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VERY LOW EARTH ORBIT (VLEO): THE EMERGING BAND OF INTEREST IN SPACE

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INTRODUCTION

The domain of Outer Space has seen growing interest in recent years. This has been enabled by technological advancements and innovations and increasing space enabled applications across various civil, defence as well as commercial sectors. The most important developments have been the increasing demand for remote sensing data and the Low Earth Orbit (LEO) enabled communications. This has caused greater participation, leading to overcrowding of this belt of space. In this evolving landscape, Very Low Earth Orbit (VLEO) is emerging as an alternative orbital band of interest. The first use of this belt was by the U.S.' Corona reconnaissance satellites in the 1960s and early 1970s that operated at around 150 kilometres altitude and interestingly jettisoned their camera films back to Earth, which were then captured mid-air by aircraft, to be processed by intelligence analysts.

As with the lower boundary of space, there is no consensus on the exact band that constitutes the VLEO. This is because there is no clear demarcation in terms of physicality of the atmosphere/space that could delineate these bands. Except for the Corona programme, satellites in the LEO region were deployed above 500 kilometres to obviate multiple physical challenges experienced below this altitude. Therefore, VLEO is taken as the orbital area below approximately 450 kilometres altitude, with 100 kilometres above the Earth's surface broadly accepted as the lower boundary of space.

Spacecraft operating in the VLEO band could potentially provide significant benefits over those operating in LEO and manned and unmanned aircraft operating in near space regions. It could also help unlock new possibilities for military intelligence and communication operations. VLEO operations could potentially offer cheaper alternatives to the growing number of private initiatives in the domain, seeking commercial gains. There are attempts to overcome the unique physical and operational challenges that it presents through technological advances in miniaturisation, digitisation, materials and propulsion. In recent years, the European Union, U.S., Japan and China have all expressed their interest in VLEO, testing and demonstrating utilisation concepts.

ADVANTAGES OF VLEO

VLEO offers great advantages for both remote sensing and telecommunications missions, influencing technological features as well as functional characteristics.

- **Higher Resolution Imagery.** Physically, a reduction in orbital altitude improves the spatial resolution for a given electro-optical (EO) equipment. Alternatively, simpler instruments could achieve equivalent results, thereby enabling reduction in mass and size of the payload.[1]
- **Active Sensing.** Active sensing includes Synthetic Aperture Radar (SAR) and Light Detection and Ranging (LIDAR). For these, being closer to the target reduces the power requirements and improves the signal-to-noise ratio. Consequently, at lower altitudes, for a given power, the same spatial resolution can be achieved over larger swath widths, reducing the requirement of the number of satellites in a constellation for a desired coverage.[2]
- **Communication Efficiency.** Lesser distance between the satellite and terrestrial stations reduces the power requirements for communication.

This can be used to either lower the power demands or achieve higher data transfer rate at the same power, or a combination of both.[3]

- **Temporal Resolution.** A lower altitude results in smaller orbits and hence a better temporal resolution, (time between satellite reappearing over a given point). Hence, similar coverage can be achieved with lesser number of satellites. [4]
- **Lower-Latency Data Transfer.** Latency is the time taken between transmission of data from the source to reception at the destination. Lower latency has become an important requirement of modern satellite enabled communications (SATCOM). This has caused the recent race for LEO based SATCOM constellations that offer a latency of around 32 milliseconds, as compared to the close to 600 milliseconds provided by GEO based satellites. Even lower latency could be achieved by further lowering the orbital altitude of satellites to VLEO.[5]

Various studies have highlighted these advantages. One such study paper, sponsored by Thales Alenia Space in 2016 for its proposed Skimsats VLEO satellites explained, "The decrease of altitude, with respect to a 650 kilometres orbit, by a factor of four (around 160 kilometres) leads to a 64x reduction in radar RF power, 16x reduction in communications RF power and 4x reduction in optical aperture diameter to achieve the same performance. It also helps reduce the weight and cost of optical payloads by 50 percent while providing the same resolution."[6] The study also highlighted that at an operating altitude of 160 kilometres, the Skimsat platform can provide SAR and optical imagery at 1 m Ground Sample Distance (GSD) with a launch mass of less than 75 kilogram.[7]

Additional benefits that would impact space operations, applications and employability include:

- **Spacecraft Design and Manufacture.** Reduction in power requirements for sensing and communications also cuts into the requirements for large solar panels, positively influencing the spacecraft design and manufacture.

- **Access to Orbit.** Presently, satellites headed for VLEO are carried to LEO from where they manoeuvre to their planned orbits. As VLEO operations become more regular, dedicated launchers would deploy satellites at their designated orbits, enabling saving on precious onboard propellant. Involving shorter flight times and having lesser gravity losses to be overcome would allow usage of smaller launch vehicles or permit more satellites to be delivered per launch to orbit,[8] enhancing the commercial viability.
- **Self-Cleaning Orbits.** Growing participation in space has contributed to orbital crowding in the LEO. At the same time, low cost, mass production of satellites coupled with cheaper launch alternatives, has eliminated the requirement of longevity of deployment. Space overcrowding and orbital debris have been identified as major challenges to safety and sustainment of space operations by all major space faring nations. The Inter-Agency Space Debris Coordination Committee's (IADC) "Space Debris Mitigation Guidelines" is an international regulatory document on space debris mitigation, based on consensus among the IADC members (space agencies of all major space faring nations, including ISRO). These include the capability for end-of-life manoeuvres for de-orbit or towards graveyard orbits to ensure efficacy and safety of future missions. VLEO not only provides an alternate orbital space, but also the advantageous characteristic of auto-cleaning. All spacecraft placed in VLEO orbits and the orbital debris created as part of their deployment and operations are exposed to relatively higher degree of gravitational pull and atmospheric drag. They will more easily undergo orbital decay at the end of their operational life, with eventual burn up on re-entry, keeping the orbit clean for future missions. The self-cleaning characteristic of the orbit also obviates the requirement of carrying additional propellent for end-of-life de-orbit manoeuvres, with associated cost savings in terms of propellent weight and launch costs.
- **Radiation.** Satellites operating at these altitudes face a more benign radiation environment, reducing the requirement of satellite hardening

and allowing the use of commercial off the shelf (COTS) components.[9] This would lower the complexity of production and reduce the costs and developmental timelines.

- **Advantage over Near Space Operations.** VLEO based constellations score over UAVs and airships operating in Near Earth Space, as they can overfly all regions of the Earth without any regulatory restrictions, covering significantly larger areas with more persistence. They are less vulnerable to terrestrial weapons and offer redundancy due to numbers.[10]
- **Satellite Enabled Communications (SATCOM).** LEO enabled satellite communication is already seeing much interest owing to the benefits it offers in terms of lower latency, reduced electromagnetic propagation losses, lesser power requirements and lower production and launch costs, when compared to GEO enabled telecommunications. These advantages have made SATCOM being considered as an important component of 5G-Advanced and 6G networks of the global communications ecosystem that envisages integrating terrestrial and non-terrestrial networks to achieve economies of scale, wider global utilisation and cost-effective services.11 Commercially, these communications would be critical for emerging use cases such as autonomous vehicles, smart cities, smart homes, human-computer interaction, smart manufacturing and industrial Internet of Things.12 Militaries are especially showing interest in these for providing reliable connectivity and broadband services in remote and dispersed deployments and while on the move and for pursuing futuristic concepts like Internet of Military Things (IoMT) that would require incessant, ubiquitous, low-latency, automatic real-time information sharing. Reducing altitudes further to VLEO would add onto the contributory advantages, even as technologies developed for LEO based constellations, such as high-quality pointing subsystems, could be effectively utilised for VLEO constellations with some upgradations/ modifications.
- **Better Turnaround.** Presently, satellites once deployed cannot be serviced or upgraded. This has become an operating challenge in an environment

where technology is upgrading faster and becoming obsolete sooner. Shorter orbital lives would allow replacement by satellites with latest hardware and software, improving upon the performance and services.

Challenges. Operations from VLEO have not yet achieved maturity owing to several challenges that need to be overcome towards reliability, safety and profitability.

- **Constellation Numbers.** A lower altitude comes with a penalty of decreased instrument swath width for EO instruments and lesser ground coverage for communication satellites, necessitating more satellites in a constellation to achieve the desired regional or global coverage.
- **Platform Stability.** Operating in residual atmosphere could cause aerodynamic perturbations reducing platform stability and adversely affecting missions that require stable attitudes for precise pointing of instruments.
- **Ground Stations.** Shorter orbital periods at lower altitudes would reduce the communication window available over a ground station, impacting data transfer and tracking. A VLEO constellation would thus require more globally widespread ground station network to support its operations.
- **Propulsion Systems.** Unlike satellites deployed to LEO and GEO that require little or no propulsion to maintain orbit, satellites in VLEO would require onboard propulsion, with sufficient propellent for providing continuous or periodic thrust, to overcome atmospheric drag and higher gravitational forces to achieve a practicable operational lifespan. Fuel consumption would also increase exponentially as orbits get closer to the Earth. In the VLEO belt itself, an increase in altitude of the International Space Station (ISS) from 350 kilometres to 400 kilometres in 2011 reduced the average fuel consumption from 8,600 kilogram per year to 3,600 kilogram per year.[13]
- **Satellite Design.** Conventional satellite designs of a large square object with huge solar panels would generate significant drag in VLEO, making it unsuitable for operations.

- **Knowledge of Lower Thermosphere.** The atmospheric drag in the lower thermosphere belt varies diurnally and is affected by solar radiation.[14] This makes it difficult to predict operating conditions and programming satellite handling accurately.
- **Atomic Oxygen.** Satellites in VLEO are exposed to very high levels of elemental oxygen, also known as atomic oxygen (AO), a highly reactive form of oxygen that corrodes most substances quickly. It is estimated that at some VLEO bands, up to 96 percent of the atmosphere is AO.[15] This has remained one of the main limiting considerations for utilising these altitudes.
- **Regulations.** The very nature of VLEO may require adaptation and even modification of launch and operating licensing procedures to account for its inherent features and their impacts on space activities.[16]

Evidently, making operations in this band viable would require constant efforts to balance the advantages and challenges, for achieving meaningful orbital lifetimes whilst minimising spacecraft size, mass and complexity. Designers and engineers would require calculation of optimal altitudes that best balance the savings in terms of payload and reduced number of spacecrafts in a constellation for achieving the mission goals and the increased mass related to addition of the propulsion and electrical systems. Success would depend upon the developments in enabling technologies and applications that would allow development of satellites and systems optimised for operation VLEO.[17]

ENABLERS

- **Spacecraft Design.** Novel aerodynamic designs that combine smaller size and more streamlined shapes for drag reduction are being explored. Aerospace Corporation, a U.S. based company, is testing DiskSat, a satellite shaped like a plate with onboard thrusters to keep it upright.[18] Stingray, another satellite being developed in the U.S., envisages a 'space shuttle' styled bus, with solar panels on the wing structures.[19] The residual atmosphere has also allowed designers to envisage control surfaces for aerodynamic attitude and orbit control methods. These would enable better spacecraft control and limited manoeuvrability for drag reduction in a variable atmosphere and for end-of-life de-orbit manoeuvre.[20]

- **Propulsion.** Operations in VLEO are being envisioned through the development of smaller, lightweight and efficient engines utilising different concepts for propulsion.
  - **Solar Electric Propulsion (EP).** These systems utilise electrical energy to accelerate charged particles through controlled nozzles to generate thrust. Being pursued for decades, some of the methods have now achieved maturity and are gaining traction as the propulsion of choice for commercial satellites being deployed in LEO, including the Starlink constellation.[21] These systems have a higher propellant efficiency (more thrust per unit of propellant), thereby reducing the requirement of fuel to be carried at launch.[22] Although presently limited in the amount of thrust that they can generate, they can provide it more consistently and precisely over extended periods, making them suitable for smaller spacecraft operating in regions requiring persistent thrust. They do however present challenges in terms of complexity of design, testing, reliability and scalability. A major shortcoming of EP for VLEO operations is the high electric power requirements, necessitating larger solar arrays, with the associated drag penalty. New propellants, such as water or air, are also being pursued to reduce cost and environmental impact.
  - **Atmosphere-Breathing Electric Propulsion (ABEP).** In addition, the residual atmosphere in VLEO band offers opportunities to develop and utilise novel atmosphere-breathing electric propulsion (ABEP) systems, thrusters that absorb the surrounding air and generate plasma from it to be used as the propellent. Using just air and solar power for this process would greatly reduce the mass and volume of fuel to be carried at launch. However, the power consumption of such engines is likely to be high for per unit of thrust,[23] requiring greater

solar power generation and storage capacity. Improvements in solar power generation and storage capability are helping overcome challenges related to these propulsion systems.

- **Materials.** Advanced lightweight and durable materials and coatings that could help reduce drag and protect from AO corrosion are being developed and tested. Success in these would provide a further impetus to regular use of VLEO belt.
- **Commercial Exploitation.** Lowered cost of access to space is democratising the domain and has resulted in more private initiatives seeking novel spaces and technologies for commercial gains. This has spurred growth in the sector through investments in technology development, innovative applications, increased use cases and establishment of supportive ecosystems. Investments seeking cheaper alternatives would help generate ideas to bring down the launch costs and the complexities related to this band.

GLOBAL EFFORTS

Recent years have seen a growing global interest in VLEO, both by governments and private enterprises for scientific, military and commercial applications.

EUROPE

The interest in VLEO was first demonstrated in 2009, with the launch of European Space Agency's (ESA) Gravity Field and Steady-State Ocean Circulation Explore (GOCE), a scientific satellite designed to take accurate measurements of the Earth's gravitational field.[24] It demonstrated a sustained orbit between 250 and 300 kilometres for three years from 2009 to 2013, with the help of xenon-fuelled electric thrusters. [25]

The European Union has devoted 5.7 million Euros ($6.7 million) to Discoverer, a Horizon 2020 research program aimed at a "radical redesign" of Earth observation satellites for low-altitude operations.[26] University of Manchester's Rarefied Orbital Aerodynamics Research is being used to test materials for drag reduction. In-orbit tests were carried out on its Satellite for Orbital Aerodynamics Research (SOAR), a CubeSat deployed from the ISS on 14th June 2021 into a naturally decaying orbit, finally deorbiting on 14th March 2022. Using a set of steerable fins that allowed attitude changes, it tested aerodynamic performance of different materials at VLEO altitudes.[27] It also made measurements of atmospheric properties at these altitudes.[28]

In July 2022, the ESA awarded the Skimsat program, which aims to reduce the cost of Earth observations by operating in VLEO, to Thales Alenia Space and Redwire Space. Funded under ESA's Discovery Preparation and Technology Development (DPTD) activities, Thales Alenia Space, along with QinetiQ Space team in Belgium, carried out an exhaustive study for VLEO operations.[29]

In October 2023, the ESA launched a 'Call for Ideas' towards exploring and exploitation of VLEO – seeking new and innovative solutions to take advantage of the unique characteristics of VLEO and to mitigate the challenges. These include technology development activities specific to VLEO, such as atmospheric-breathing propulsion, protective materials and coatings, navigation and control. Ideas related to re-entry and possible re-use of space assets have also been included.[30]

JAPAN

Japan Aerospace Exploration Agency (JAXA) operated its Super Low Altitude Test Satellite (SLATS) from 2017 to 2019. The satellite, powered by xenon-fuelled electric thrusters, operated at seven different altitudes, decreasing from an initial altitude of 630 kilometres to 167.4 kilometres, for testing purpose.

UNITED STATES

In the U.S., the efforts are being led by private enterprises, supported by the government. In 2016, U.S.' private company Skeyeon, filed the first VLEO satellite patent on a propulsion system using a self-sustaining ion engine. The company, which seeks to provide high-resolution daily Earth imagery from VLEO, now has seven U.S. patents across satellite designs, materials, satellite communications and air breathing propulsion.[31] The company claims to have identified promising sample materials in a dedicated AO test facility and these are now being tested on an exterior ISS platform.[32]

Albedo, a U.S. based start-up, is developing a VLEO constellation with an aim to collect 10-centimetre optical imagery and 2-metre thermal infrared imagery. The technology is eliciting interest and the company has been able to garner a total funding of $97 million.[33]

Earth Observant (EOI) is developing a VLEO Earth-imaging satellite with a contract from U.S. Air Force that seeks a capability of collecting 15-centimetre-resolution imagery and transferring data "directly to the warfighter" in minutes.[34] The first satellite in the 'Stingray' constellation is planned for launch in 2024, with an aim to deploy six satellites to VLEO by the end of the year. This is expected to upscale to a 60-satellite constellation with multispectral (MS), near-infrared (NIR) imagers, for both government and commercial use. Operating at an altitude of 250 kilometres utilising electric propulsion, the constellation is expected to have a 10-to-15-minute revisit period.[35] They will also make use of on-board computing (edge computing) to improve latency.[36]

CHINA

As with much of its space program, China has defined the roadmap for developing its capability in the VLEO space, with commensurate investments. Its 14th Five Year Plan (2021-2025) has proposed building a remote sensing space infrastructure system with global coverage and efficient operation, and VLEO is an important component of this infrastructure.[37] It has already gained some experience of this band of space, through its space stations. (Its Tiangong-1 and Tiangong-2 space stations orbited at an average altitude of 355 kilometres and its main space station Tiangong operates between 350 and 450 kilometres). As with its other developments in the domain, it is supporting and encouraging its commercial space sector to develop technologies and enabling sustainable supply chains and ecosystems.

An experimental Chinese satellite Tianxing-1 was launched in June 2022, which maintained an orbit of around 300 kilometres before its orbit continually decayed over a month. Analysts have speculated that one of the tasks for the satellite could have been technical verification tests for VLEO.[38] Its Shiyan 25 (SY-25) launched in June 2023 has now sustained operations at an altitude of around 275 kilometres since early Sept 2023.[39] CSPACE, a private Chinese company, is developing Qiankun (QK) series satellites for operating in VLEO for remote sensing and telecommunication. Its first experimental satellite, QK-1 was launched onboard China's commercial launch company, Galactic Energy's Ceres-1 solid fuel rocket in July 2023.[40] It has continued its slow descent and was last reported operating at around 350 kilometres.[41]

Senior officials of its Second Academy of the China Aerospace Science and Industry Corp (CASIC), a state-owned space contractor, made statements in diverse forums in March[42] and July[43] 2023 about its interest in VLEO. As per CASIC, its first prototype VLEO satellite had already emerged from the design and production phase in July 2023.[44] Although the launch planned for December 2023 has been delayed, once in orbit, the satellite is planned to study the VLEO environment and demonstrate and verify VLEO orbital flight and key technologies, including high-resolution ground imaging technology, onboard intelligent processing and direct data transmission to user terminals.[45] Subsequently, the company plans to have a nine-satellite constellation for service verification and demonstration in orbit by end 2024. The operational constellation is expected to have a network of 192 satellites in orbit by 2027, further upscaling to 300 satellites by 2030, for both communication and remote-sensing services.[46] According to Zhang Nan, chief designer of the constellation, the constellation will achieve 0.5-metre spatial resolution and transmit spatial information to users within 15 minutes.[47]

Chinese VLEO efforts are going to benefit from the advances made in electric propulsion. Premier government institutes that have developed electric propulsion systems are Shanghai Spaceflight Power Machinery Institute, the Centre for Space Science and Applied Research (CSSAR) under the Chinese Academy of Sciences and the Lanzhou Institute of Physics.[48]

The most significant development has been the scaled-up ion thrusters being used on its Tiangong space station, which has allowed substantial mass saving on fuel when compared to the ISS which uses conventional propulsion. Kongtian Dongli, a Chinese company established in March 2022, is developing Hall thrusters and microwave electric propulsion systems to power future spacecraft.[49]

SPAIN

A Spanish company, Kreios Space, is developing an ABEP system for VLEO satellites.[50] In December 2023, it signed an agreement with Elecnor Deimos, a space engineering company, to jointly develop and commercialise the world's first commercial satellite designed to operate indefinitely in VLEO.[51]

INDIA

India also needs to add VLEO into its list of future initiatives to exploit its benefits and contribute to the overall capability and capacity building in the domain. Technology pursuance and advancement by Indian Space Research Organisation (ISRO) in recent years is encouraging. For example, it first demonstrated an EPS system onboard its GSAT-9 launched in the year 2017[52] and is now gearing up to demonstrate the use of an indigenously built EPS (developed by its Liquid Propulsion Systems Centre) on board a Technology Demonstration Satellite (TDS-01), expected to be launched in the second half of 2024.[53] Recent policy enablers have energised Indian private sector participation in the domain, but most new players are looking at commercial gains by exploiting contemporary capabilities. Operationalising this belt would require focussed efforts in novel technologies, design and materials and this would be best served through collaborative research and development involving ISRO, academia and 'new space' industrial communities. However, emphasis should be on standardisation and interoperability for seamless integration into the information and communication networks.[54]

For the armed forces, operations in this band have the potential to significantly contribute to improving the quality and quantity of imagery and speeding up the information flow for C4ISR and other applications, thereby contributing to the shortening of the OODA loop. Dedicated or dual-use VLEO operations could initially supplement the existing and more mature LEO-based and Near Space capability, utilising an optimum combination of platforms and altitudes (including UAVs, near space platforms and aircraft) to achieve the best end products or communication extent.[55]

China's Civil Military Fusion strategy would support exploitation of the dual-use potential of the capability developed and have implications for its military operations in far-flung, remote and dispersed areas, including those of its Western Theatre Command. Chinese developments in this belt of space need to be continuously monitored for formulating a comprehensive capability picture and response options.

CONCLUSION

VLEO is emerging as a promising space mission regime to supplement imaging and communication services and to contribute to the sustainability of outer space operations by mitigating the threats related to overcrowding and space debris. Most capabilities that are required for overcoming technical and economic challenges of this belt are still in their nascent stages and would take a few years to fructify and operationalise. Technology development would need constant study and addressing of issues specific to understanding of the lower thermosphere and its variable aerodynamic drag and AO corrosion. The armed forces need to study how VLEO missions could contribute to their capability enhancement, offer novel applications, and shape the dynamics of space defence strategies. Efforts would benefit from a defined plan, such as that laid out by China, for achievement of timebound goals. In pursuance of VLEO operations, it is pertinent to highlight that the success of applications like reusable rockets and LEO enabled communication constellations had faced much scepticism from established space farers in the past. With SpaceX now reaping the first comer advantage, the same organisations are now striving hard to catch up.

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