In-Orbit-Demonstrator of the Skimsat VLEO Platform

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Abstract: The benefits of flying in Very Low Earth Orbits (VLEO) are numerous – increased resolution for optical payloads, reduced power for active payloads, and no long-lived debris to name a few. In order to demonstrate the feasibility of operating at sub-300km altitudes for a prolonged duration without the price-tag of a mission like ESA's GOCE, and to increase our knowledge of this environment, we present an initial design for a SkimSat In-Orbit Demonstrator (IOD) Mission. The mission aims to fly at an altitude of 220-260km for a duration of 1-3 years, utilising electric propulsion to counteract the drag. In order to demonstrate the concept with minimal cost and schedule, a flight proven avionics suite (comprising data handling, attitude control, power and communications) is coupled with a new propulsion system and structure. To demonstrate the value of VLEO, a LIDAR instrument is considered as an example payload, based on a modification to an existing unmanned aerial vehicle (UAV) product, as well as several other payloads measuring the radiation, atomic oxygen and incoming particle flux to validate environmental models. To minimise drag and increase passive aerostability, the satellite consists of a narrow body with solar array "wings" at the rear. This mission will represent the first multi-year VLEO mission since GOCE, and the first flight of the Skimsat platform. The IOD study was funded under a General Support Technology Programme (GSTP) De-risk Activity run by the European Space Agency (ESA). Further work will be carried out under a Discovery Preparation and Technology Development (DPTD) activity also funded by ESA.
Keywords: In-Orbit-Demonstrator, Mission, Platform, Skimsat, VLEO

1. DECLARATIONS

Funding: This project is funded under a General Support Technology Programme (GSTP) activity run by the European Space Agency.

Conflicts of interest/Competing interests: The authors declare that they have no conflict of interest

Availability of data and material: Not applicable

Code availability: Not applicable

2. INTRODUCTION

A huge driver of the performance of satellite remote sensing and communication is the large distance between the satellite and its target, usually 500km or greater. For an optical system the ground resolved distance (GRD) is proportional to this distance (for a fixed aperture diameter), for a communication system the power required is proportional to this distance squared (for a given performance), and for a radar system the signal-to-noise ratio (SNR) is inversely proportional to the distance cubed (for a fixed power level). LIDAR, being an active optical system, suffers from both the reduced SNR and larger GRD with increasing distance. Operation from traditional Low Earth Orbit (LEO) altitudes imposes a lower limit on this distance, necessitating larger and higher power (and therefore more expensive) payloads and satellites to improve performance. Moving from LEO to VLEO altitudes (below 300km) can significantly improve the performance of these payloads by bringing them closer to their targets, or achieve the same performance as higher altitude satellites with a much smaller (and cheaper) satellite.

Aside from the improved payload performance, VLEO offers several more advantages over LEO. The significantly reduced radiation dose allows the use of cheaper components for both the platform avionics and the payloads, and the increased drag ensures that there are no long-lived debris, a growing concern in LEO due to the proliferation of mega-constellations. Lower altitudes also allow for increased launcher capacity, and the reduced distance between a communications satellite and a ground user can significantly reduce the latency compared to LEO and GEO satellite communications. The lower radiation levels potentially also allow the use of significantly more powerful processor, allowing increased autonomy, image processing, machine learning and edge-computing, thereby reducing the amount of data that needs to be downlinked and allowing valuable information to be already extracted by the time it has reached the user, reducing the latency.

Despite these advantages, VLEO has generally been avoided. The significantly increased atmospheric density at VLEO altitudes drives the design of the satellite while significantly limiting the lifetime and/or necessitating a large propulsion system. The increased atomic oxygen density also significantly increases the erosion of satellite components. As a result, utilisation of these lower altitudes has been rare, generally limited to large government or scientific projects, and often out of necessity. The early spy satellites of the United States' CORONA program were short lived missions (generally less than 30 days) operating at altitudes between 180km and 400km, while the current KH-11 satellites operate with a perigee at VLEO altitudes. In 2009 the ESA Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission launched and operated at 268km for over 4 years, utilising an electric propulsion system to maintain its orbit – VLEO operation was necessary to achieve the required accuracy and resolution of the gravity measurements.

Despite the challenges outlined above, it is believed that by utilising electric propulsion, drag-optimal designs, cheaper components and smaller payloads, VLEO satellites can offer comparable performance to much larger LEO satellites at a much lower cost, despite the restricted lifetime. Skimsat is a platform design to do just that.

3. THE SKIMSAT CONCEPT

The philosophy behind the Skimsat concept is outlined in Fig. 1. Skimsat is a small (<200kg), low cost platform designed for 3 years operation at an altitude of 220-260km, capable of supporting a 55kg payload and providing up to 75W of power (orbit average). The platform is suitable for a wide range of missions, and could support payloads offering 0.5m resolution optical and multispectral imagery, 15m resolution thermal infra-red imagery, 1m (horizontal) and ~cm (vertical) resolution LIDAR and 1m resolution spotlight SAR (synthetic aperture radar) imagery (in X-band).

The Skimsat concept reduces cost not only through its smaller size, but also by adopting a modular architecture to allow great flexibility across a range of missions. This reduces the engineering effort required for each new application, and the reuse of the same components across missions allows for reduced costs due to higher volume manufacture. Finally, the lower radiation environment and shorter lifetime reduces the reliability and product assurance effort and allows the use of cheaper (potentially COTS) parts, not only for the platform itself but also the payload.

The small size and mass makes it compatible with a range of current and near-future small satellite launchers, which when coupled with rapid AIT due to its modular architecture, allows for rapid and agile deployment.

For optical payloads, the satellite includes a 2-axis scan mirror to allow agile pointing of the payload field of view without needing to slew the entire satellite.

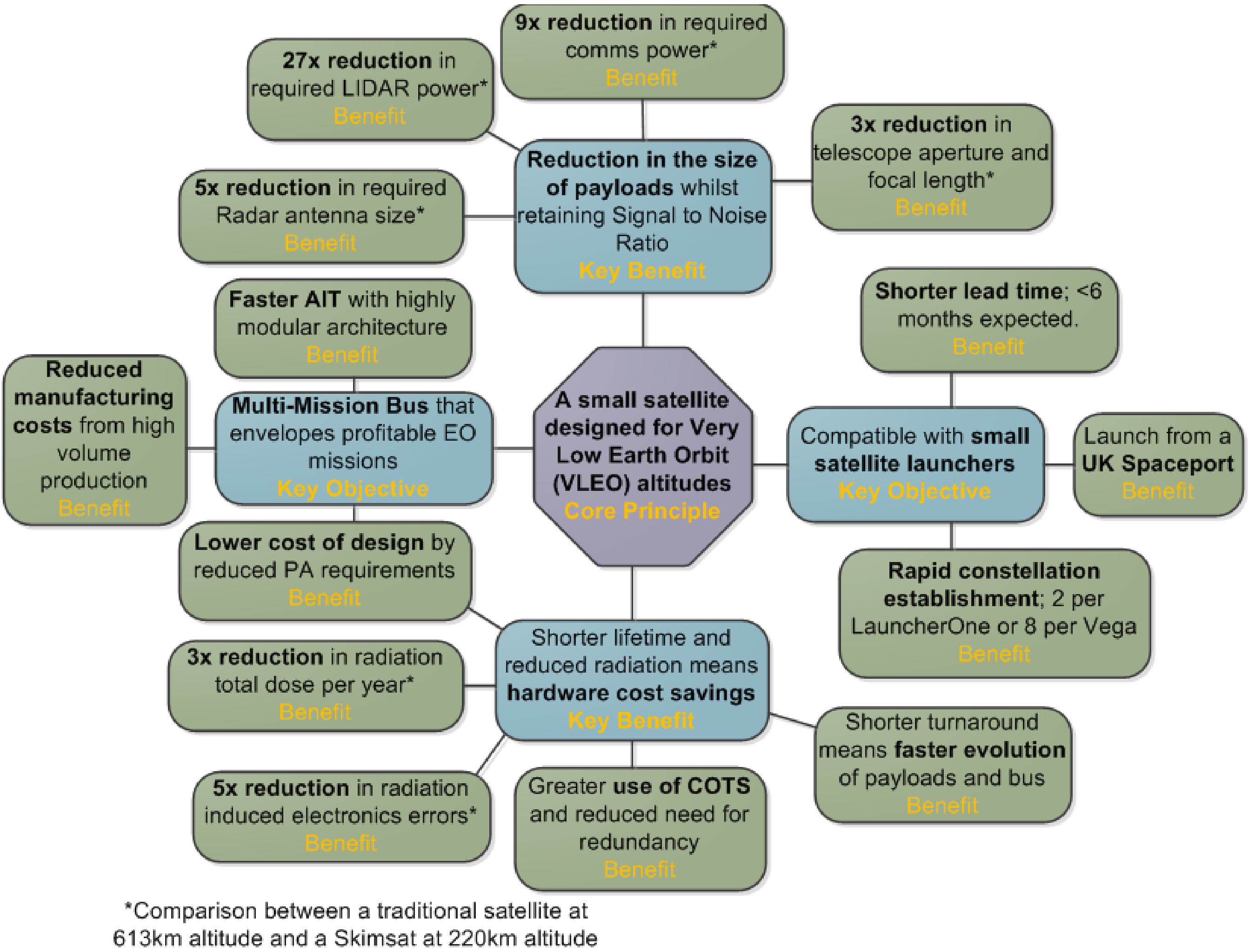

Fig. 1 The philosophy behind the Skimsat concept. Proximity to the Earth reduces the size and power of the payloads, while the reduced radiation allows for cheaper components. The small platform and modular architecture reduces AIT cost and time, allowing rapid production and deployment.

4. THE IN-ORBIT-DEMONSTRATOR

Before undertaking the full development, an IOD (in-orbit-demonstrator) mission is planned to demonstrate the feasibility and value of the concept, while providing a testbed for a range of critical technologies. To reduce risk and schedule, it is intended to make maximum reuse of an existing, flight proven avionics suite based on the P200 platform produced by QinetiQ, only making modifications where necessary. There are three main goals for this IOD mission:

1. *To demonstrate long operational lifetime in VLEO of a platform similar in size and capability to a production Skimsat, with the target goal of 12 months and stretch goal of 36 months*. In order to be a commercially viable, the Skimsat platform needs to be able to operate for multiple years to justify the expense of its development and launch. Additionally, waiting lists for launch slots can be greater than two years in many cases and so a multi-year lifetime is required for maintaining a constant EO capability.

2. *To demonstrate aspects of future low cost operations for a VLEO platform.* GOCE was described by ESA's Space Operational Centre (ESOC) as operationally challenging, owing the extensive recovery activities required in case of an anomaly, and an exceptional number of anomalies that occurred [1]. While a lot of this operational load comes from the complexity of the GOCE mission and configuration steps required to reach nominal operation, some aspects will still be relevant for other VLEO missions, namely the need for rapid recovery (to minimise altitude loss) and the less predictable orbit evolution due to drag. Therefore there is a significant risk that the cost of operations might erode some of the cost advantages of operating in VLEO. A key objective for the IOD mission is to determine the best methods for overcoming these operational issues. It is expected that many can be solved by increasing the intelligence of the on-board operational systems, in particular the Attitude and Orbit Control System (AOCS) which by including more information about the drag environment in VLEO can use new control laws that understand and compensate for these issues. By having on-board information about the expected atmospheric composition, the platform could make on-board decisions about the thrust level to be used and what torques to apply when slewing the satellite, to reduce on-ground operator load.

3. *Demonstrate key platform and payload technologies for future low cost VLEO platforms*. As described above operation in VLEO creates additional constraints on platforms and payloads. A range of technologies have been identified to help mitigate many of these challenges, and de-risking activities have been planned to increase the Technology Readiness Level (TRL) of these technologies sufficiently for use in the IOD.

The mission has a range of secondary goals, depending on which payloads are included on the mission:

1. *Demonstrate the value of VLEO for Earth Observation (EO)*. Embarking an EO payload will also increase the value of the mission by providing useful scientific or commercial data. For the feasibility study, a LIDAR based on an adapted UAV product was used as an example payload.

2. *Increase knowledge of the VLEO environment*. Several potential small payloads have been identified which would provide accurate measurements of the environment, providing complimentary data to existing models, reducing uncertainty for future VLEO missions.

3. *Provide launch opportunities for other small payloads*. Spare payload capacity may be utilised to provide a low cost opportunity for future, as yet unidentified, payloads to increase their TRL.

The planned orbit is a circular SSO with a 6:00 LTAN (to maximise power availability) at an altitude of 260km[1,2]. The target lifetime is 1 year, but is designed to carry enough propellant for 3 years. It will launch to a higher altitude for commissioning before dropping to the operational altitude (launched either a on dedicated small satellite launcher or as a rideshare passenger). Launch is targeted for 2024. As a controlled deorbit is not deemed feasible, the satellite will be designed to fully disintegrate upon re-entry.

5. DESIGN AND ANALYSIS

5.1. OVERVIEW

Fig. 2 shows the external view of the satellite. The main design features are the long narrow body to reduce the frontal cross-sectional area and the solar arrays towards the rear of the platform for stability. The star trackers are inset into body to reduce drag, and protect the optics from atomic oxygen. The main platform body is approximately 2.7m x 0.4m x 0.4m, with the solar array “wings” about 1.5m in length. The dry mass of the satellite is 225kg and carries 29kg of xenon propellant.

To minimise drag, the satellite nominally maintains its long axis in the velocity direction. This restricts the ability to pitch or yaw, allowing only one degree of freedom about the roll axis. A nose cone on the front reduces the drag on the main body [2].

Fehler! Verweisquelle konnte nicht gefunden werden. shows the internal accommodation of the units. At the rear of the satellite (right side of the image) are the avionics units. The propellant tank can be seen in the centre, with the star trackers (with baffles) and reaction wheels in front. The cylinder represents the LIDAR optics, with smaller payloads and some of the other avionics units around it. At the front is the 2-axis scan mirror.

Analysis has shown that the selected avionics suite is suitable for the proposed mission, only requiring the addition of a propulsion power unit (PPU) for the thruster and a mass memory unit (MMU) for increased data storage.

[1] Altitude relative to the mean Earth radius of 6371km
[2] The orbit is subject to change depending on the final payload selection

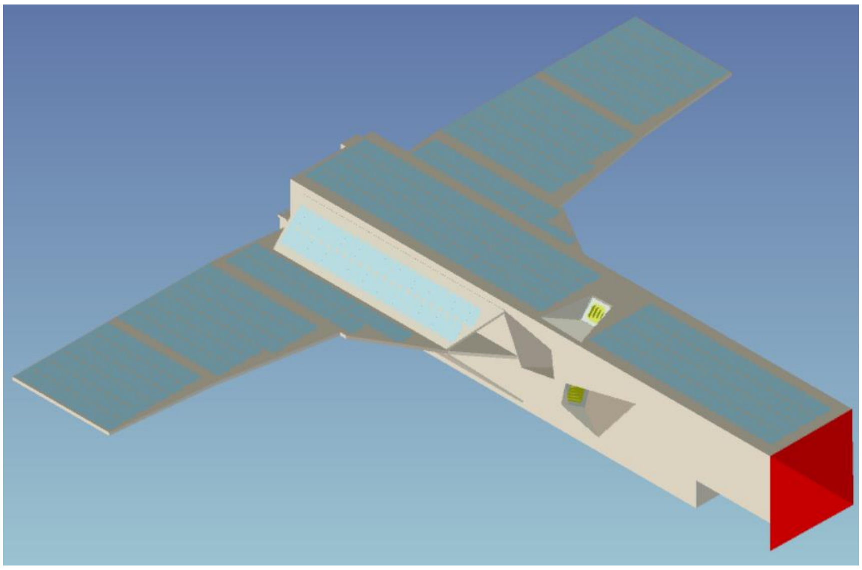

Fig. 2 External view of the Skimsat IOD satellite, showing the narrow body to reduce drag, and rearward solar arrays for stability.

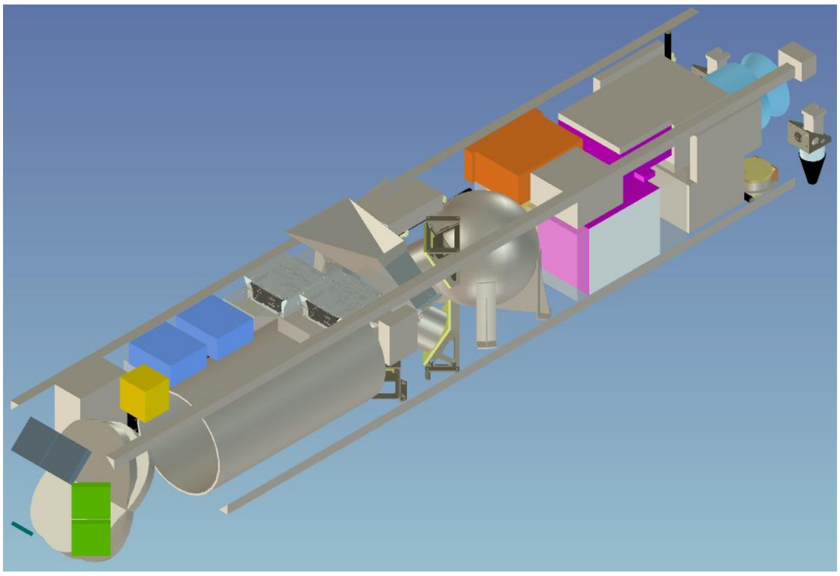

Fig. 3 Internal view of the Skimsat IOD satellite, showing the accommodation of the thruster and avionics units (rear), propellant tank and AOCS equipment (centre) and payloads (front). The front of the satellite is in the left of the image.

5.2. STABILITY

It is intended for the platform to be aerostable in the minimum-drag orientation to reduce the load on the AOCS and to maintain this orientation in case of a loss of attitude control. This is achieved by ensuring the centre of aerodynamic pressure (CoP) always remains behind the centre of mass (CoM). Positioning the solar arrays at the rear ensures the CoP remains behind the CoM. Initial stability analysis has been performed using free molecular flow analysis [3]. The aerodynamic torques about each satellite axis are shown in Fig. 4 and Fig. 5 for varying Angle of Attack (AoA) about the pitch axis, and Side Slip Angle (SSA) about the yaw axis. The X, Y and Z axes represent the roll, pitch and yaw axes of the satellite respectively.

Fig. 4 shows that over the full AoA range, a negative AoA generates a moment in the positive direction, and a positive AoA generates negative moment, indicating that the aerodynamic torques always act as a restoring force to orient the satellite back to an AoA of 0°, therefore the satellite is stable about the pitch axis. Fig. 5 shows that the satellite is only stable if the SSA is less than ±90°. In both graphs, a small torques about the other axes is present – this is due to a slight misalignment between the position of the CoM and the CoP in the Y and Z axis and slight asymmetry in the structure. Further optimisation of the internal layout and structure should significantly reduce these torques. It may be necessary to add vertical fins to improve aerostability about the yaw axis. Higher fidelity stability analysis will be performed in the future utilising Direct Simulation Mote Carlo (DSMC) techniques, as well as covering the full range of combined AoA and SSA.

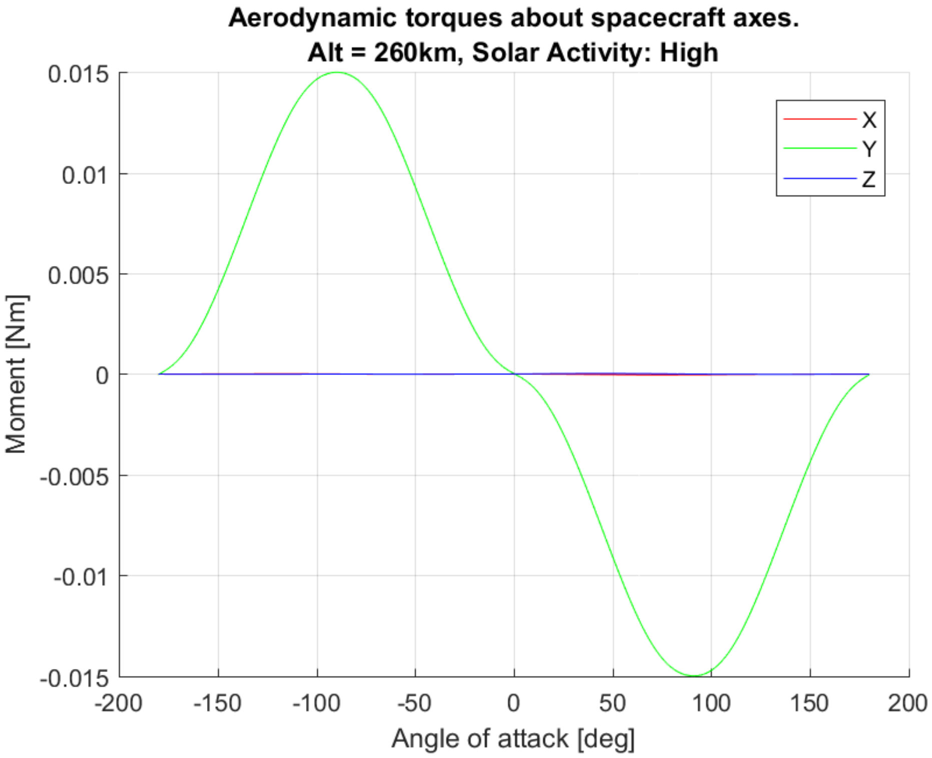

Fig. 4 Spacecraft aerodynamic torques for a range of angles of attack (AoA) with high solar activity and an orbit altitude of 260km. The aerodynamic torque is positive AoA and negative for a positive AoA.

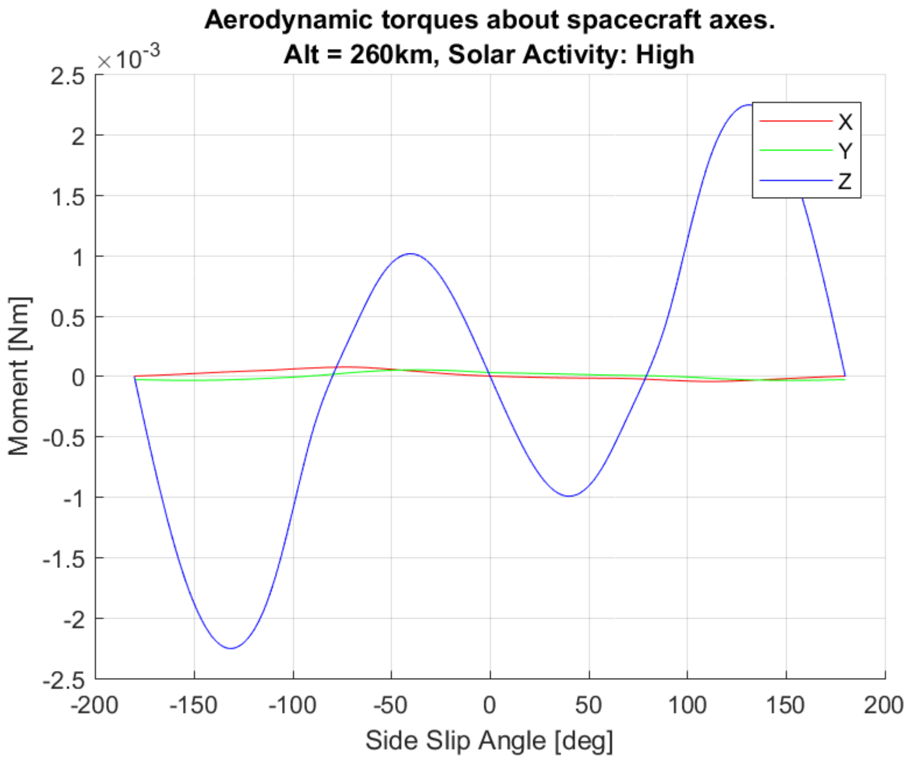

Fig. 5 Spacecraft aerodynamic torques for a range of side slip angles (SSA) with high solar activity and an orbit altitude of 260km. The aerodynamic torque is positive SSA and negative for a positive SSA for SSA values less than ±90°.

5.3. PROPULSION

To simplify the thruster flow control and power supply, and to allow the thruster to operate at its optimum performance point, the thruster will be operated at a single thrust level, periodically boosting the orbit and allowing it to decay. A thrust level of 15mN at a power of 450W and a specific impulse (I_{sp}) of 2000s has been assumed, which is comparable to the T5 thruster level used on GOCE. The expected drag force is approximately 2.2-4.5mN at 260km altitude – the margin on the thrust provides greater opportunity to recover if the satellite drops below its operational altitude.

Providing drag compensation for 3 years requires 21.7kg of xenon propellant (including a 15% margin). A further 450ms^{-1} ΔV is assumed for inclination and altitude correction in case of a rideshare launch. The total propellant required is 29kg, which corresponds to a ΔV of 2.03kms^{-1}.

The propellant tank is aligned with the CoM in the Y and Z axis to limit the shift in CoM over the lifetime of the mission as propellant is consumed, which would otherwise impact the aerostability.

5.4. STRUCTURE

The structure is designed to provide an optimal load path from the interface with the launcher towards the payload and the propulsion tanks. The structure will also accommodate all sub-systems and equipment during the complete lifetime of the spacecraft.

The main concern with the structural design is its slender shape with a small cross-sectional area, which puts the CoM quite high. The high CoM combined with a slender structure reduces the natural frequency of the satellite, which makes it vulnerable to the vibration environment of the launcher. Therefore, it's important to have the natural frequency of the satellite structure to stay above the natural frequency requirement of the launch vehicle. A structural analysis using a finite element model (FEM) was performed to check the structural integrity of the proposed design, indicating that the structure could be made stiff enough by adjusting the thickness of the honeycomb structural panels and the base plate.

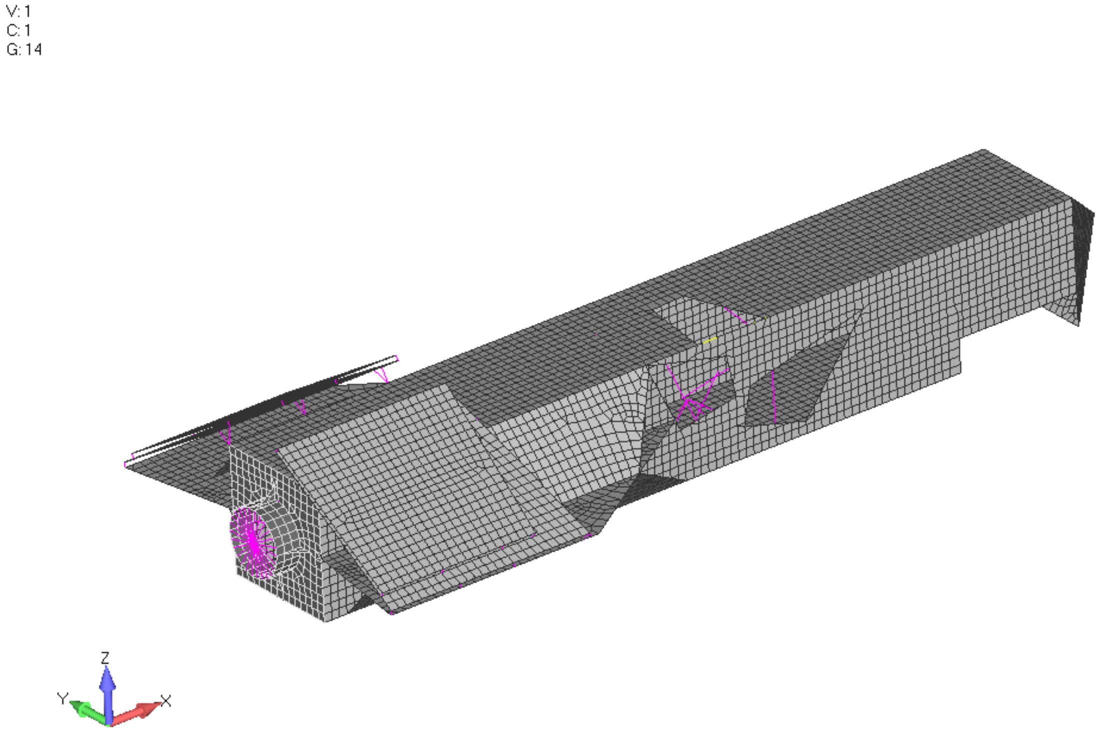

Fig. 6 Finite Element Model (FEM) of the Skimsat IOD satellite.

5.5. POWER

To minimise drag the solar arrays are “edge on” to the velocity direction and the satellite is only free to rotate about the roll axis, significantly impacting the ability to generate power. To quantify this, the term solar array geometric efficiency (GE) is introduced: the GE is the ratio of the average power (over one orbit) a solar array is able to generate compared to the power the same array would generate if it were oriented directly to sun. This value accounts for both the restricted pointing as described above, and also eclipses. Fig. 7 shows the GE calculated for a range of altitudes and solar beta angles (the angle between the sun and the plane of the orbit), showing some increase with altitude (due to the reduced eclipse durations), and a larger increase with beta angle (due to both the reduced duration of eclipses and the improved incidence angle on the solar arrays).

Fig. 8 shows the variation in GE over the course of a year for the selected 260km, 6:00 LTAN SSO due to the varying beta angle. The variation in GE over the year is driven by the two eclipse seasons occurring around the solstices, with longer eclipses occurring around the northern hemisphere winter solstice that drive the worst case GE value of 0.64. To ensure the satellite can always provide sufficient orbit average power, the solar array needs be large enough to generate a peak power (when pointed directly to the sun) equal to the average power divided by 0.64.

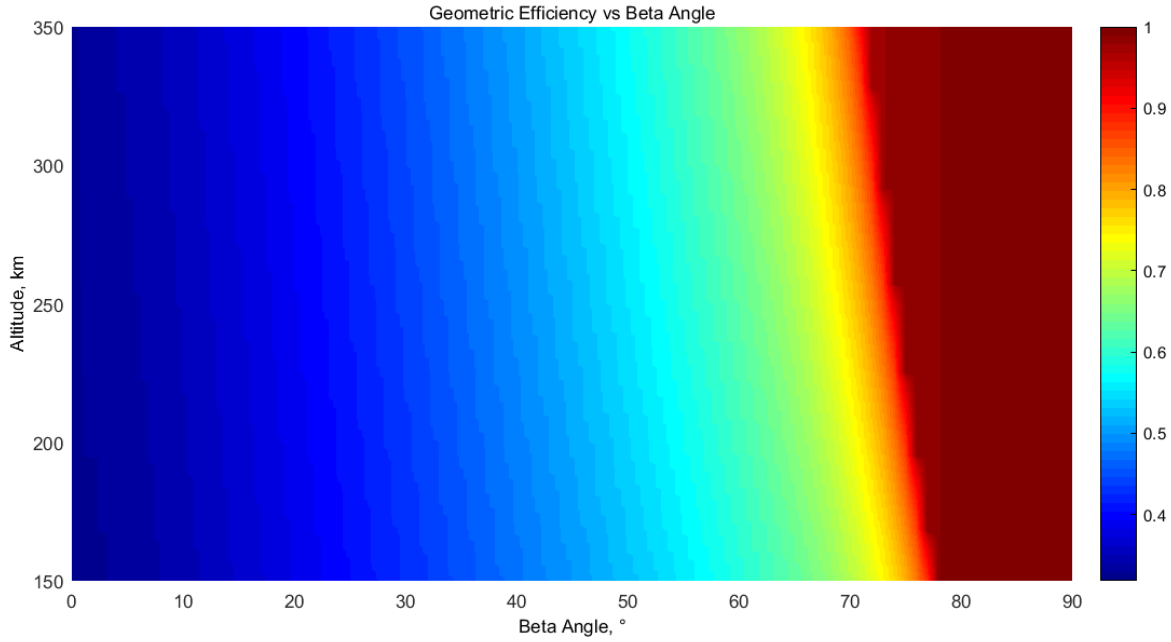

Fig. 7 Geometric Efficiency vs Beta Angle and Altitude

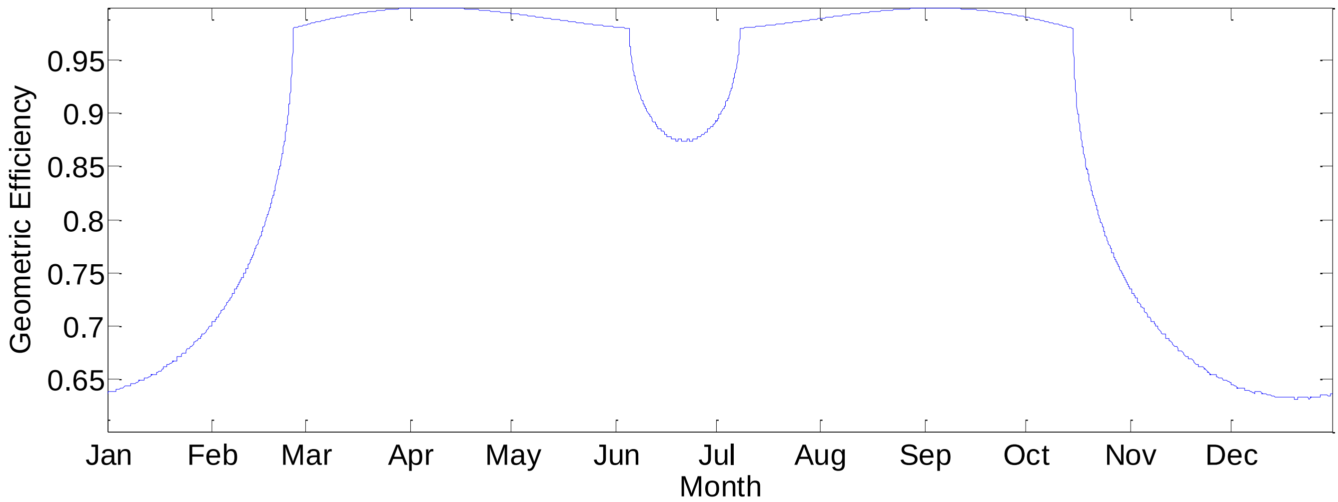

Fig. 8 Geometric efficiency over the course of 1 year, for a 260km altitude 6:00 LTAN SSO.

6. POTENTIAL PAYLOADS

6.1. PRIMARY

For the feasibility study, a LIDAR instrument based on an existing UAV product was investigated as the primary payload. LIDAR instruments are likely to significantly benefit from VLEO altitudes due to reduced power required and smaller optics. The LIDAR instrument occupies a volume 0.3mx0.3mx0.6m with a mass of 9kg and a peak power consumption of 192W. A LIDAR instrument could offer a wide range of data products, including ground topography, biomass measurements, plant health assessment, bathymetry and wind measurements.

Going forward, a higher TRL primary payload is sought for the IOD mission, with a target launch date of 2024.The payload capacity for the primary payload is planned to be 30kg (out of a total payload capacity of 50kg), 200W peak power, 100W orbit average power, and a volume of 0.3mx0.3mx0.6m. These values are subject to change depending on the final orbit, secondary payload configuration and propulsion configuration.

6.2. SECONDARY

A list of the potential secondary payloads is shown in Table 1. To minimise the required mass, power and volume, these payloads are predominantly based on existing cubesat compatible payloads. These payloads are split into three categories, depending on their contribution to the mission:

- Future VLEO Platform Technology Development (FVPTD): technologies that may increase the value or performance of future VLEO platforms and missions
- In-Situ Lower Thermosphere Measurement (ISLTM): payloads that will increase understanding of the VLEO environment to inform the design of future VLEO missions
- Earth Observation (EO): payloads that provide further Earth Observation data.

Where possible, existing examples of the selected payloads have been identified to provide mass, power, size and data rate values to assess the relevant budgets.

Payload	Category	Benefit	Example/Developer
Novel Aerodynamic Materials	FVPTD	Reduction in drag, allowing longer duration missions	University of Manchester
Active Aerodynamic Control	FVPTD	Utilising aerodynamic forces and torque to augment traditional AOCS actuators	University of Manchester
Orbital Flux Vector Sensor	FVPTD/ ISLTM	Provide accurate knowledge of incoming wind direction for attitude control (particularly aerodynamic control). Also providing accurate data on the wind directions in the upper atmosphere.	University of Manchester

Atomic Oxygen Sensor	ISLTM	Accurately measure atomic oxygen fluxes to validate existing models, particularly those modelling atomic oxygen ingress through openings in the satellite body	APOLLON Atomic/Molecular oxygen sensor - University of Dresden
Mass Spectrometer	ISLTM	Accurately measure the chemical species in VLEO	Ion and Neutral Mass Spectrometer (INMS) - Mullard Space Science Laboratory
Langmuir Probe	ISLTM	Measure the plasma environment	Multi Needle Langmuir Probe (m-NLP) - University of Oslo
Radiation Sensor	ISLTM	Accurately measure the radiation environment to validate existing models. Accurate knowledge of the radiation environment is important to assess the performance, reliability and feasibility of using lower grade components than conventional space-grade ones	Radiation Monitor Unit (RMU) - TAS-CH
Camera	EO	To demonstrate the acquisition of optical imagery from VLEO, while providing context to data from the primary EO payload.	Nanocam C1U Optical Camera - GOMSPACE

Table 1 Summary of the potential secondary payloads**,** identifying the payload, category, benefit to the mission and example existing payloads used in the accommodation and budget calculations.

7. NEXT STEPS

The current work has focussed on the assessing the feasibility of the selected avionics, developing the mission to demonstrate the goals of the IOD and producing an initial architecture and design of the satellite to identify any potential show-stoppers. The study has indicated that there are none, and that the mission and concept is feasible with the identified avionics. Further work is needed to refine the satellite and mission design, including some activities to de-risk certain elements including atomic oxygen resistant coatings and materials, and the scan mirror mechanism.

The planned schedule is shown in Fig. 9. The next step is split into two phases. Phase 1 covers the standard Phase A/B1 activities, refining the mission and system design and identifying the development work required in critical areas. This phase includes the Preliminary Requirements Review (PRR) and culminates in the System Requirements Review (SRR). In parallel with the Phase 1 study there will also be a series of preparatory activities undertaken to secure the schedule and the TRL status.

Phase 2 covers the traditional Phase B2/C/D/E1 activities leading up to the launch. At the Preliminary Design Review (PDR) at the end of Phase B2 all technologies are typically TRL 5 or higher to allow the mission to continue into detailed design towards the Critical Design Review (CDR). Post CDR the flight versions of all subsystems will be assembled and then integrated and tested to reach the launch milestone. The platform, payload and ground segment developments would need to be carried out in parallel to ensure that a short development schedule can be maintained.

The Skimsat mission is well suited for maximising the use of the UK space supply chain, and the innovative technology can all be developed in the UK. The mission is capable of being launched on a variety of European and US launch vehicles, either as a dedicated launch or part of a rideshare agreement. The mission is also compatible with small satellite launchers potentially launching from the UK in the future.

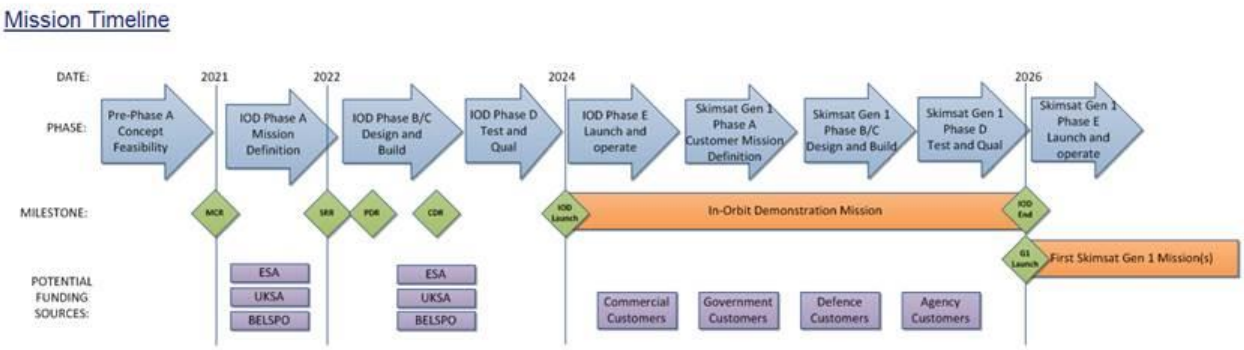

Fig. 9 Preliminary mission timeline for launch in 2024.

Based upon the current schedule (and with the required funding availability), a launch circa Mid-2024 for the Skimsat In-Orbit Demonstration (IOD) is considered feasible. In parallel to the Skimsat In-Orbit Demonstration (IOD), the first Skimsat Generation 1 mission is planned to be further defined.

These next steps will be carried out under a Discovery Preparation and Technology Development (DPTD) activity funded by the European Space Agency.

8. CONCLUSION

The study has demonstrated that a small VLEO platform capable of supporting a 3 year mission can be realised using mostly existing avionics and equipment, with only the structure and propulsion subsystem considered as new developments, paving the way to the first demonstration of the low-cost Skimsat concept in 2024. To effectively operate optical payloads, a new scan mirror mechanism will also be developed. The study has also shown that the Skimsat IOD can be launched using small launch vehicles such as the Virgin Orbit LauncherOne, with subsequent iterations targeting smaller launchers such as the Rocket Lab Electron for increased flexibility.

The multi-mission VLEO platform can present benefits to commercial, defence and agencies including increased resolution for optics payloads, reduced power for active payloads, no long-lived debris and increased processing power. Key challenges remain including aerostability, atomic oxygen resistance and the development of the scan mirror. The mission and platform design and analyses will be refined in the upcoming phases.

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