$^2$ and are commonly employed to study the erosion effects on materials due to AO exposure [53–56].<br>The samples in these facilities are commonly analysed for mass loss by assessing the surface recession using atomic force or scanning electron microscopy. In situ measurements with quartz crystal microbalances are also often performed. Such detection systems and beam characteristics are better suited for erosion studies [22,57,58].<br>A range of materials with atomic oxygen erosion resistance have been characterised using ground-based testing capabilities. Published | Simultaneous characterisation of optical properties of materials (reflectivity, and transmissibility) with exposure is required to ensure long-term compatibility with imaging payload and solar array coatings.<br>*Community feedback will be sought going forward to identify further technical challenges related to the future development of atomic oxygen exposure facilities.* | Increased and improved ground-based testing capabilities so that the response to AO, vacuum UV, temperature variation and other factors of the VLEO atmosphere can be assessed.<br>Development of enhanced AO testing capabilities (flux, fluence).<br>*Community feedback will be sought going forward to identify milestones related to the future development of atomic oxygen exposure facilities.* |

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| information and databases of such materials are openly available [59–63]. | | |
| **5.4.2. Orbital Aerodynamics Beam Scattering Facilities** | | |
| These facilities combine a gas-beam with a sensor suite to measure the GSIs of different material samples.<br>Enhanced facilities for rarefied orbital aerodynamics investigations may utilise multiple gas beam sources and incorporate other environmental effects to simulate the on-orbit environment in VLEO more completely.<br>To measure the orbital aerodynamic properties of the materials, sensors that can measure the scattering behaviour of the incident gas-beams are more suitable.<br>Current facilities are operational at Montana State University [56]. The ROAR facility is currently being commissioned as part of the DISCOVERER project [24,54,55]. | Generate an environment (flux, energy distribution, temperature variation, radiation doses, gas species, etc) that more closely simulates that of VLEO.<br>Improve the detection systems so that gas-surface interactions can be better characterised, i.e. the angular distribution of characteristics such as flux, energy distribution, gas species, which requires a mass spectrometer or other in situ spectroscopy techniques.<br>Scaling of experimental facilities for testing of system components (e.g. subscale aerodynamic intakes).<br>Standardisation of methodologies for calibrating, testing, and sharing of experimental data for easy comparison, interpretation, and better correlation between experiments. | Development of improved facilities for synergetic studies with of GSIs with other environmental factors in VLEO.<br>Development of new AO production technologies for improved beam characteristics (flux, diameter, energy distribution, composition).<br>Development of new sources of hyperthermal beams of different gas species relevant for VLEO.<br>Implementation of improved detection systems to better suit the measurement of GSIs. |
| **5.4.3. Rarefied Flow Sensors** | | |
| Sensors that accurately measure the atmospheric flow vector (including velocity, flux, and composition) are required for both ground-based and on-orbit measurements. Knowledge of how the environment varies is crucial for predicting the behaviour and setting the requirements of relevant systems with significant impact in the mission design.<br>Different sensors have been tested focusing on AO flux, most commonly using quartz crystal microbalances, changes in the electrical properties of materials, and by material degradation [64,65].<br>AO flux measurements using material degradation were shown to deviate by up to 16% compared to standard method of using Kapton profilometry [65].<br>Sensors measuring the changes in electrical properties of materials (actinometers) have presented a linear behaviour for 160 hours of exposure, an equivalent AO fluence of the order of $10^{23}$ atoms/$m^2$ [66]. | Integration of multiple flow sensor types to provide the necessary information of the VLEO environment.<br>Development of these sensors face challenges such as reliability, resolution, correlation issues with ground-based calibration tests, limited lifetimes, and contamination (including during satellite integration). A range of sensors may need to be developed to address these factors. | Development of improved ground-based testing capacity of materials and different sensor technologies and concepts.<br>Perform testing and demonstration of candidate sensors under relevant environmental conditions.<br>Implementation of rarefied flow sensors (including combinations) for VLEO-based applications (e.g. improved aerodynamic control, scientific measurement of flow properties, and flow-alignment of ABEP). |
| **5.4.4. Payload Design for VLEO Platforms** | | |
| **Optical Payload Design**<br>Design of high-performance optical payloads has typically focused on | Long-term compatibility of materials used in optical payloads with AO environment (i.e. stray light reduction, | *Community feedback will be sought going forward to identify milestones related to the future development of payloads for VLEO applications.* |

| Description and State of the Art | Technical Challenges | Developmental Milestones |
|---|---|---|
| compactness (length) and mass for launch vehicle compatibility [67].<br>However, for use in VLEO, reduction of the nominal cross-sectional area may be more critical in the overall system design trade. Such systems may hold similarity to the early reconnaissance spacecraft e.g. KH-8 satellites [68].<br>The selection of materials used for different optical surfaces (e.g. mirrors [69]) also requires careful consideration for operation in the AO-rich environment of VLEO. | transparent, and highly reflective surface coatings).<br>Design of external spacecraft geometries and payloads to avoid ingress of AO and degradation of more sensitive internal components.<br>Design of optical payloads to support drag mitigation and operations in VLEO, i.e. reducing platform cross-sectional area and to enable off-axis viewing without drag increment or inducing disturbing torques may result in large primary mirrors/lenses and associated increases in mass. | |

## 5.5. Further Supporting Technologies

A range of further technologies can be considered relevant for the establishment of operations in VLEO and the improvement of mission and application-specific performance. However, these technologies are applicable to the wider space industry and will therefore not be considered in detail here. Notes on their application to the development of satellites in VLEO are provided below.

### 5.5.1. Access to Orbit and Launch Opportunities

A range of frequent and diverse options for launch to orbit is desirable from the perspectives of convenience, competition (leading to reduction in cost) and resilience against launch failures. The growth of commercial launch services has increased the number of launch opportunities for launch to LEO. Dedicated launch even for smaller sized satellites is becoming more readily available. A range of rideshare or secondary payload launch options (utilising excess launcher volume or performance margin) have also become more commonplace, for example traditional secondary payloads or auxiliary/piggyback opportunities, often arranged through external brokers or aggregators.

However, while the utilisation of VLEO remains low, the number of opportunities for direct access to these lower altitude orbits remains limited. Aside from a direct, dedicated launch into VLEO, deployment from the ISS remains the principal option for access to these altitudes. Alternatively, use of propulsion systems can enable insertion into VLEO following launch into higher altitude orbits.

### 5.5.2. Intersatellite Links (ISLs)

ISLs or crosslinks can be used in constellations to route excess demand between satellites and reduce requirements on the size and distribution of ground segment infrastructure. ISLs can enable real-time data link capability to all satellites in the constellation. RF ISLs have been used by several constellations to date, whilst optical (laser-based) ISLs have only recently started to deployed commercially in orbit.

For VLEO, the use of ISLs may be important to counteract the reduction in ground access area that is associated with reduced altitude. Constellations of satellites in VLEO may therefore benefit from ISLs to provide global connectivity without a proliferation of well distributed ground stations. Additional challenges of implementing ISLs in VLEO may include the complexity of stabilising and pointing of ISL antennas or apertures under the additional aerodynamic disturbances and additional requirements on ISL link-budgets that may pass through the denser atmosphere. The minimisation of additional size, mass, and power of ISL subsystems is important for integration on possible spacecraft platforms.

### 5.5.3. Increased Data Rate Communications

Enhanced communication data rates are desirable to improve link capacity for downlink of data collected on orbit (e.g. imagery for EO satellites) and for both user and gateway services on communications satellites. In VLEO, the general shortening in access time with reducing altitude can contribute to a reduction in total data downlink. Increased data rate communications could support VLEO operations by compensating for the shorter ground contact times and enabling suitable data downlink capacity.

### 5.5.4. Mitigation of Spacecraft Charging

The atmospheric and ionospheric environment in VLEO presents challenges with regards to the charging of spacecraft surfaces. As the electron flux is greater than the ion flux, surfaces are generally negatively charged. In addition, as electrons can more readily penetrate the wake region behind a spacecraft than heavier ions, differential charging may occur. This may be further influenced by photoemission (during sunlit phases), the presence of positively biased solar arrays, and the presence of ionised emissions (e.g. from EP systems). The possible effects of such charging issues include static discharging and damage to onboard electronics, interference with instruments and sensors, and parasitic power loss on solar arrays. For operation in VLEO, the encapsulation (materials and method of integration) of solar arrays and relative location of EP thrusters and other sensitive subsystems may be critical.

### 5.5.5. Orbit & Constellation Design

Whilst the lower orbital altitudes of VLEO can provide benefits in terms of payload performance (i.e. spatial and radiometric resolution) the corresponding access area or coverage from a given sensor or antenna may be reduced. Fewer low maximum revisit time (MRT) windows are also available at VLEO altitudes. Thus, to provide similar access, coverage, and revisit capabilities more satellites may be required in comparison to higher orbital altitudes. A trade-off between number of spacecraft and their design may therefore arise and should be considered through appropriate constellation and systems modelling approaches.

# 6. Application of VLEO Technologies to Known Mission Opportunities

In the below subsections, known mission opportunities that are likely to be operated within VLEO or may benefit from enabling technologies for VLEO spacecraft are explored. Development of the different technologies may be directly necessary for the success of the mission (i.e. mission pull) or may contribute to the improvement of the mission or system if available (i.e. technology push).

## 6.1. Daedalus (ESA Earth Explorer)

The Daedalus mission is a proposal for the ESA Earth Observation program's 10th Earth Explorer that will perform in-situ measurements of the lower thermosphere-ionosphere (LTI) [70]. The proposed mission consists of a primary spacecraft that will operate for a period of at least 3 years in a highly elliptical "dipping" polar orbit (perigee <150 km, apogee 2000 km to 3000 km) and several CubeSats that will be deployed from the primary spacecraft at selected intervals to enable further, differential temporal and spatial measurements in the LTI.

Relevant Technology Areas

- Aerodynamic attitude stabilization and orbit control for operation at low altitudes.
- Materials to reduce drag and atomic oxygen erosion.
- Mitigation of spacecraft charging effects.
- Improved atmospheric flow sensors for scientific data collection.

## 6.2. ESA Next Generation Gravity Mission (NGGM)

The ESA NGGM programme is currently in the concept definition phase for a future mission to monitor variations of the Earth's gravity field. The mission will broadly follow on from the previous GRACE and GRACE-FO missions and will utilise two satellites to measure the small variations in the Earth's gravity field [71]. To maximise the measurement signal of the gravity field, the satellites must orbit as low as possible. Altitudes of between 325 km to 400 km are therefore under consideration, supported by a high performance attitude and orbit control system for drag compensation and precise pointing control [72,73].

Relevant Technology Areas

- Aerodynamic attitude stabilization and orbit control for spacecraft operation at low altitudes.
- Materials to reduce drag and atomic oxygen erosion.
- Mitigation of spacecraft charging effects.
- Atmospheric flow sensors to assist assessment of spacecraft drag forces.
- ABEP for drag compensation.

## 6.3. Project Oberon (DSTL)

Project Oberon aims to develop SAR capabilities for the UK Ministry of Defence (MoD). An initial feasibility study has been conducted by Airbus Defence and Space for DSTL with on-orbit demonstration possible by 2022 and operational capability as early as 2025. Support for project Oberon using VLEO technologies could include the development of future improvements in system design and mission capability through reduced orbital altitude.

Relevant Technology Areas

- ABEP for drag compensation to increase mission lifetime.
- Aerodynamic materials to reduce drag and atomic oxygen erosion.
- Aerodynamic attitude control and stabilization.

### 6.4. RED (Ram-EP Demonstrator)

The Ram-Electrical Propulsion for Low Altitude Satellites Demonstrator (RED) is an ESA funded project that aims to demonstrate the use of atmosphere-breathing electric propulsion. The project is currently preparing for Phase-B preliminary definition studies.

Relevant Technology Areas

- ABEP components and system technologies.
- Aerodynamic materials to reduce drag and atomic oxygen erosion.
- Aerodynamic attitude control and stabilization.
- Atmospheric flow sensors to characterize ABEP performance.

### 6.5. Orbital Stations

Technologies developed to support the operation of commercial satellites in VLEO may also be relevant to existing (e.g. ISS) and next-generation in-orbit stations that orbit close to the Earth.

Relevant Technology Areas

- Atmosphere breathing electric propulsion for drag compensation.
- Aerodynamic materials to reduce drag and atomic oxygen erosion.
- Mitigation of spacecraft charging effects.
- Aerodynamic attitude control and stabilization.

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### 7.1. Internal Reference Documents

| Ref. | Document Title | Version | Date |
|---|---|---|---|
| RD-2.1 | DISCOVERER-D2.1-VLEO Aerodynamic Requirements | 1.0 | 2019-03-23 |
| RD-2.2 | DISCOVERER-D2.2-VLEO Satellite Aerodynamic Control Techniques and Mechanisms | 1.0 | 2019-09-30 |
| RD-4.1 | DISCOVERER-D4.1-Literature Review of ABEP Systems | 1.0 | 2017-07-11 |
| RD-4.3 | DISCOVERER-D4.3-Technical Specification and Design of Intake and ICP based Thruster | 1.0 | 2020-02-15 |
| RD-5.1 | DISCOVERER-D5.1-EO Market Overview | 11.0 | 2018-03-21 |
| RD-5.2 | DISCOVERER-D5.2-Benefits and Applications of VLEO for EO | 1.0 | 2018-08-31 |
| RD-5.3 | DISCOVERER-D5.3-VLEO Market Assessment | 1.6 | 2020-06-29 |
| RD-5.7 | DISCOVERER-D5.7- Business Model Roadmaps for Stakeholders in the VLEO Market | 5.4 | 2020-11-19 |

# 8. Tables and other Supporting Documents

## 8.1. Acronyms and Abbreviations

| | |
|---|---|
| ABEP | Atmosphere-Breathing Electric Propulsion |
| AO | Atomic Oxygen |
| EO | Earth Observation |
| EP | Electrical Propulsion |
| ESA | European Space Agency |
| GSI | Gas-Surface Interaction |
| IPT | Inductive Plasma Thruster |
| ISL | Intersatellite Link |
| LEO | Low Earth Orbit |
| LTI | Lower Thermosphere-Ionosphere |
| SAR | Synthetic Aperture Radar |
| TRL | Technology Readiness Level |
| VHR | Very-High Resolution |
| VLEO | Very Low Earth Orbit |