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EDITORIAL

1st Symposium of Very Low Earth Orbit Missions and Technologies

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Operating remote sensing and communications satellites in very low Earth orbit (VLEO) offers significant payload and platform benefits. Optical payloads have increased resolution or reduced aperture sizes, and radiometric performance is improved. Radar and communications payloads have significantly improved link budgets, reduced antenna sizes and transmission power, and latency is reduced. In addition, the orbital radiation environment is more benign, cost per kg of launch mass is reduced, and the environment is sustainable with satellites and debris objects removed rapidly from orbit due to drag. That same drag, however, must be overcome during the operational life of the satellite.

The 1st International Symposium on Very Low Earth Orbit Missions and Technologies ran as a virtual event on 28–29 June 2021, sponsored by the DISCOVERER project [1]. Bringing together representatives, from industry, academia, space agencies and government, it was the first opportunity for stakeholders in the development of VLEO missions to come together and share their knowledge and experience. With nearly 200 registered attendees from all over the world, the meeting was a significant success. Some of papers presented form this special Issue, with others available on the DISCOVERER website [1].

The symposium was also the starting point for the development of a community of interest in VLEO missions and technologies.

This editorial, by way of introduction, covers some of the background to the technology problems that need to be solved, whilst also discussing what the future of VLEO missions might look like.

1 The benefits and challenges of commercially viable VLEO satellites

Interest in the use of VLEO for a variety of mission types has grown significantly in the recent years. The benefits of operating satellites at lower altitude for Earth observation were first expounded in [2] and further developed in [3]. Critical to these benefits is the relationship between orbital altitude/range to an imaging target and system parameters such as resolution or payload size and mass, which link directly to cost. For example, halving the orbital altitude for an optical telescope can be used to either increase the ground resolution by a factor of 2 or halve the telescope diameter. Radiometric performance is proportional to the inverse square of the range to a target. Consequently, sensor system link budgets are significantly improved for both optical and radar payloads. Perhaps the most comprehensive review of the benefits for communications satellites is the outcome of a European Space Agency funded study by Thales Alenia Space [4]. It highlights key benefits including reduced latency, improved link budgets and optimised use of the frequency spectrum. In addition to these application-specific benefits, there are platform benefits, again thoroughly captured in [2]. These include a reduced radiation flux and a reduced launch cost per unit mass. But perhaps most significant is that VLEO represents an environment that can be used sustainably, with atmospheric drag rapidly removing satellites and debris alike from orbit, simplifying end-of-life considerations and minimising the collision risk with the existing debris population.

The residual atmosphere in VLEO also presents the primary challenge to the commercial use of the orbit regime. A satellite moving through the rarefied gas experiences induced drag, variations in density and thermospheric winds can create attitude disturbances, and the primary atmospheric constituent, atomic oxygen, can erode exposed surfaces.

Any mission operating in VLEO must address these issues. Sessions within the symposium focussed on mission concepts and on key technologies to enable commercially viable,

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sustained operations of satellites in this orbital regime: aerodynamic materials, atmosphere-breathing electric propulsion, and orbital aerodynamic control.

2 Aerodynamic materials

VLEO can be defined as the altitude range below around 450 km altitude, where aerodynamics starts to have a significant impact on satellite design, and above the Karman line. The atmosphere in this range is highly rarefied. As such, the mean free path between gas–gas collisions is much larger than typical satellite dimensions, meaning orbital aerodynamics is driven by the interactions of individual gas particles with satellite surfaces. Empirical data suggest that these particles are adsorbed, exchanging their momentum into the surface, and then diffusely and thermally reemitted when interacting with traditionally used materials [5, 6]. This is in part due to the nature of the predominant gas species in VLEO, atomic oxygen, which is highly reactive. That the orbital velocity of satellites is much larger than the thermal reemission velocity means that drag is then mostly due to the momentum exchanged from the initial adsorption, and proportional to the cross-sectional area of the satellite to the flow.

Aerodynamic materials, those that specularly reflect the flow, if combined with surfaces at shallow angles to it, have the potential to minimise the momentum exchange, whilst also producing usable lift for aerodynamic control. Such materials would necessarily also be either resistant to atomic oxygen erosion or would maintain their specular properties whilst being eroded. Just as hard as identifying these materials is developing facilities to characterise them.

3 Atmosphere-breathing electric propulsion

Atmosphere-breathing electric propulsion systems (ABEP) combine an atmospheric intake, optimised to efficiently capture the rarefied atmosphere in the ram direction, and an electric thruster to ionise and accelerate the captured gas. Such systems have the potential to compensate for drag provided the exhaust velocity exceeds the velocity of the satellite through the gas whilst also compensating for the inefficiency of the system. However, avoiding the need to carry propellant is only one lifetime limiting factor as any intake and thruster must also resist erosion due to atomic oxygen.

4 Aerodynamic attitude control

Minimising the cross-section of the satellite to minimise drag means most VLEO satellite concepts tend to have slender aspect ratios. This in turn means they are also typically aerostable by design. However, that aerostability can then cause control problems. Co-rotation of the atmosphere combined with thermospheric winds, and changes in atmospheric density with varying solar activity, mean an aerostable satellite is rarely pointed perfectly into the flow causing time varying disturbance torques. Whilst conventional attitude control actuators, such as reaction wheels, can compensate for these disturbances at higher altitudes, the magnitude of these disturbances is proportional to atmospheric density, and lower in the VLEO range they may exceed the control authority of actuators. As such, aerodynamic control is required, most likely in combination with traditional actuators for fine pointing.

5 The special issue papers

This special issue contains 13 papers on a range of topics related to VLEO missions and technologies including mission designs and concepts, atmosphere-breathing electric propulsion, ground testing of materials, and the business environment for VLEO missions.

The mission designs and concepts session of the symposium presented mission designs addressing the commercial and scientific use of VLEO. The first paper by Berthoud et al. considers whether VLEO satellites are a solution for future telecommunications needs. Considering both the payload and the platform design, it demonstrates that constellations of VLEO satellites can provide a cost-effective way to deliver 5G direct access to handset data services. The second paper by McGrath et al. considers remote sensing services from VLEO, specifically for global mapping. The paper describes the Global Lidar Altimetry Mission (GLAMIS) which proposes a constellation of VLEO satellites with space-borne lidar, and demonstrates the significant potential cost benefits of operating at lower altitudes. A third paper moves on to science of, and within, the thermosphere. Siemes et al. describe the CASPA-ADM mission concept which aims to use cold atom interferometry, and other in-situ sensing technologies, to make thermospheric density observations within the VLEO altitude range.

Two papers then follow which are perhaps unique in that they present missions which have flown in VLEO and returned scientific data. The paper by Crisp et al. describes the Satellite for Orbital Aerodynamics Research (SOAR), and specifically the method it used to experimentally characterise the aerodynamic performance of materials within the thermosphere. Launched in June 2021 and re-entering the atmosphere in March 2022, the mission data are still being analysed. Whereas the fifth paper, by Reddy et al., explores the effects of spacecraft charging on a thermospheric plasma analyser flown on the Phoenix satellite launched in 2017.

There are then five papers which describe developments in atmosphere-breathing electric propulsion (ABEP), also known by alternative names in some of the papers such as RAM-EP. The first of these five, by Vaidya et al., explores novel mission scenarios enabled by the use of ABEP. These include not only missions which require drag compensation in Earth orbit, but also concepts that collect and store propellant for space tug missions, and even orbit maintenance around Mars. Four papers then follow on specific ABEP thruster developments. The first of these, by Romano et al., provides an overview of the ABEP work carried out to date in the DISCOVERER project. This includes the optimal design of aerodynamic intakes, the development and test of an RF helicon-based plasma thruster, and on-going activities to measure the performance of the thruster prototype. The next by Andreussi et al. provides an overview of activities within another Horizon 2020 project developing ABEP—AETHER [7]. This again covers the optimal design of intakes, but in this case focuses on adapting the design of Hall thrusters for use in VLEO, and in particular on the problem of developing alternative neutralisers. A third paper by Obrusnik et al. describes recent progress in the development of electron-cyclotron-resonance-based ABEP. The work primarily focuses on the design and modelling of the ioniser by a consortia of organisations including SpaceLabEU, PlasmaSolve, Brno University of Technology and the Czech Aerospace Research Centre (VZLU). Finally, in this section, Miya et al., describe work by JAXA on another electron-cyclotron-resonance plasma generator with ion optics. They detail the design, fabrication and performance testing of the generator.

Only one paper on facilities for environmental simulation of VLEO makes it into this special issue. The paper by Tagawa et al. details the adaption of their existing laser-detonation atomic oxygen source to include a second beam of hyperthermal molecular nitrogen, or argon as a proxy for nitrogen, as a way to explore the influence of the additional gas species on erosion.

Finally, two papers are included which explore the business environment relevant to VLEO missions. The first, by Rodriguez-Donaire et al., explores the strategic similarities between VLEO Earth observation constellations and low-cost airline carriers. Using the Strategy Canvas methodology, they find that the competitive factors that drove the drove the establishment of low-cost airlines, cost reductions, efficiency, utility and standardisation, are also driving the interest in VLEO EO. The second, also by Rodriguez-Donaire et al., presents a business roadmap for the European Union for access to space, with special consideration of the “New Space” ecosystem and including VLEO access. They present a list of recommendations to improve the competitiveness of the European market, the support the EU can provide and the projected benefits of that support.

6 What the future holds

Since 2017, when DISCOVERER commenced, there has been strong growth in interest in VLEO missions, technologies, and applications. This is perhaps most graphically captured in a simple graph of Google Scholar catalogued documents using the phrase “Very Low Earth Orbit” or the acronym VLEO (see Fig. 1). Another metric could be the number of new start-ups declaring expertise in VLEO technologies and platforms.

Regardless of the catalyst for this recent growth, it is clear that there is a growing community, within industry and academia, invested in the development of the VLEO regime for remote sensing, communications, and science applications. The 1st International Symposium on VLEO Missions and Technologies [8], was a key opportunity to bring this fledgling community together to find synergies, identify common ground and collaborative opportunities, create critical mass to encourage investment in technology development and demonstration from key stakeholders, and

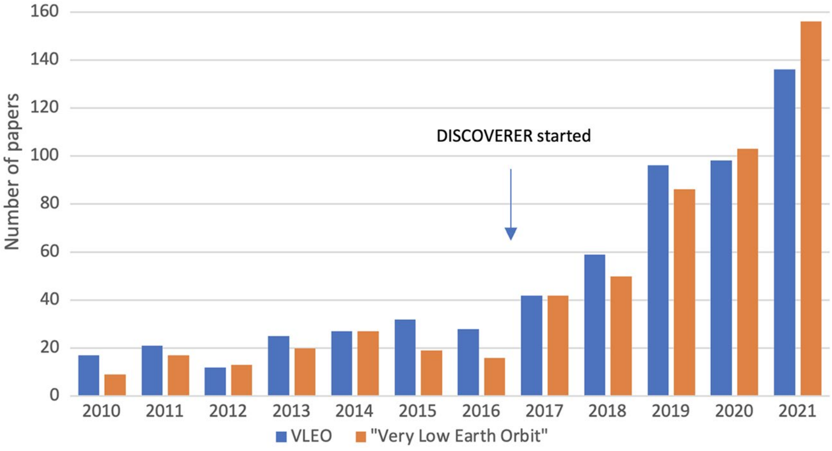

Fig. 1 Google Scholar papers using the phrases “VLEO” or “Very Low Earth Orbit” by year of publication showing the rapid year-on-year increase in publications related to VLEO since DISCOVERER commenced

place VLEO satellites on space agency and industrial technology roadmaps.

Why is this important? Low Earth orbit, similar to the geostationary ring, is a finite resource. Increasing use of the LEO altitude range above VLEO, especially for mega-constellations of communications satellites, poses a debris proliferation risk. Yet VLEO represents a sustainable alternative, with additional benefits, provided technology developments and demonstration can present its use as a commercially viable alternative.

One could imagine future where international policy dictated that VLEO was utilised for mega-constellations of communications and remote sensing satellites, safe in the knowledge that individual satellite failures would not add to the long-term debris population and jeopardise future operations. Such an approach would also reduce platform reliability requirements, further reducing cost. Rapidly reducing launch costs, driven by launch vehicle reusability, may also drive the need for this approach—as the cost to launch and replace satellites decreases, the number of satellites being launched is likely to increase along with acceptable failure rates. Limiting debris proliferation through the use of VLEO may, therefore, become even more important and urgent.

In such a scenario, higher LEO altitudes could then be reserved for crewed missions where debris collisions can represent a risk to life, and science where expensive monolithic satellites for astronomy are the norm. Of course, this would require a sustained effort to actively remove existing debris from these higher orbits.

Has the case been made such that market forces drive the further development and demonstration of VLEO technologies and platforms? The answer to this question is not yet clear. However, a coordinated approach by a VLEO community of interest, continuing to promote and highlight the benefits of using VLEO, and continuing to demonstrate the viability of the enabling technologies, can only help to move the field in that direction.

7 Conclusions

The development of a community of interest in VLEO mission and technologies has been demonstrated by the number of attendees and the level engagement at the 1st International Symposium on VLEO Missions and Technologies, and in the rapidly increasing number of documents using the phrase "very low Earth orbit" captured by Google Scholar. Forming this community is a first step in gaining wider support from key stakeholders for the development and demonstration of key VLEO technologies and their inclusion in technology roadmaps, as well as the development of supportive policy for the operational use of the VLEO altitude range for communications and remote sensing missions.

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