Systems Modelling of Very Low Earth Orbit (VLEO) Platforms with Atmosphere-Breathing Electric Propulsion (ABEP)

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Abstract

The operation of satellites in very low Earth orbit (VLEO), those below 450 km, has been linked to a variety of benefits to both the spacecraft platform and mission design. For Earth observation (EO) and communications missions, a reduction in altitude can enable smaller or less powerful payloads to achieve the same performance as larger instruments or sensors at higher altitudes, with potentially significant reductions in manufacture and launch costs. However, a key obstacle to sustained operations in VLEO remains the increased aerodynamic drag that must be mitigated or compensated for to provide a useful orbital lifetime.

Atmosphere breathing electric propulsion (ABEP) systems present the potential for drag compensation in VLEO to be performed using only propellant collected in-situ, dramatically reducing the need for stored propellant, and significantly increasing the possible mission lifetime at low altitudes.

Whilst specific technologies to enable ABEP are still being developed, a systems modelling approach can be used to investigate the integration of these systems with different satellite platform concepts and for different mission applications. The trade-offs between required power, atmospheric drag, and the platform geometry (incorporating the ABEP system and required power supply) are of particular importance in ensuring the feasibility of possible design concepts. This paper will consider the variation of intake and thruster performance, based on state-of-the-art emerging technologies, to explore the thresholds of performance required to enable sustainable operation of novel platforms in VLEO using ABEP.

Keywords System engineering · System modelling · Very low Earth orbit (VLEO) · Atmosphere-breathing electric propulsion (ABEP) · Drag compensation · Aerodynamic drag

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1. Introduction

Operating spacecraft at lower altitude has been linked to a number of benefits, particularly for Earth observation [1] and communications missions [2]. These benefits of reducing orbital altitude can be broadly summarised:

- The aperture diameter of optical payloads can be reduced, or for a given aperture size, the resolution increases.
- The radiometric performance of optical, radar, and communications payloads is also increased, allowing for improved signal-to-noise and link-budgets or reduced sensitivity and power.
- The latency of communications is reduced, and a more efficient use of the available spectrum may be possible.
- The radiation environment may be less aggressive allowing wider use of non-radiation hardened, commercial-off-the-shelf, and consumer electronics.
- The payload mass of launch vehicles is increased, reducing the cost per unit mass and possibly increasing the number of vehicles available.
- The increased atmospheric density and drag ensures deorbit at the end-of-life and within industry guidelines. As debris is also quickly removed from these orbits the risk of on-orbit collision remains low.

However, despite this range of benefits, challenges to the operation of spacecraft in lower altitude orbits remain and limit their wider use, particularly for commercial missions.

At altitudes below 450 km, known as very low Earth orbit (VLEO), the principal challenge to long-term spacecraft operations is the increased atmospheric density that causes aerodynamic drag with associated orbital decay and eventually re-entry. The high proportion of atomic oxygen (AO) in this altitude range can also erode and damage surfaces and components that come into contact with the atmospheric flow. Such damage to materials may reduce optical transmission qualities with consequences to payload performance and solar-array efficiency or compromise the aerodynamic performance of external surfaces.

Technologies to extend and sustain the operations of spacecraft in VLEO can be broadly classified as either methods of drag mitigation or compensation. Drag mitigation measures aim to reduce the magnitude of the drag experienced in orbit, principally though the geometric design and configuration of the spacecraft and by improving the aerodynamic properties of the materials used on the external surfaces.

Drag compensation, on the other hand, works to directly counteract the drag force experienced by the spacecraft by using methods of propulsion. However, for long-term operation in the VLEO environment, a large volume or mass of propellant may be required, with significant effects on the platform size and design. Atmosphere-breathing electric propulsion (ABEP), a novel class of propulsion system, aims to eliminate this need for on-board propellant by collecting the residual atmospheric gases through an intake and subsequently using this in an electric thruster.

Progress in these areas of aerodynamic material performance, spacecraft geometric design, and novel propulsion systems hold the promise of improving drag mitigation and compensation methods and enabling the sustained operation of spacecraft in VLEO. This paper will explore the potential of these technologies and demonstrate their effect on the design of new VLEO platforms though methods of integrated system modelling.

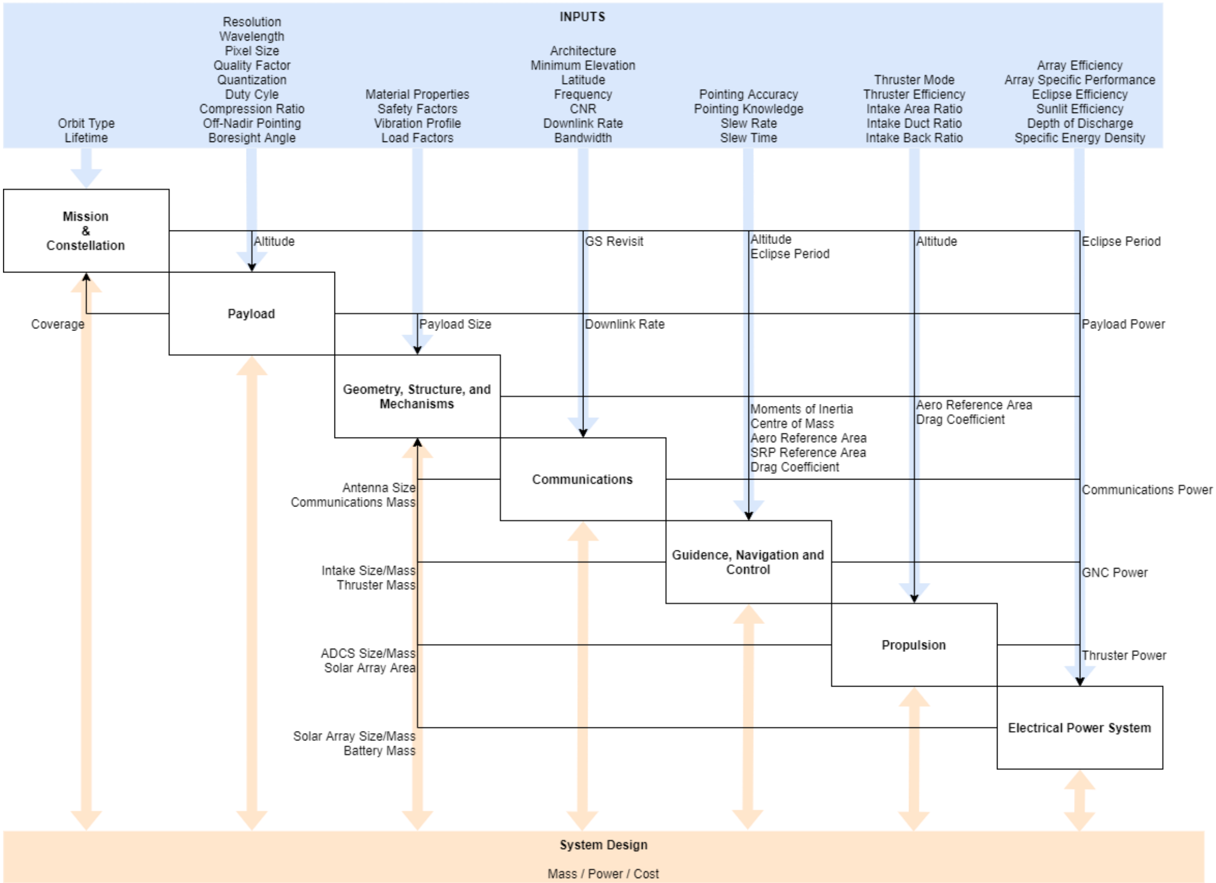

Fig. 1 System modelling framework for VLEO spacecraft.

2. Systems Modelling for VLEO

An integrated system model approach can be used to explore the design of spacecraft at different altitudes in VLEO and to understand the trade-offs associated with different technologies and their level of performance. A representation of a framework for VLEO spacecraft conceptual design containing different systems models is presented in Fig. 1. Critically, for the analysis of VLEO spacecraft, the aerodynamic performance of the design (including the use of novel materials) needs to be captured within the *geometry, structure, and mechanisms* module. The design of novel propulsion systems, for example ABEP can be considered within the *propulsion* module. Descriptions of the further contributing system models are provided in [3].

For a spacecraft operating in VLEO, the design of the external geometry will principally determine the magnitude of drag that must be compensated for to ensure that orbital decay does not occur, and operations can be sustained. Meanwhile, the power requirement of the drag compensating propulsion system may necessitate large solar arrays that may significantly affect the external geometry and magnitude of the drag. This intertwined nature of the aerodynamics and drag compensation propulsion system is indicated by the feedback mechanisms shown in Fig. 1 and can lead to challenges in design convergence.

3. Aerodynamic Modelling

The aerodynamic drag force experienced by an object can be determined from the flow density ρ, relative velocity V_{rel}, reference area A_{ref}, and drag coefficient C_D.

$$F_D = \frac{1}{2}\rho {V_{rel}}^2 A_{ref} C_D \tag{1}$$

As a result of the low density of the atmosphere at VLEO altitudes, the flow condition for a typical spacecraft is typically characterised as free-molecular. Under these conditions, the interactions between the atmospheric gas particles and the spacecraft surfaces dominate the production of aerodynamic forces [4, 5]. For typical materials used on spacecraft, these gas-surface interactions (GSIs) are typically characterised by high levels of energy accommodation and diffuse reemission patterns. As a result, drag is the predominant force generated by aerodynamic interactions in VLEO. For diffusely reemitting materials, the magnitude of this drag is principally related to the total cross-sectional area of the body and not to the specific design or surface orientation.

However, materials that can promote more specular GSI characteristics may hold the potential for significant drag reduction in VLEO. These materials may also be able to produce lift forces of greater magnitude with applications to novel aerodynamic control manoeuvres. Crucially, for specular or quasi-specular interactions, the surface incidence with respect to the flow becomes important to the calculation of the aerodynamic coefficients. To capture these considerations within the design, appropriate modelling of the spacecraft aerodynamics is required.

First, a model that can suitably describe the aerodynamic interactions of the spacecraft surfaces with the flow is needed. A range of GSI models have been developed, with differing assumptions of flow conditions, surface properties, and the subsequent scattering pattern and associated exchange of energy and momentum [4, 5]. These different models are therefore not universally valid and apply to different classes of GSI and assumed material aerodynamic performance.

Maxwell's model [6] combines diffuse and specular particle interactions. The accommodation coefficient (α) is used to define the proportion of particles that are fully accommodated and re-emitted both thermally and diffusely whilst the remaining proportion are reflected specularly. In Fig. 2, the variation of drag coefficient for different accommodation coefficient and surface incidence with respect to the flow is shown. At close to normal incidence, a reduction in accommodation coefficient is shown to result in a significant increase in the drag coefficient. Comparatively, as the surface approaches parallel to the flow, the drag coefficient can be substantially reduced.

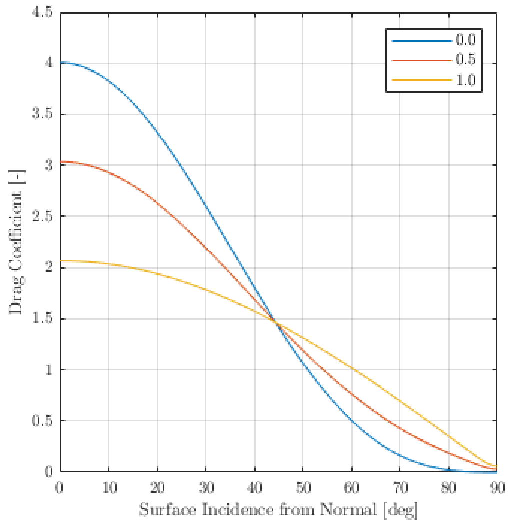

Fig. 2 Drag coefficient for varying surface incidence angle and accommodation coefficient α using Maxwell's model.

Secondly, a means of implementing the selected GSI model to the spacecraft geometry is required. This can be performed using a panel method, in which the aerodynamic coefficients are calculated for a set of discrete panels that comprise the overall geometry. Panel method tools, for example *ADBSat* [7, 8] can be used to perform such calculations for more complex CAD geometries.

Finally, to determine the magnitude of the forces that will be experienced at the different orbital altitudes, an estimate of the atmospheric density is required. The NRLMSISE-00 model will be used to provide this measure.

4. Atmosphere-Breathing Electric Propulsion (ABEP)

Compared to conventional propulsion systems, ABEP aims to eliminate the need for a store of on-board propellant by collecting it from the residual atmosphere. The thruster then accelerates this collected propellant to counteract the experienced drag force. A schematic of the ABEP system concept is provided in Fig. 3.

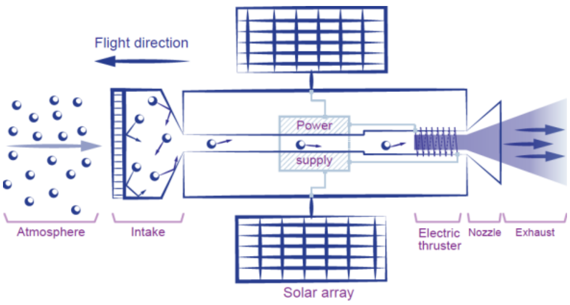

Fig. 3 Conceptual ABEP system schematic [1].

However, to consider ABEP at the conceptual design level, the two principal system components can be considered: the atmospheric intake and the electric thruster.

Like the external performance of a spacecraft in the aerodynamic environment of VLEO, the design of atmospheric intakes is also highly dependent on the geometry used and the GSI performance of the surface materials. The critical parameter for these intakes is the collection efficiency η_c, that effectively describes the proportion of the incoming flow to the intake that is transmitted to the outlet and therefore to the thruster. For intakes designed based on diffuse material performance, the efficiency is restricted to a maximum of approximately $\eta_c = 0.6$. For intakes based on specular or quasi-specular materials, the intake performance is expected to increase to a maximum of $\eta_c = 0.94$ [9].

Thruster designs for ABEP systems differ from conventional electric propulsion as they must be compatible with the variety of gas species present in the atmospheric in-flow. Component degradation by the erosive effects of AO should also be avoided, leading to gridless, electrodeless, and contactless designs. However, given these required developments, ABEP thrusters are expected to have lower efficiencies than conventional thrusters for electric propulsion. ABEP thruster efficiencies have presently been demonstrated to a maximum of $\eta_T = 0.25$ [10].

The power required by an ABEP thruster can be calculated from the propulsive efficiency η_T, required thrust force F_T, mass flow rate into the intake $\dot{m}_c$, and the intake efficiency η_c:

$$P_T = \frac{F_T^2}{2\dot{m}_c \eta_c \eta_T} \qquad (2)$$

5. System Case Studies

The trade-offs for spacecraft operating at different altitudes and with different assumed performances for the spacecraft aerodynamics and ABEP design. A notional platform with an optical Earth observation payload providing a ground resolution of 0.5m is considered to perform these investigations. Further input variables for this platform design are provided in Table 1. It should be noted that in each analysis the benefit of reducing altitude on the payload mass will also reflected.

Table 1 Mission input parameters for the VLEO platform.

Parameter	Value
Design Lifetime [years]	5
GRD [m]	0.5
Payload Power [W]	400
Orbit Type	SSO
LTAN	10:00h
Max Off-Nadir Angle [deg]	20
Max Slew Rate [deg/s]	3

The range of parameters considered within the following analyses are shown in Table 2. For each individual analysis, the midpoint of the remaining two parameters is provided as a constant input variable. Finally, a combined analysis can be performed to show the range of designs and output performance that is available when the different technologies are simultaneously varied.

Table 2 Parameters for the system design exploration.

Parameter	Min	Max
Intake Efficiency	0.3	0.9
Thruster Efficiency	0.3	0.6
Accommodation Coefficient	0.0	1.0

5.1. ABEP Intake

The variation of system mass for different altitudes and ABEP intake efficiency is provided in Fig. 4. The trend presented demonstrates that increasing the intake efficiency enables a general reduction in system mass and also enables design convergence at lower altitudes.

As the intake efficiency of the ABEP system is increased, the mass flow rate to the thruster increases (for the same inlet-to-outlet ratio) and the required power for drag compensation can decrease. The system mass reduction is therefore primarily a result of the reduction in power requirement and associated mass of the solar arrays and/or batteries.

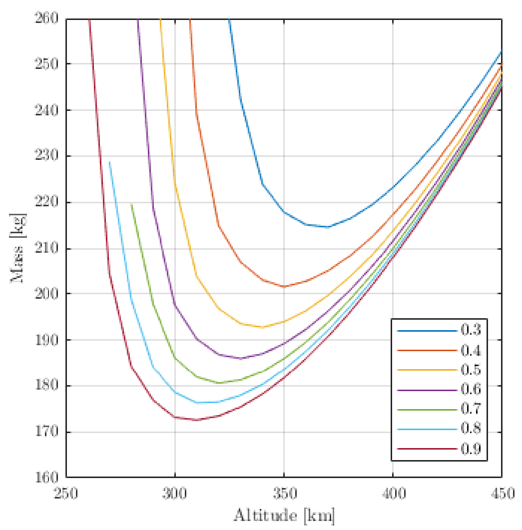

Fig. 4 Variation of system mass with altitude and intake efficiency.

5.2. ABEP Thruster

The variation of system mass for different altitudes and ABEP thruster efficiency is provided in Fig. 5.

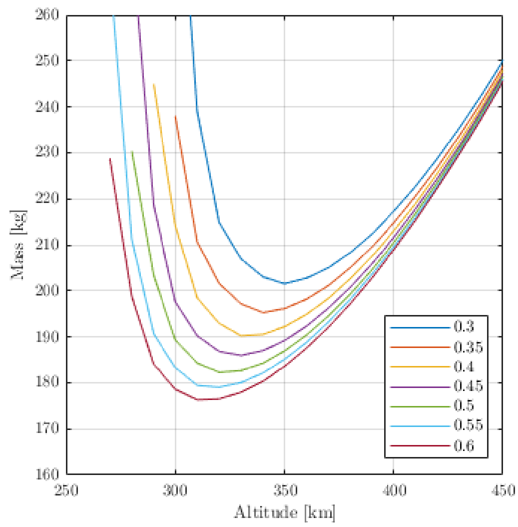

Fig. 5 Variation of system mass with altitude and thruster efficiency.

Like the trend associated with the intake efficiency, the increase in thruster efficiency clearly enables a reduction in system mass and reduces the altitude at which the minimum design mass can be achieved. Again, this is primarily due to the reduction in power required by the ABEP system and therefore the mass of the electrical power system.

5.3. Material Performance

The variation of system mass for different altitudes and the surface accommodation coefficient is provided in Fig. 6.

In contrast to the intake and thruster efficiencies, the variation in the material performance acts to reduce the drag contribution of the solar arrays that increase in required area with reducing altitude to support the drag compensation. Compared to systems that don't have a propulsion system, or would utilise a conventional EP, the forward-facing surfaces for an ABEP-equipped system are typically used to locate the intake and thus cannot benefit from the increased surface aerodynamic performance by being angled to the flow, for example in an optimal wedged shape [11]. Thus, at higher altitudes, where the magnitude of drag is lower, the variation in output system mass with accommodation coefficient is small.

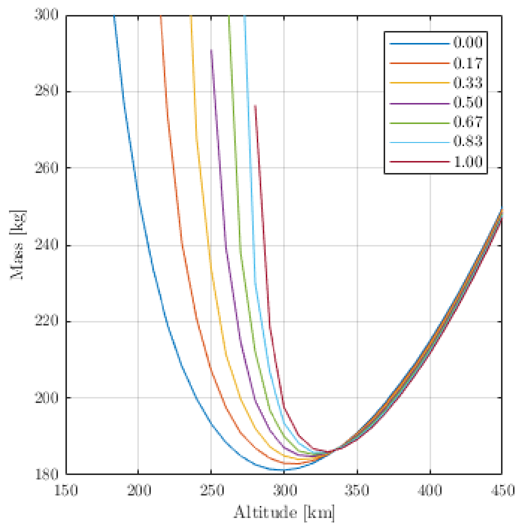

Fig. 6 Variation of system mass with altitude and surface material accommodation coefficient.

However, as the required power increases at reducing altitude, the benefit of reducing accommodation coefficient is demonstrated. A lower accommodation coefficient is shown to enable both a lower mass and a lower altitude. Furthermore, the reduced accommodation coefficient allows design convergence at even lower altitudes despite the increase in mass required to enable such systems.

5.4. Combined Analysis

When the previous analyses are combined, a more complete potential for VLEO platforms based on the level of available technology development can be considered.

The output system mass for combinations of the intake efficiency, thruster efficiency, and material accommodation coefficient are presented in Fig. 7. Given expectations of current technology performance (i.e. $\eta_c = 0.3, \eta_T = 0.3, \alpha = 1$), systems with ABEP are shown to operate sustainably at altitudes of down to approximately 350km.

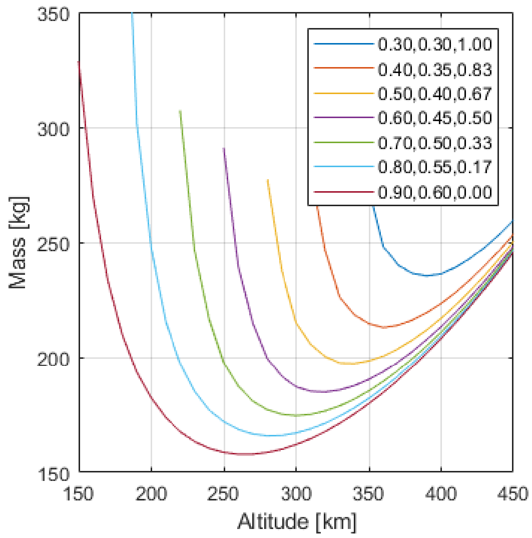

Fig. 7 Variation of system mass with altitude and combined intake efficiency, thruster efficiency, and surface material accommodation coefficient.

Combined advances in performance of the different technologies demonstrate the significant possibility for both reduction in the altitude at which operations can be sustained and also the required system mass.

6. Conclusions

The system exploration shown in this paper demonstrates the significant potential for reduction in mass that operating in VLEO presents. In addition to being strongly linked with the system cost, a reduction in system mass also enables more satellites to be launched on a given vehicle, or for smaller and cheaper launch vehicles to be used.

The use of new propulsion systems, for example ABEP, and the development of materials that can improve the aerodynamic performance are necessary to enable the sustained operations at these lower altitudes.

The results presented herein indicate the benefit that improving component performance can have on the system level design and clearly demonstrates the need for ongoing research and development into these technologies if benefits of lower altitude orbits are to be realised.

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