HOW LOW CAN YOU GO: ADVOCATING VERY LOW EARTH ORBIT AS THE NEXT FRONTIER FOR SATELLITE OPERATIONS

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ABSTRACT

Our paper will examine the prospect of greater utilisation of Very Low Earth Orbit (VLEO) for commercial and government satellite operations, particularly those utilising small satellite form factors, and suggest technical adaptations necessary to achieve it. An increased proportion of satellite activity in VLEO will reduce crowding in higher orbits, thereby lowering the risk of conjunction events and militate against further space debris accumulation by encouraging operations in a high atmospheric drag region that naturally enables rapid deorbit. In addition to the environmental benefits endemic to VLEO, operators will also be able to avail themselves of a wide range of commercial and operational benefits. In this paper, we will examine these benefits, as well as the requisite technical capabilities necessary to successfully operate in VLEO, and provide a detailed look at legal considerations and implications for regulation.

1. INTRODUCTION

Very Low Earth Orbit (VLEO) is the region between 100-450 kilometres in altitude. Operating within this region confers a number of benefits to both private and public sector satellite operations, including drastically reduced payload power draw and improved signal-to-noise ratios for synthetic aperture radar, enhanced resolution for optical imaging, and lower latency for satellite communications. VLEO is also, in effect, a ‘self-cleaning’ region of space, owing to the high amount of atmospheric drag which is capable of naturally deorbiting most space objects within weeks. It is also significantly easier, and hence cheaper, to insert payloads into VLEO instead of higher, more conventional orbits. Therefore, operating in VLEO represents a business-positive means for satellite operators to strengthen their value propositions through reduced operational costs and improved payload function, while at the same time mitigating the impact of increased satellite activity on the orbital environment. An increased proportion of satellite activity in VLEO will therefore reduce crowding in higher orbits, thereby lowering the risk of conjunction events and militate against further space debris accumulation by encouraging operations in a high atmospheric drag region that naturally enables rapid deorbit. In addition to these environmental benefits, operators will also be able to avail themselves of a wide range of commercial and operational benefits.

Our paper’s proposition arises from the confluence of several emerging trends, including the recent rapid increase of satellite activity in Low Earth Orbit (LEO) with constellations such as Starlink, the industry-wide shift toward small satellites with form factors below 500kg, and the consequent crowding of conventional orbits resulting in a heightened risk of in-orbit conjunction events.

In this paper, we will consider the environmental, operational, and economic benefits of greater VLEO utilisation. We will also consider the requisite technical capabilities necessary to successfully operate in VLEO, and provide a detailed look at legal considerations and implications for regulation.

2. ENVIRONMENTAL BENEFITS OF VLEO UTILISATION

Operation in VLEO has the potential to solve one of space’s greatest environmental problems: the accumulation of space debris. In VLEO, the atmospheric drag is so high that objects of all sizes de-orbit on a timescale of mere weeks to months, as opposed to years in higher orbits. While many satellites today choose to perform a deorbit manoeuvre at the end of their life, there is no way to also remove accidental emissions from satellites, such as parts and particulates expelled when a satellite explodes and which keep flying along the same orbit, spreading into a dangerous cloud.

We will now examine how the increased atmospheric drag can be calculated and related to faster deorbit times.

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2.1. Estimating Drag

The region of the upper atmosphere that VLEO is a part of is ever-changing, and is heavily influenced by solar activity. The resulting differences can be quite large: in 2009 ESA launched the Gravity Field and Steady-State Ocean Circulation Explorer observation satellite (GOCE), which was intended to fly at a 255km altitude for 20 months. However, because of favourable solar activity, the upper atmosphere provided much less drag, and the mission actually lasted for 55 months, spending the last 11 months at an even lower altitude of 235km [4]. There is no way to analytically model this sort of atmospheric behaviour. However, we can establish the minimum drag force that a satellite will experience – the aerodynamic drag – using the well-known drag equation:

$$F_D = \frac{1}{2}\rho u^2 C_D A \tag{1}$$

where F_D is the drag force, $C_D$is the drag coefficient, A is the frontal area of the satellite, ρ is the atmospheric density, and u is the velocity of the satellite.

It can be seen that C_D and A depend on the build of the satellite (which we will term shape contribution), while ρ and u depend on its orbit (which we will term orbit contribution). Separating these two components in Tab. 1 below, we can observe the drag forces experienced by the GOCE mission, and easily substitute it with a satellite of a different design to understand how it might fare. For GOCE, C_D= 0.5 and A = 12.2, giving 6.1.

Table 1: GOCE data from [1] and [2]

altitude (km)	Orbit contribution	Shape contribution of GOCE	Drag force (N)
100	1.404E+00	6.1	8.563908
150	5.576E-02	6.1	0.340128
200	8.186E-03	6.1	0.049935
235	2.991E-03	6.1	0.018246
250	2.016E-03	6.1	0.012296
300	5.972E-04	6.1	0.003643
350	2.048E-04	6.1	0.001250
400	7.525E-05	6.1	0.000459
450	2.921E-05	6.1	0.000178
500	1.198E-05	6.1	0.000073
1000	1.26E-07	6.1	0.000001

What can be seen is that drag significantly increases below 250km, going above 10mN for the first time. This means that the deceleration caused by the drag force at altitudes below 250km is therefore sufficient enough to de-orbit satellites within a timespan of weeks to months. This is because as the altitude of the satellite drops the atmospheric density increases and its gravitational potential energy is converted into increased velocity, leading to an exponentially increasing drag force from Eq. 1 as time goes on. This leads to the satellite spiralling downwards faster and faster over time.

Additionally, seeing that deceleration is the drag force divided by the objects mass, and the drag force is proportional to area, the deceleration is proportional to a ratio of object's area to its volume. In other words, the smaller the dimension of the object the greater its deceleration due to drag, meaning that even smaller parts and particulates from accidental emissions will be de-orbited even faster.

Therefore, VLEO functions as a range of de facto 'janitor orbits' since they are essentially self-cleaning. Even in the presence of a full-on Kessler cascade, any debris present in VLEO would decay rapidly through the natural operation of the region's inherent traits, meaning that any satellite assets in that region would still be protected. Since this debris-resilient property is a feature of the natural environment in VLEO and not due to any technological capability, these janitor orbits should be able to maintain their resilience for millennia to come.

3. OPERATIONAL AND ECONOMIC BENEFITS OF VLEO

Broadly speaking, the main advantage for satellite operators is that smaller, lighter platforms using less expensive payloads flying in VLEO can match the performance of larger, heavier platforms using more expensive payloads flying at conventional LEO altitudes [9]. This offers satellite operators an opportunity to reduce costs on their satellite constellations and thereby offer a more competitively priced service to customers. Alternatively, the same platform with the same payload can be moved from LEO to VLEO , thereby increasing the value gained from said platform and improving the competitiveness of their value proposition to customers. In addition to this, there are certain benefits of VLEO that are cross-applicable to all operations in that region, regardless of specific application. However, it must be noted that the environment also has significant drawbacks, which are noted in the next section. The environment in VLEO also necessitates novel technologies, modifications to satellite platforms such as streamlining, and new control methods [10].

3.1. Benefits of operating in VLEO

The main applications that benefit from operating or being placed in VLEO can roughly be divided into:

1. Earth Observation;
2. Telecommunications; and
3. Space habitats.

Additionally, there may be other applications that we have not listed here that may benefit from VLEO, and potentially even applications that are only enabled by VLEO. We will also consider the application-independent benefits of VLEO operations, which apply to all of these categories and many more besides.

3.1.1. Earth observation

Earth Observation refers to the surveillance of the Earth's surface from space across a broad range of wavelengths, with the two main categories being optical imaging and radar imaging.

Consider an optical imaging satellite orbiting at a standard LEO altitude of 1000km being lowered to an operational altitude of 250km. This would decrease the Ground Sampling Distance (GSD), which is the distance between pixel centers measured on the ground, of the image, and proportionally increase the spatial resolution, as spatial resolution is inverse to GSD [11].

The GSD of an optical imaging system is given by the equation below:

$$GSD = \frac{pR}{f} \tag{2}$$

where p is the pitch of the optical sensor, R is the distance to the target i.e. the orbital altitude, and f is the focal length of the sensor. We can therefore see that since spatial resolution is inversely proportional to the altitude, decreasing the orbital altitude by 4x increases the spatial resolution by 4x.

Alternatively, if the operator wanted to reduce the cost and mass of their payload while preserving the same resolution, the quality of the optics could be reduced, or the size of the aperture could be minimized. Since the cost of optics grows exponentially with size, this would make for significant cost-savings. Since the size of the satellite is generally fixed by the size, mass, and power requirements of the payload, a smaller and lighter satellite platform can then in turn be utilised, leading to lower launch and in-space transportation costs for it.

Furthermore, the signal-to-noise ratio (SNR) of the optical payload will also be improved. Signal-to-noise ratio (SNR) is the ratio between the desired information or the power of a signal and the undesired signal or the power of the background noise [12]. The power density for optical imaging is given by the expression:

$$P \propto 1/r^2 \tag{3}$$

with P being the power density of the signal, and r being the distance to the source, in this case the surface of the Earth. Since r would then be reduced by 4x, P and hence the SNR would increase by 16x.

Alternatively, the cost and mass of the payload and satellite could again be reduced by using a smaller, lighter, cheaper, and less sensitive sensor, which would lead to cost and mass savings on the satellite and the launch vehicle.

Now consider a synthetic aperture radar (SAR) satellite [13] once again orbiting at 1000km, and being shifted down to 250km. There would again be a 4x decrease in the GSD, and therefore a 4x increase in the spatial resolution, as per Eq. 2. Alternatively, if the satellite operator wished to keep the resolution of the SAR satellite constant, then a smaller, lighter and cheaper radar dish and instruments could be used. This would lead to a smaller, cheaper and lighter satellite platform, and again, lower launch costs for the platform.

Lowering the operational altitude of SAR satellites also improves the SNR. Since SAR works via bouncing a signal off of the Earth's surface, the performance gain is even greater. Using the well-known radar equation [14]:

$$R = [\frac{P_t G_\sigma A_e}{4\pi^2 P_r}]^{\frac{1}{4}} \tag{4}$$

where R is the range to the target i.e. the surface of the Earth, P_t is the amount of power transmitted by the radar transmitter, G_{Sigma} is the gain of the antenna, A_e is the effective aperture, and P_r is the power received by the radar.

Rearranging,

$$SNR = \frac{P_r}{P_t} = \frac{G_\sigma A_e}{R^4} \quad (5)$$

Therefore, decreasing the range i.e. the orbital altitude by 4x would lead to a 256x improvement in SNR. In other words, the radar image would become 256x times clearer.

Again, a smaller and lighter radar antenna with less sensitive instruments could be used instead, leading to a smaller, cheaper and lighter satellite platform, and also attendant lower launch costs.

3.1.2. Telecommunications

For telecommunications purposes, VLEO would enable a smaller and lighter radar antenna with less sensitive instruments to be used instead, leading to a smaller, cheaper and lighter satellite platform, and also attendant lower launch costs.

When it comes to telecommunications applications, we are mainly discussing satellite internet and Internet of Things and Machine-to-Machine (IoT/M2M) satellites and constellations. The main advantage of VLEO operations for telecommunications is lower latency. This is generally a boon for consumer internet, and is also important for IoT, due to the need for devices to communicated with each other on a constant basis. We find that the time taken for a round-trip signal is given by,

$$t = \frac{2h}{c} \quad (6)$$

where t is the time taken for a signal in seconds, h is the orbital height in metres and c is the speed of light in metres per second. Note that this is simply the time taken while the signal is travelling through space.

For a satellite at 1000km, the time the signal takes for a round-trip signal is,

$$t = 2 \times \frac{10^6 m}{3} \times 10^8 ms^{-1} \quad (7)$$
$$t = 6.67ms$$

For a satellite at 250 km, the time the signal takes for a round trip is,

$$t = 2 \times 2.5 \times \frac{10^5 m}{3} \times 10^8 ms^{-1} \quad (8)$$
$$t = 1.67ms$$

As shown, there is a latency reduction of **5ms** for the telecommunications satellite, a significant decrease especially for certain niche applications, as well as for IoT.

Operating in VLEO also results in significant improvements in communications link budgets. Broadly speaking, a link budget is an accounting of all the power gains and losses that a communication signal experiences in a telecommunication system, from a transmitter, through a communication medium, to the receiver. It can also be used as a design aid to ensure that the information is received appropriately with a signal-to-noise ratio that is intelligible [15].

The power lost during transmission is known as the free-space path loss. This is expressed by,

$$FSPL = 20 \times \log(d) + 20 \times \log(f) + 92.45 \quad (9)$$

where d is the distance in kilometres, f is the frequency in GHz, and FSPL is given in dB.

The free-space path loss for a satellite at 1000km is given by,

$$FSPL_{1000km} = 20 \times \log(1000) + 20 \times \log(f) + 92.45 \quad (10)$$

The free-space path loss for a satellite at 250km is given by,

$$FSPL_{250km} = 20 \times \log(250) + 20 \times \log(f) + 92.45 \quad (11)$$

Then, the decrease in free-space path loss is given by,

$$FSPL_{diff} = 20 \times \log(1000) - 20 \times \log(250) = 12.04dB \quad (12)$$

3.1.3. Space Stations

Since there is at least an order of magnitude less space debris at lower altitudes, the risk of a collision with errant space debris is much lower. This means that any space habitats at these altitudes would be much safer for their human habitants.

Because of the thicker atmosphere in VLEO, any space stations operating in that region will also be exposed to much less radiation, again making it safer for their human inhabitants.

Alternatively, for short-lived space habitats where longevity is less of an issue, it is possible to take advantage of the lowered collision risk, and use less expensive shielding for said space habitat. The same principle would apply to radiation dosage, meaning that less investment in radiation shielding and other similar protective measures would be required.

3.2. Application-independent benefits of VLEO

Firstly, the lowered de-orbit time and the fact that cheaper payloads with shorter lifetimes can be deployed in VLEO, means that satellite operators have an opportunity to refresh their technology on a regular basis. This means that there is more of an opportunity to keep up with market and technological trends, allowing for greater adaptability and flexibility. Whereas a traditional systems engineering architecture in VLEO would update roughly every 5 years or so, a satellite constellation in VLEO using a fractionated approach would update once every 12 to 18 months. It is also possible to have even shorter update times on the order of a few weeks or a few months, and to launch satellite assets into orbit as needed.

As with space stations, lowered collision risks due to the presence of less space debris means that there is lower collision risk across the board, which is a significant advantage regardless of application.

Lowered radiation exposure is also an advantage for other applications, as it allows commercial-off-the-shelf (COTS) technologies to be used that would not be possible in higher orbits. Plus, the lower radiation exposure means a longer lifetime for any satellite assets in orbit.

4. REQUISITE TECHNICAL CAPABILITIES

The VLEO environment requires some adaptation from the usual orbit correction devices that satellites employ. For some satellites, simply repurposing existing technology will suffice. For other satellite sizes, it is worth exploring other propulsion technologies altogether, such as air-breathing engines or electrodynamic tethers. This section explores the aspects of orbit correction that need to be considered and compares several solutions.

4.1. Orbit correction

Orbit correction needs to compensate for forces acting on the satellite in all 3 dimensions. Aerodynamic drag, as already calculated in this paper, mainly decelerates a satellite in the direction of its motion, but even if it was a perfectly straight flow, the boundary layer created between the satellite and fluid would give rise to minor forces in other directions that displace the satellite laterally and vertically. This changes not only the orbit's velocity, but also the inclination and direction of the periapsis. Random atmospheric winds also have the potential for significant displacements in these directions.

The frequency of orbit corrections is dependent on the individual mission. Speaking generally, most would probably want to comply closely to the planned orbit, but based on the European Space Agency's Aeolus satellite that is currently flying at 320km, a correction once every week could suffice [3]. This is beneficial when the form of propulsion used interferes with the mission instruments, e.g. very precise observation is needed but firing the thruster adds minor vibration that reduces the precision. Other missions might prioritise eliminating accelerations and decelerations, for example when measuring gravitational field strength, as in ESA's GOCE, in which case thrust should be firing as constantly as possible, precisely matching drag at all times to maintain a constant orbital velocity [4].

These three-dimensional aerodynamic forces mentioned are also able to rotate the satellite, which, if there was no correction to the attitude, once rotated would present an asymmetrical face to the oncoming flow and strongly increase the size of lateral forces, worsening the displacements. There is a chance to explore new forms of attitude controls reliant on the presence of aerodynamic forces – for example, with an aerofoil shape which, like an airplane, experiences a moment that brings the aerofoil back to an equilibrium attitude. This is employed in both GOCE and Bacon & Olivier's Skimsat concept [5].

It is clear that what the orbit correction process needs to match is not the instantaneous drag forces on a satellite, but rather the overall impulse that drag presses on the satellite, that is to say the integration of force over time. It is beneficial to have a thruster with built-in redundancy capabilities in case upper atmospheric conditions change, or a particularly strong wind displaces the satellite by a large amount. To correct this instance, the thruster should either be rated to output more force when needed, or be chosen for non-continuous operation, and therefore have additional time to fire to make up for any strong displacements.

Any candidate stationkeeping technology must be able to successfully perform these outlined tasks, in addition to further evaluation on performance in two categories: mass budget and power budget.

4.1.1. Mass budget

Perhaps the most common limiting factor in space missions is mass budget, which in this context means what additional mass a satellite has to take on in order to perform its desired mission in VLEO as compared to a conventional LEO orbit. It should be noted however that it is also possible for VLEO to allow for a significant reduction of mass, because as explained prior, simpler equipment can be used to achieve the same resolution as at a higher orbit, thereby saving mass [5].

The features that are likely to increase mass in adapting a satellite for VLEO operation are additional propellant, bigger propellant tanks, and if applicable, the additional stationkeeping device and aerodynamic features such as wings or atomic oxygen shields.

4.1.2. Power budget

The amount of electric power consumed by the stationkeeping device is another key consideration since there is only a limited amount available from a satellite's solar panels. A thruster that operates almost constantly might especially be an issue as the satellite will need to power it as well as its usual systems and instruments, and it may consequently require a bigger array of solar panels. In this case a thruster that fires rarely is preferred as it may allow for the substitution of instrumentation power as a power source. If a satellite is not in a sun-synchronous orbit where it has constant exposure to the sun, but instead goes through periods of light and darkness, additional battery capacity may be needed.

4.2. Candidate Technologies

We consider below three candidate technologies for stationkeeping, including ion thrusters, electrodynamic tethers, and air-breathing electric propulsion devices.

4.2.1. Ion thrusters

Also known as 'conventional electric thrusters', this technology is widely used on many satellites for orbit correction at present. It has proven itself useful in terms of reliability, price, flexibility of operation, and non-interference with the satellites instruments in terms of vibrations. It has been used both in almost-constant firing mode with the GOCE mission, and for weekly corrections with Aeolus.

However, ion propulsion is limited by the large amounts of xenon gas propellant necessary to enable VLEO operation – in practice, it would only offer satellites a 2-year lifetime VLEO. Taking the GOCE as an example, the satellite, with an 872kg dry mass, carried 40kg of xenon dedicated to orbit correction for its 55 month mission [4]. A mass budget of 8kg per year is however prohibitive for smaller satellites that aim to be commercially profitable.

Additionally, electric propulsion is not very efficient in terms of power consumption. Estimates on unbuilt state-of-art technologies such as the Cubesat Ambipolar Thrust system give maximum performances of about 70mN per kW, which at an altitude of 235km, will face a minimum 20mN drag orbit, necessitating at least 285W worth of power consumption. As a comparison, GOCE carried approximately 1600W of power capacity. The mass of this thruster is however very low at about 1kg, and still requires propellant.

4.2.2. Electrodynamic tethers

Tethers as a technology have undergone limited testing. They utilise the Earth's magnetic field to propel themselves using the Lorentz force, enabled in turn by a current running through the tether. They can only operate at points in the orbit where the magnetic field lines of the Earth run as close to perpendicular to the flight path as possible; failing which they will require a component to change inclination. Two tethers perpendicular to each other, which can run bidirectional current, provide thrust in all 3 dimensions. By far tethers' greatest strength is that they eliminate the need for propellant altogether, and therefore save significant amounts of mass for longer-term missions.

Tethers perform well on power performance, and based on an ISS orbit boosting study, manage with 500mN per kW, rendering them almost ten times more efficient than electric propulsion in this regard. However, they pose numerous problems that as-yet do not have ready solutions, and will likely require years of development to find adequate fixes for. For one, they tend to shift the centre of mass of the vehicle by a few metres when deployed.

For another, to date it has been difficult to achieve a reliable deployment mechanism, with problems ranging from electrical arcing due to high currents, to rapid heating and cooling from solar radiation as the satellite goes around the Earth causing problems in the tether reel.

Another concerning problem relates to the libations and vibrations in the tether, which happen both when it is firing and when it is passively experiencing drag. These disturbances have the potential to interfere with satellite observations. However this should be less of an issue for satellites with telecommunications payloads. Regardless, a partial solution potentially exists in utilising the gravity gradient of the long tether to restore it back to vertical, but a lot more experimentation is needed to verify this method's effectiveness.

4.2.3. Air-breathing electric propulsion

While air-breathing electric propulsion devices have been proposed [5], they have not been built and tested at scale. They would theoretically also eliminate the need for propellant, and would in fact improve as atmospheric drag worsens. At present, they are being developed by the ESA [6]. The power consumption is likely to be high per newton of thrust however.

4.3. Other technological adaptations

The VLEO environment also introduces atomic oxygen erosion and increased stress on ground tracking equipment.

4.3.1. Atomic oxygen erosion

One major challenge present in VLEO operations is the prevalence of atomic oxygen at these lower regions of the atmosphere, which leads to the significant erosion of satellite surfaces and degradation of satellite and payload performance, limiting mission lifetimes. While its concentrations are actually small, it is the direct frontal impact of the satellite's velocity that leads to highly effective incidences of atomic oxygen, and therefore strong erosive effects.

Table 2: Atomic oxygen density according to NRLMSISE-00 Atmosphere Model [1]

Altitude (km)	Atomic oxygen (number of atoms per m^3)
100km	4.29E+17
150km	1.69E+16
200km	4.50E+15
250km	1.60E+15
300km	5.90E+14

One vulnerable component is any field emitter on a spacecraft, which is typically used for radiating heat into space and maintaining a temperature balance in the satellite; an essential function [7].

The issue of atomic oxygen erosion will require a study into protective materials for satellites, or new satellite architectures with shields that aerodynamically deflect away from vulnerable components. Such a shield is currently being studied [8].

4.3.2. Ground communication from VLEO

There is another set of technical challenges associated with VLEO operations that deals not with the satellite's technology, but rather with ground systems' ability to successfully track and communicate with these satellites. Lower orbits, faster speeds, and less ground coverage per satellite all pose challenges for any telecommunications constellation to perform smoothly in VLEO.

One proposed solution is to have VLEO satellites relay to a geostationary satellite, with ample line of sight to many of the constellation satellites at once, which will in turn communicate with Earth. This is ideal for Earth observation constellations which require clear signals, but this solution features major drawbacks to latency since signals would have longer distances to travel than with traditional geostationary telecoms satellites. If latency reduction is the goal, then ground tracking and communication capabilities will have to improve and adapt to the rapidly passing VLEO satellites overhead in a direct link.

4.4. Final thoughts

GOCE demonstrated that long term VLEO stationkeeping is possible. However, for cost-efficient commercialisation, a lot more work will have to be done.

5. LEGAL CONSIDERATIONS

In addition to the foregoing operational and engineering challenges that have been identified, there are also several foreseeable legal and policy issues that may result from a shift of commercial satellite activity from conventional higher orbits into VLEO. Chief amongst these are the following:

1. Concerns related to the increased difficulty in ensuring the accuracy of space situational awareness (SSA) activities and performing space traffic management (STM), owing to the inherent challenges of tracking space objects in VLEO, which may in turn affect freedom of exploration and use, result in harmful interference with other actors' space activities, and detract from State Parties' ability to provide continuing supervision over the space assets of non-governmental entities;
2. The increased risk, liability, and environmental impact resulting from potential atmospheric contamination and terrestrial debris impacts as a result of more frequent de-orbit events, which may, in the interest of safety, consequently require further stipulations as to the form factors of and materials used in the construction of VLEO satellites;
3. Licensing considerations arising from the inherent nature of VLEO satellite operations; and
4. Other ancillary legal considerations such as the delimitation of boundaries that may be brought to the fore as they become increasingly relevant commercial issues.

At the outset, it should be noted that VLEO as a region of space falls comfortably under the ambit of our existing space law regime. Prior missions have been conducted in the region as per the exact same set of rules, with little disruption to the existing regulatory regime [16]. It can therefore be assumed that the very occurrence of VLEO activity itself does not give rise to the aforementioned considerations as inherent issues. Rather, this segment considers whether an increased amount of VLEO satellite activity at scale, and all the implications contained therein, might prove so disruptive that it necessitates substantial changes to our existing legal mechanisms, and whether as a result this constitutes a deterrent to greater utilisation of the region.

We posit that such an increase would be minimally disruptive to existing legal structures even at scale. Our space law regime is sufficiently robust to contend with these issues, and whilst they are not insignificant in terms of their impact, on the balance and in light of the numerous environmental and operational benefits availed by greater VLEO utilisation, it would appear that these legal considerations should not be regarded as so major as to give one pause regarding the prospect of increased VLEO satellite activity. Ultimately, while there might be some growing pains as these and further, as yet unforeseen, regulatory challenges emerge, on the whole there is more here to be gained than potentially lost.

5.1. A brief overview of space law

Modern space law comprises a mix of public international law instruments and corresponding domestic legislation and regulation [17], and finds its origins in the four major space treaties: the Outer Space Treaty 1967 (OST), the Rescue Agreement 1968 (ARRA), the Liability Convention 1972, and the Registration Convention 1976. The latter three instruments primarily serve as elaborations on the substantive obligations created by the OST, which itself laid out the key tenets undergirding the wider jurisprudence. These tenets, trite as law today, include briefly such provisions as freedom of exploration and use; non-militarisation; non-appropriation; non-interference; non-contamination; the responsibility of national governments to provide continuing supervision over space activities of non-governmental entities including private companies; and liability and attribution stipulations which provide State Parties with jurisdiction and control over any space objects launched and registered under their authority [18].

Also of note are the numerous 'soft law' instruments that have been promulgated and which, though not legal in the strictly Austinian sense as it concerns enforceability, nonetheless serve normative functions and may in future come to embody customary international law [19]. These include United Nations General Assembly (UNGA) Resolution 62/217 endorsing the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (Space Debris Mitigation Guidelines), as well as UNGA Resolution 47/68 on Principles Relevant to the Use of Nuclear Power Sources in Outer Space.

We now turn to consider how this general framework of space law may conceivably interact with an increase in commercial VLEO satellite activity, what principles or fundamental tenets may be implicated, and what the nature and degree of the impact such activity will be on existing space law structures and institutions.

5.2. Legal and policy issues specific to VLEO

5.2.1. Difficulties in performing space traffic management and ensuring accurate space situational awareness

The inherent nature of VLEO operations poses substantial challenges to the conduct of STM and SSA activities. This in turn implicates both the responsibilities of State Parties under Article IX concerning harmful interference to the activities of other actors, as well as their obligations under Articles VI, VII, and VIII to provide continuing supervision where a space object registered under their authority is owned and/or operated by a private actor.

Accurate SSA and STM is key to ensuring the safety, operability, and viability of the near-Earth orbital environment, and it impacts the rights of parties to freely explore and use space as well as to not suffer harmful interference without consultation [20]. From a practical perspective, maintaining a register of space objects as per the OST and the Registration Convention serves little purpose unless each object can actually be accounted for and appropriately managed so as to minimise its impact on other actors. Without the ability to appropriately manage space traffic, the enjoyment of these rights is rendered untenable, and arguably the rights themselves become toothless in the face of unenforceability. Aside from constituting a substantial operational hazard, the inherent difficulty of tracking objects in VLEO therefore poses a challenge to the workability of commercial VLEO utilisation as a prospect because actors are unable to enjoy their rights of access to space, and since this is fundamentally an operational problem, there is unlikely to be a legal solution that completely addresses this issue in its entirety.

Furthermore, since liability for instances of on-orbit damage caused by conjunction events or other accidents is decided according to a fault-based regime [21], the identities of the parties involved is critical for the dispute resolution process. This is given practical force by SSA and space object tracking. However, with reduced efficacy of these capabilities in VLEO, independent verification of accidents and the parties involved will prove that much harder. In turn, the inability to reliably seek compensation from insurers or recover damages from other parties may serve to disincentivise commercial activity by rendering investments in VLEO space assets unsafe.

These factors taken in conjunction, unless addressed, may render the VLEO environment unsafe for commercial activity to operate in sustainably at scale. However, despite being an operational problem, there are legal and policy measures that could be taken so as to ameliorate its impact. Greater international cooperation on information sharing in regard to space objects and orbital events, as well as greater promotion and support from states for capacity building initiatives with regard to SSA and STM capabilities, will both go some way toward addressing these issues. Incidentally, these solutions also feature prominently in the UN Office for Outer Space Affairs (UNOOSA) Long Term Sustainability Guidelines [22] as objectives to be pursued and implemented by state parties.

Initiatives such as these aimed at improving transparency will however encounter the standard bevy of issues relating to the confidentiality of space national security assets which, depending on specific payload and application, also generally stand to gain from operating in VLEO in the same ways that commercial operators do. This is another issue that cannot be readily addressed, especially since the difficulty of tracking objects in VLEO may be specifically advantageous to national security assets; the difficulty of tracking these assets in VLEO renders them less vulnerable to interference, hence making it in the operating state's interest to allow these issues to persist.

Nonetheless, a partial cure is better than none at all. The implementation of more comprehensive information sharing practices for SSA and STM among nations, as well as greater efforts toward capacity building, are good first steps.

5.2.2. Risk, liability, and environmental impact of more frequent de-orbit events

The high level of atmospheric drag inherent to VLEO, which ranks chief amongst the factors that make the region difficult to operate in, also renders it highly attractive from the perspective of space debris management, since it ensures that any debris generated will be naturally de-orbited in a timely fashion. However, the flip side of that coin is a potential increase in the frequency of these sorts of de-orbit events, especially in the face of greater commercial utilisation of VLEO by large satellite constellations.

Greater commercial utilisation of VLEO, coupled with the wider industry trend toward larger satellite constellations [23], will logically entail more de-orbit events since there are more operational satellites to be disposed of and such disposal will require minimal positive effort on the part of the operators themselves. This opens the door to the dual possibilities of a higher frequency of terrestrial impact events from debris that has failed to break up during re-entry, and a higher likelihood of atmospheric contamination from the debris that has been successfully broken up [24].

Anywhere between 10-40% of a satellite's mass will fail to burn up on re-entry, leaving the surviving mass to impact onto the Earth's surface [25]. This poses a significant risk to both those on Earth as well as the satellite operators themselves in the form of potential liability. Unlike the liability regime explained above that pertains to in-space damage, the liability regime is absolute for any damage caused on the surface of the Earth or to aircraft in flight [26], meaning that any such damage will have to be compensated in full. While most states generally require private operators to take out insurance to indemnify the national government under which the asset is registered for up to a certain amount, the state will remain liable for any amount beyond what has been insured for [27].

With a greater number of operational satellites and much shorter de-orbit times, the assumption follows that the number of potential terrestrial impacts and hence damage being occasioned to aircraft, persons, or property will increase commensurately. From the satellite operator's perspective, this is in turn likely to raise insurance premiums since the underlying risk will have increased, thereby substantially affecting operating costs and capital requirements. For everyone else, the hazards endemic to being struck by errant debris should not be understated, nor should the risk. In a recent study conducted by the Aerospace Corporation [28] wherein the potential risk posed by SpaceX's Starlink satellite constellation was examined, the possible incidence rate for harm caused to aircraft operators was estimated to approach as high as one casualty per year by 2030 [28]. In the same timeframe, the risk posed to people on the Earth's surface was estimated at one casualty per every 4 years [28]. Recent opposition to Starlink has also cited these predictions [29], and considering the lowest altitudes that Starlink's satellites are slated for are between 340-370km, it stands to reason that a greater volume of satellite activity even lower will only exacerbate this issue.

Meanwhile, for the debris that does get successfully vaporised, the potential for atmospheric contamination is worrying in more ways than one. From a legal perspective, it contravenes the obligation by state parties and operators to prevent harmful contamination of the Earth and its atmosphere as a result of space activities. De-orbited satellites generate "a zoo of complex chemical types" [30], the combination of which have the potential to damage the atmosphere in any number of as-yet unforeseen ways. Based on our present understanding, at a minimum the aluminium oxide produced as a result of the burning up of aluminium satellite components is known to absorb more radiation coming up from the Earth than it reflects from the sun, and thereby likely contributes to climate change. Whilst scarce research on this particular phenomenon exists, it is an area of increasing interest as the space industry becomes more cognisant of the significant risk that backward atmospheric contamination poses to our planet. Incidentally, it should also be noted that the first issue of an increase in terrestrial impact would also contravene the legal commitment on non-contamination, since any de-orbited debris upon landing will constitute a de facto pollutant.

Again, it follows that an increase in the frequency of de-orbit events would exacerbate this issue, and arguably this should prove to be the more concerning issue since we do not yet fully understand this problem or its potentially wide-reaching implications. One key legal solution will likely prove to be the institution of stipulations as to the materials used in the construction of VLEO satellites, as well as the maximum tonnage allowed, to ensure maximally safe vaporisation upon being de-orbited. Unlike the later discussion on the future of launch and operating licensing procedures, the basis of these stipulations should take on a more global dimension.

The obligations undergirding the wider principles of space sustainability, and in particular those concerning the prevention of the contamination of Earth and its atmosphere, are fundamental features of the international space law regime. It would therefore make sense for the animating force for any stipulations on satellite activity in VLEO to originate at the international level as well, even if they are ultimately only given real enforceability by national legislatures. Whilst a separate treaty may be impractical at this juncture [27], multilateral adoption of these stipulations as a UNGA Resolution in the same fashion as the Space Debris Mitigation Guidelines [31] will provide a clearer picture of widespread state practice, thereby opening up a route to recognition of these stipulations as customary international law. The difference here, though fine, matters from both the practical and jurisprudential perspectives [32].

In terms of substantive content, given the current lack of research on the issue, it is unwise to prematurely prescribe specific standards. This is however not to say that we should continue to suffer a dearth in applicable legal principles, which should minimally require the following:

1. Firstly, a re-affirmation of the principles of non-contamination and adherence to international law enshrined in Articles IX and I OST respectively;
2. Secondly, a commitment toward the acceptance, if not the implementation, of the LTS Guidelines in creating national standards to give force to the stipulations on VLEO;
3. Thirdly, a general commitment to minimising adverse environmental impacts arising from VLEO activity in general, expanding the scope of the stipulations to include more than just satellite activity; and
4. Fourthly, an undertaking by state parties to regularly review any standards promulgated to give effect to the stipulations, so as to account for and incorporate any advancements in our knowledge and understanding of how de-orbited debris contributes to atmospheric contamination.

Since the resulting UNGA Resolution will inevitably be broad in scope and generally lacking in specific detail, it will fall to state parties to ensure that the spirit of the law is accurately embodied in its letter at the national level. This brings us to our next issue.

5.2.3. Licensing considerations arising from the inherent nature of VLEO satellite operations

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.

For example, in the interest of incentivising greater utilisation of VLEO in service of the wider goal of ensuring more timely de-orbiting of space debris, it may behove national authorities to make debris mitigation and/or end-of-life disposal requirements easier to satisfy by virtue of a proposed activity's occurrence in VLEO.

That having been said, other requirements may become more stringent. Considering the reductions in contact time a satellite will have with ground stations as a result of operating in VLEO, additional standards focused on the maintaining of operational control or operability in general may be necessary. These could include requirements such as a minimum bandwidth to ensure timely uplink and downlink capability, the presence of programmable fail-safes to prevent on-orbit loss-of-control, or the hardening or protection of key components with atomic oxygen-resistant materials so as to prevent environmental degradation.

This however invites secondary considerations. VLEO, as a spectrum of altitudes, is not binarily separated from the rest of LEO. The question then of course is at what point do certain standards begin applying, and to what degree? One possible suggestion is the application of a graduated scale which would separate VLEO into numerous altitude bands, each of which would correspond to a necessary set of standards which in turn would grow or ease in stringency, as is appropriate, the farther along the spectrum they are. We suggest that these bands should not be defined generically, but ought to be sensitive to the operational conditions endemic to the altitude band. VLEO is a challenging environment due to a number of factors, many of which are not amenable to linear extrapolations. Hence any attempt at implementing a scheme along these lines should be alive to these considerations.

5.2.4. Ancillary legal considerations

Finally, greater VLEO utilisation may also bring to the fore other ancillary legal considerations as they become increasingly relevant commercial issues. As was touched on briefly in the previous sub-section, the question of boundaries and limits is likely to revive the age-old debate on the delimitation of outer space.

As space activity extends lower in altitude, boundary definitions may become important for licensing procedures in a similar fashion to the illustration above, as well as for determining the applicable liability regime in the event of an accident. There is currently no firm legal definition as to where space begins, although most organisations place the boundary at the Kármán Line [27]. And at present, with aircraft restricted below the stratosphere and the vast majority of space activity comfortably within the boundaries of LEO, there is little risk of confusion as to which liability regime applies where. Even with launch vehicles, any potential for controversy is constrained to the limited amount of time spent transitioning through the legally nebulous region between 50 and 350 kilometres in altitude. However, a steady migration of commercial activity ever lower poses a risk of the lines blurring, thereby potentially necessitating us to finally have that conversation and state conclusively where the edge of space lies.

5.3. Final thoughts

The implications for space law of a concerted shift of satellite activity into VLEO are legion, and they should not be taken lightly. In considering them, and in balancing these concerns, the onerousness of their solutions, and the potential benefits VLEO has to offer, we have not identified any legal or policy issues of sufficient gravity to warrant foreclosing on the possibility of greater VLEO utilisation.

It is key to begin contemplating these issues now, or we risk finding ourselves in a situation wherein the law arrives too late, only to find the ground already well-worn by the boots of industry. Thus far, space law has always been sufficiently visionary as a field to keep abreast of the latest technical advancements. As we move forward into this exciting era of commercial 'New Space' activity, we should aim to keep it that way.

6. CONCLUSION

Now more than ever, the orbital environment is at enormous risk of irreversible degradation. We have explored the possibility of utilising VLEO in a more significant manner for commercial activity in support of the thesis that a shift toward increased satellite activity in the 'janitor orbits' of VLEO is beneficial for both the space environment, as well as the various actors within it.

We have considered the numerous technical challenges confronting our proposition, including the need for continuous drag compensation methods as well as the heightened atomic oxygen erosion at these altitudes, and discussed briefly the technical capabilities necessary to make it feasible. We also considered in detail the numerous legal and policy implications of greater VLEO activity, and the potential impact to both national debris mitigation guidelines and regulations, as well as the global space law ecosystem as a whole.

In summary, we believe that, these challenges and considerations notwithstanding, a shift toward greater VLEO utilisation is on the balance beneficial for both the space environment and the space industry. We must seek to move away from a zero-sum assessment of space sustainability, and develop opportunities and technologies to enable environmentally-friendly, business-positive practices. A shift toward VLEO presents a lucrative first step in this direction.

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