DOI: 10.13009/EUCASS2017-449

Reducing spacecraft drag in Very Low Earth Orbit through shape optimisation

Jonathan A. Walsh and Lucy Berthoud†
University of Bristol
Queen's Building, University Walk,
Bristol, UK BS8 1TR
jonathan.walsh@bristol.ac.uk
†Corresponding author

Abstract

There is increased interest in operating satellites within the Very-Low Earth Orbit (VLEO) region (less than 300km in altitude) especially for Earth observation missions. However, the aerodynamic forces acting on a satellite increase with decreasing orbital altitude. It is therefore desirable to minimise the drag in order to extend the life of the platform or to reduce the fuel mass fraction. The study presented here explores the use of surrogate models coupled with Direct Simulation Monte Carlo data to optimise the shape of the satellite to reduce the drag.

1. Introduction

Very Low Earth Orbit (VLEO) describes the region of orbital altitudes below 300km in altitude and is characterised by mission-limiting levels of drag from the atmosphere. Despite this, there is considerable interest from both research institutes and industry to operate satellites within this region, as it could provide improvements in payload performance over traditional LEO orbits.[1] For instance, for a given ground resolution, an optical sensor payload operating in VLEO can be much smaller (in size and mass) than a similar sensor operated in a higher orbit. It has also been demonstrated that there would be a reduction in the power requirements as well as improvements in the data rate.[2,3]

While there are certainly many benefits to operating in VLEO there are still a number of challenges.[4] One such challenge is combating the levels of atmospheric drag that a satellite in VLEO would experience. Thus, in order to maintain altitude, a satellite would require regular orbit-raising manoeuvres or a low thrust drag compensation scheme. An example of such a satellite is ESA's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), a 1 077kg Earth observation satellite launched in 2009 to examine the Earth's gravitational field.[5] Operating at an altitude of 260 km, it employed an ion propulsion system to provide the necessary thrust to compensate for the drag it experienced. Under this regime it was able to maintain orbit for 55 months before running out of fuel. JAXA also intend to send their own satellite to this region of orbit called the Super Low Altitude Test Satellite (SLATS) with the aim to studying the effects of atomic oxygen in VLEO. Scheduled for launch in 2017, the 400kg satellite will also employ an ion propulsion system, but is only expected to operate in the area of interst (250-180km) for up to 90 days.[6]

Due to their high specific impulse (I_{sp}), electrical propulsion systems are the ideal choice for supporting long duration drag compensation, however, they still require an appreciable amount of fuel.[7] In both the case of GOCE and SLATS, the life of the platforms are limited by the fuel that they could carry. Furthermore, the fuel required is proportional to the thrust and by extension the drag that the satellite experiences. So it is therefore desirable to minimise the drag as much as practicable, in order to extend the life of the platform or to reduce the fuel mass fraction. It is interesting, therefore to test various satellite geometries, to identify if features such as tapering of the nose and tail could provide any benefit within the rarefied gas of the thermosphere.

In order to answer this question, it is necessary to perform aerodynamic simulations on the satellite body. The atmospheric density in VLEO is so low that the medium is no longer continuous, but can rather be described as a molecular flow (Knudsen Number>1),[8] for which there are a number of simulation methods available. These include analytical methods such as those presented by Sentman.[8] Analytical methods can provide fast estimates of

Copyright © 2017 by J. A. Walsh & L. Berthoud. Published by the EUCASS association with permission.

DOI: 10.13009/EUCASS2017-449

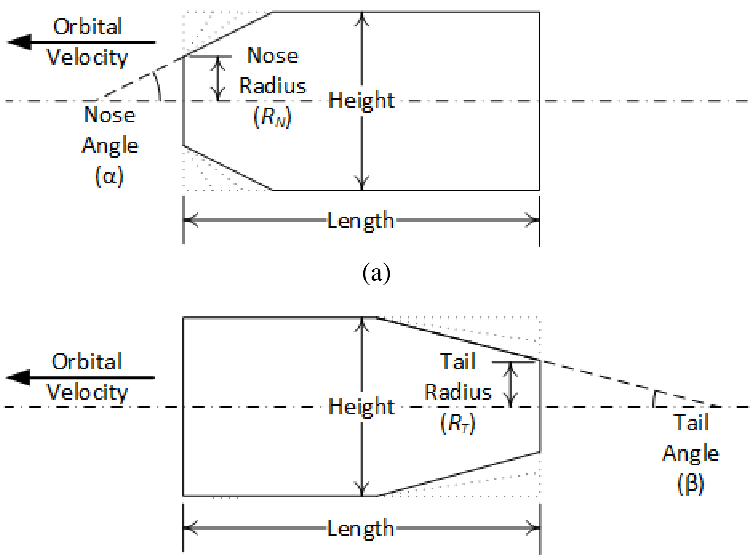
the aerodynamic forces a body might experience but are less useful with more complex shapes, especially where secondary particle-surface interactions occur.[9] Alternatively, particle simulators such as the Direct Simulation Monte Carlo (DSMC) methods pioneered by Bird[10] can provide a more accurate assessment of the aerodynamic forces as they endeavour to replicate the physics behind molecular flow. However, this comes at the cost of longer simulation time. For the work being performed here, the ability to capture the non-linear aspects of the flow around complex bodies is desirable. For this reason the DSMC code 'SPARTA' (which stands for Stochastic PArallel Rarefied-gas Time-accurate Analyzer)[11,12] was used.

As discussed above, performing the simulations using DSMC methods can be time intensive which would normally make it prohibitive to explore the effects of various body configurations and geometries with sufficient fidelity. The solution to this is to employ a surrogate model as demonstrated by Queipo et al[13] for optimising the aerodynamic properties of wings. Surrogate models are able to reduce number of simulations through the careful selection of the sample points and effective interpolation.

This paper will therefore explore the effects of geometry on the aerodynamic forces of satellites operating in VLEO. It will achieve this by using the mathematical technique of surrogate models coupled with data collected from the DSMC software SPARTA.

2. Methodology

2.1 Body Geometry



(a)

(b)

Figure 1: Geometry of simulation body

For this study, it was chosen to focus on the geometry of the central body of the satellite, ignoring the impact of exterior equipment or solar arrays. This meant that the analysis could be simplified to basic 2D axisymmetric bodies. The work examined the effects of Nose and Tail geometry for which two sets of simulations were performed. In the first set, the nose geometry was varied, specifically the interior nose angle (α) and nose radius (R_N) (see Figure 1-a), while the tail geometry was held constant.

A similar set-up was used for the second set of simulations but with the tail geometry varying while the nose geometry was held constant as in Figure 1-b. As with the first set of simulations, the interior tail angle (β) and tail radius (R_T) were the geometric properties that were varied. In order to explore the effect aspect ratio has on the choice of nose and tail geometry in this paper the body's height has been kept constant at 0.5m with body lengths of 0.5m, 1m, 2m, and 4m corresponding to a length to width ratios of 1:1, 2:1, 4:1 and 8:1 respectively.

DOI: 10.13009/EUCASS2017-449

The geometry of the satellite may also be the subject of a number of internal and external constraints. For example the payload and other satellite subsystems have very specific, sometimes bulky, volume requirements. In some instances the payload volume will often dictate the shape of the satellite. It is therefore necessary to place some constraints on the geometries in order to limit the loss of internal volume. A number of constraints will be explored including; fixed cone lengths, fixed cone angles and fixed nose/tail radius. In addition to the constraints, simulation will not be performed on nose geometries with cone lengths greater than half the length of the body, thus limiting the opportunity for unrealistic or unpractical results. A similar but more relaxed constraint is placed on the tail tapering, limiting it to the rear three quarters of the body. This is in order to examine the effects of low tail cone angles and large tail radii on the drag.

In addition to the geometry it is necessary to define the surface properties of the spacecraft for the DSMC simulations as this effects how much energy is transferred to the surface by the particle collisions. For this run of simulations a surface temperature of 300 °K was assumed with a thermal accommodation coefficient of 0.95.[14]

2.2 The Atmosphere

To perform the simulations it is necessary to define the gas properties of the atmosphere in VLEO. VLEO represents a significant range of orbits with diverse atmospheric properties as summarised in Table 1. These properties vary according to the solar cycle, the diurnal cycle as well as the latitude and longitude. To simplify the process, a reduced set of atmospheric conditions was created.

From this data set the average density and equivalent atmospheric temperature were used (Table 1). These densities correspond to 250km altitude during high solar activity and 210km during low solar activity. The velocity was taken to be 7.77km/s, as this is the orbital velocity of the mean of the high and low solar activity orbits.

Table 1: Atmospheric Properties in VLEO

	Minimum	**Maximum**	**Simulation**
Density [kg/m^3]	7.28×10^{-12}	2.49×10^{-09}	1.05×10^{-10}
Temperature [°K]	447	1 438	990
Velocity [km/s]	7.70	7.85	7.77

3. Results & Discussion

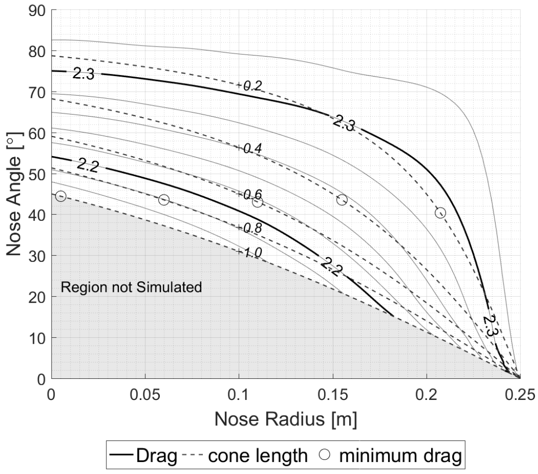
3.1 Nose Geometry

DSMC simulations were performed to assess the effect of nose geometry on the drag of the test bodies. Results are presented in Figure 2. As stated in the methodology, only the nose geometry was varied in these simulations with the tail geometry held constant with no tapering.

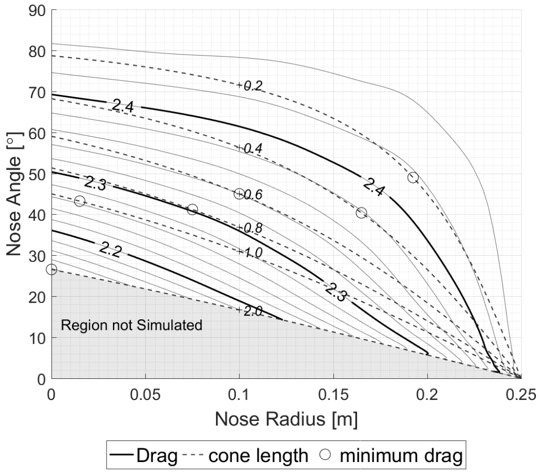
From the general trend of the data in Figure 2a-d and the data in Table 2 it can be seen that to achieve the maximum possible reduction in the drag the lowest possible internal nose angle should be selected with no nose radius. As an example for the 2m test body, this corresponded to a 19% reduction in the drag it experienced. However, the simulations were only performed on nose cones that occupied up to half the length of the test body (i.e. a maximum length of 1m for the 2m test body). Extrapolating this result would suggest the best shape would therefore be a full body wedge. The problem with this result, and the reason a full body wedge was not simulated in the first place, is the loss of internal volume for payload and satellite bus equipment.

In order to minimise the loss of internal volume of the satellite, it may be necessary to constrain the length of the cone further. The dashed lines in Figures 2 a-d represent cones of constant length (see Figure 3 for clarification) as a ratio of the half height of the body (0.125m). It can be seen that when the nose length is constrained, the lowest drag may be achieved using a combination of nose angle and nose radius. In particular if the cone length is less than half the height of the body, the cone angle tends to around 40-45°with a non-zero nose radius. If the cone length is greater than half the height of the body, the lowest drag is achieved at the lowest possible cone angle with no nose radius.

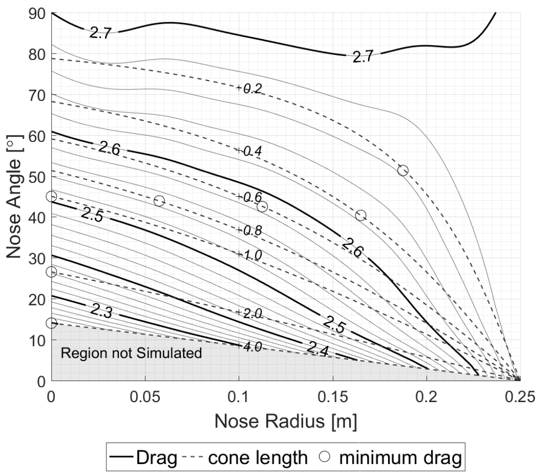
DOI: 10.13009/EUCASS2017-449



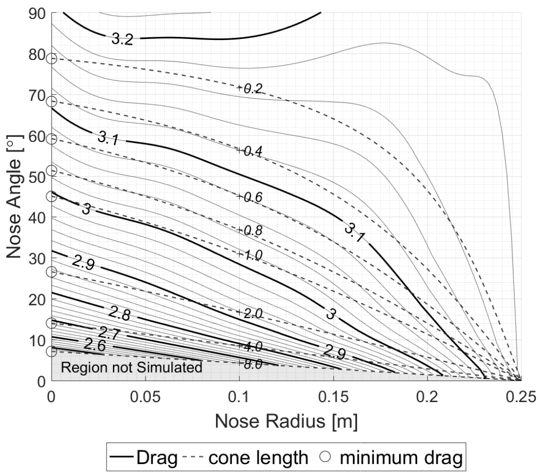
(a) 0.5m (1:1)



(b) 1.0m (2:1)



(c) 2.0m (4:1)



(d) 4.0m (8:1)

Figure 2: Comparison of the effects of nose geometry on the coefficient of drag for different body lengths with the same height (0.25m). The dashed lines represent the nose cone length as a ratio of half the body height (0.125m)

Table 2: Comparison of the effects of nose geometry on the coefficient of drag for different body lengths with the same height (0.25m) under different constraints

Body Length (length:height)	0.5m (1:1)			1.0m (2:1)			2.0m (4:1)			4.0m (8:1)		
	α [°]	R_N $[m]$	C_D $[-]$	α [°]	R_N $[m]$	C_D $[-]$	α [°]	R_N $[m]$	C_D $[-]$	α [°]	R_N $[m]$	C_D $[-]$
Cuboid Block	–	–	2.33	–	–	2.46	–	–	2.72	–	–	3.22
Half-Body Length	45.0	0.00	2.14	27.0	0.00	2.12	14.0	0.00	2.20	7.0	0.00	2.46
Fixed Cone Angle												
30°	30.0	0.11	2.16	30.0	0.00	2.15	30.0	0.00	2.40	30.0	0.00	2.88
45°	45.0	0.00	2.14	45.0	0.00	2.27	45.0	0.00	2.51	45.0	0.00	3.00
60°	60.0	0.00	2.23	60.0	0.00	2.36	60.0	0.00	2.60	60.0	0.00	3.07
Fixed Length												
0.1m	43.5	0.16	2.26	40.3	0.17	2.37	40.4	0.17	2.62	68.2	0.00	3.11
0.2m	43.5	0.06	2.18	41.2	0.08	2.30	43.9	0.06	2.55	51.3	0.00	3.03
0.3m	38.9	0.01	2.12	39.8	0.00	2.23	39.8	0.00	2.47	39.8	0.00	2.96

DOI: 10.13009/EUCASS2017-449

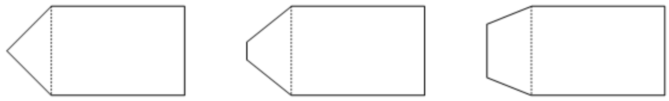


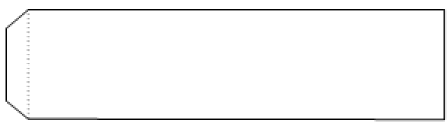
Figure 3: Test bodies with fixed cone length and varying nose angle and nose radius

For instance, for the 2m body with a fixed length of 0.2m, the optimum design is a cone angle of 44°with a nose radius of 0.06m which gives a drag coefficient of 2.55 (Table 2 & 3). Meanwhile for a fixed length of 0.3m, which is greater than half the height of the body, the 2m body has a drag coefficient of 2.47 but with an angle of 39.8°and no nose radius. Compared to the basic cuboid block, the drag reductions of these 0.2m and 0.3m cones correspond to 6.3% and 9.1% respectively. In order to maximise the drag reduction, it is certainly desirable to use a cone who's length is greater than the half height of the body. However, if the length is constrained to be less than half the height of the body then a reasonable reduction in the drag can still be achieved if some nose radius is employed.

In addition to the constraints from internal volume, there may be external factors that constrain the shape such as fairing clearance or being able to integrate multiple satellites on one launcher. This may constrain the nose cone angles that can be used on the satellite. If it is assumed that the nose cone angle is fixed, as can be seen from Table 2, the lowest drag is always achieved at the lowest nose radius. This may be as a result of the higher momentum transfer from the particle collisions on the nose tip surface compared to the tapered surfaces of the cone. On the nose tip the particles' momentum is mostly reversed, resulting in the maximum transfer of momentum to the satellite, while particles striking the tapered sections are only 'glancing off' resulting in lower momentum transfer in the drag direction. Thus, this would generally suggest that having a nose radius may not be desirable, although under certain circumstances, it may provide some benefit.

Given the constraints, it is worth asking whether the reductions in the drag experienced are worth the effort of tapering the nose of the body. This will largely depend on the platform or mission being considered. Assuming a low thrust electric propulsion drag compensation scheme and fixed specific impulse (I_{sp}) the fuel needed to maintain the orbit scales directly with the thrust (F_{thrust}) through equation 1 (assuming a low thrust electric propulsion drag compensation

Table 3: Comparison of optimum nose cone geometries for minimum drag on the 2m body with fixed cone lengths of 0.20m, 0.15m, and 0.10m. All drawings to scale

Fixed Cone Length (m)	Optimum Body for Minimum Drag	C_D (% reduction on no cone)	Volume [m^3]
No Nose Cone		2.72	1.00
0.1		2.62 (3.5%)	0.99 (1%)
0.2		2.55 (6.3%)	0.96 (4%)
0.3		2.47 (9.1%)	0.93 (7%)

DOI: 10.13009/EUCASS2017-449

scheme is employed and $\dot{m}$ is the fuel flow rate). Thus total fuel (M) to maintain the satellite's orbit for a specific period (T) will also scale with the drag. Therefore reducing the drag by 10% would theoretically result in a 10% reduction in the fuel as well. As was discussed above, however, the constraints limit the lowest coefficient of drag achievable, in some cases to the point where there is no significant improvements over the basic cuboid body.

$$\dot{m} = \frac{F_{thrust}}{g_o I_{sp}} \tag{1}$$

$$M = \dot{m}T \tag{2}$$

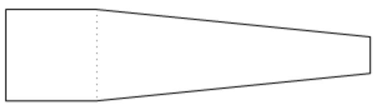
It should be noted that there are some anomalies and artefacts in the graphs in Figure 2. The most noticeable are at the edge cases: as the nose angle tends towards 90°or as the nose diameter tends towards the diameter of the body, the effective shape tends towards the same cuboid block. On the graphs in Figure 2, this is equivalent to the upper boundaries on both axes of the graphs. It would therefore be expected for these edge cases to all tend towards the same coefficient of drag, but as can be seen from the figure, this is not the case. This may be as a result of the interaction between the results of the DSMC simulations and the method employed to create the surrogate model. DSMC methods are stochastic, so a simulation run multiple times using the same input parameters will generate results that will be similar but not equal. This means that when these results are used to train the surrogate model, small errors in the data can become exaggerated, generating anomalous peaks and troughs.

3.2 Tail Geometry

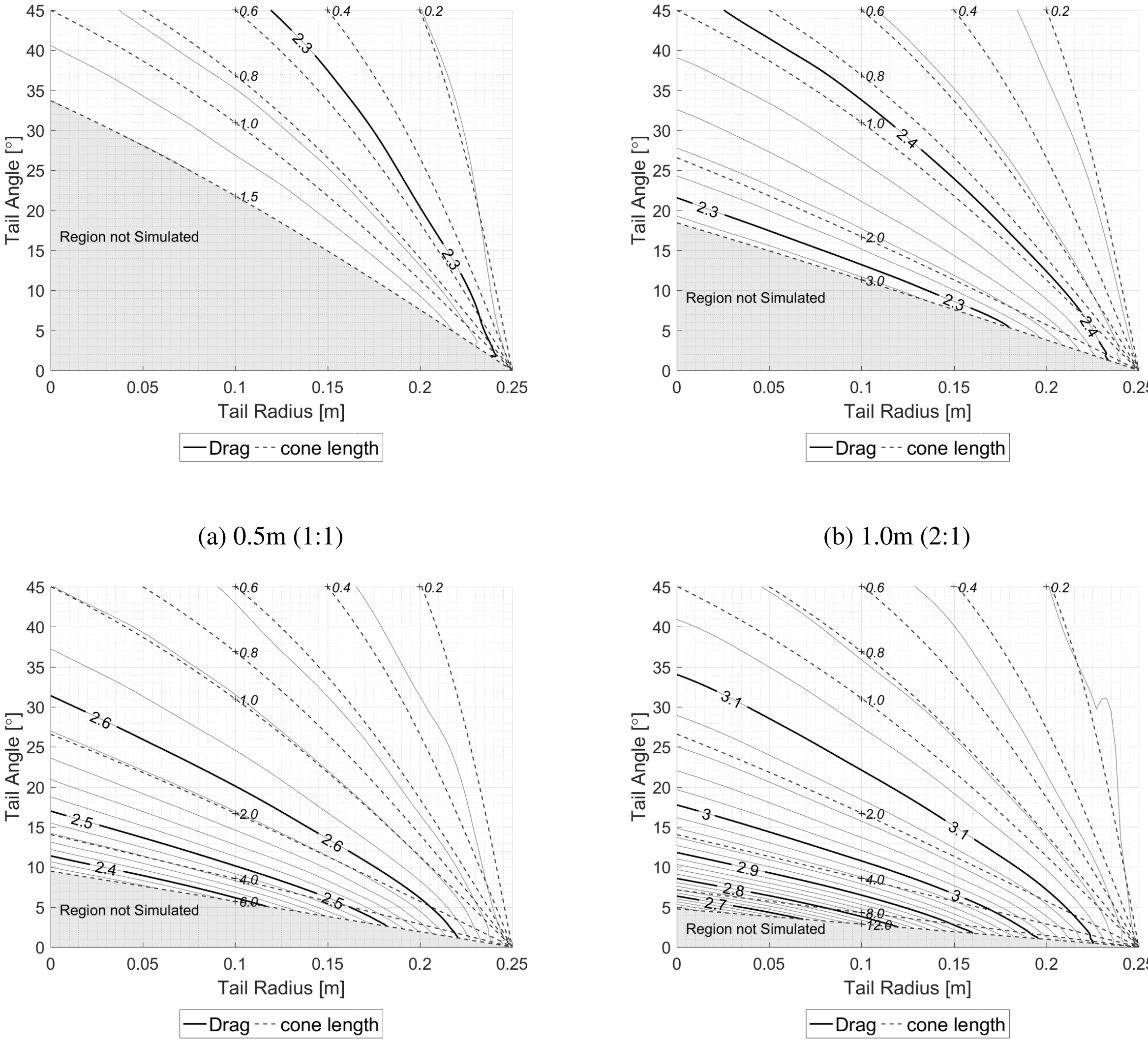
The purpose of the results presented in this section is to investigate whether an appreciable reduction in drag can be achieved by varying the geometry of the rear of the satellite. It can be seen from Table 2 (and Figure 2) that as the length of the body increases so does the coefficients of drag. This increase can be attributed to the increase in the surface area of the top and bottom panels and thus an increase in total shear drag. It has also been observed in previous work, that the drag contribution from surfaces that are turned away from the flow are significantly lower than flow-facing or even parallel surfaces.[7] This is as a result of the fewer particle-surface interactions, as the surface is shaded from the main flow.

In these simulations only the tail geometry was varied, with the nose geometry held constant with no tapering. The results in Figure 4 show that within the rarefied gas environment of VLEO, the tail geometry can have an effect on

Table 4: Comparison of optimum tail cone geometries for minimum drag on the 2m body with fixed tail radii of 0.20m, 0.15m, and 0.10m. All drawings to scale

Fixed Tail Radius (m)	Optimum Body for Minimum Drag	C_D (% reduction on no cone)	Volume [m^3]
No Nose Cone		2.72	1.00
0.20		2.54 (6%)	0.92 (8%)
0.15		2.44 (10%)	0.85 (15%)
0.10		2.39 (12%)	0.78 (22%)

DOI: 10.13009/EUCASS2017-449



(a) 0.5m (1:1)

(b) 1.0m (2:1)

(c) 2.0m (4:1)

(d) 4.0m (8:1)

Figure 4: Comparison of the effects of tail geometry on the coefficient of drag for different body lengths with the same height (0.25m). The dashed lines represent the nose cone length as a ratio of half the body height (0.125m)

Table 5: Comparison of the effects of tail geometry on the coefficient of drag for different body lengths with the same height (0.25m) under different constraints

Body Length (length:height)	0.5m (1:1)			1.0m (2:1)			2.0m (4:1)			4.0m (8:1)		
	β [°]	R_T $[m]$	C_D $[-]$	β [°]	R_T $[m]$	C_D $[-]$	β [°]	R_T $[m]$	C_D $[-]$	β [°]	R_T $[m]$	C_D $[-]$
Cuboid Block	–	–	2.34	–	–	2.46	–	–	2.7	–	–	3.19
Fixed Length												
25% of length	63.4	0.00	2.30	45.0	0.00	2.39	26.6	0.00	2.59	14.0	0.00	2.95
50% of length	45.0	0.00	2.27	26.6	0.00	2.33	14.0	0.00	2.46	7.1	0.00	2.74
75% of length	33.7	0.00	2.24	18.4	0.00	2.27	9.5	0.00	2.34	4.8	0.00	2.61
Fixed Tail Radius												
0.10m	21.8	0.10	2.24	11.31	0.10	2.28	5.71	0.10	2.39	2.86	0.10	2.76
0.15m	14.9	0.15	2.24	7.60	0.15	2.28	3.81	0.15	2.44	1.91	0.15	2.87
0.20m	7.6	0.20	2.24	3.81	0.20	2.33	1.91	0.20	2.54	0.95	0.20	3.02

DOI: 10.13009/EUCASS2017-449

the drag that the satellite experiences, though this effect is smaller than that of the nose geometry. For instance, the maximum potential reduction in drag as result of the Tail Geometry for the 2.0m body is 13% compared to 19% as a result of nose geometry.

As in the previous section it is important to consider the potential shape constraints on the body, since these will limit the achievable drag coefficients. Maximising the volume could be achieved by limiting the length of the tail and maximising the tail radius. It can be seen from Figure 4 a-d, that at low tail radii, the coefficient of drag is roughly proportional to the length of the tail (dashed lines in Figure 4) and only appears to be affected by the tail radii as the diameter approaches the width of the body. This means it is possible to increase the tail radius without significantly increasing the drag, therefore maximising the volume. As an example, for a fixed tail length of 1.5m with a 0.1m tail radius, the 2.0m body will have a $C_D = 2.39$. This is a reduction of 12% over the cuboid body, compared to 13% for the same tail length but no tail radius. However, the 0.1m tail radius would only lose 22% of the internal volume, compared to 38% of the internal volume with no tail radius. Increasing the tail radius further to 0.2m tail radius gives a $C_D = 2.54$ (a 6% reduction) but with a loss of internal volume of only 8% (see Table 4. So a reasonable reduction in the drag can still be achieved even with a large tail radius, thus limiting the impact on the internal volume.

As described above, the tail geometry can reduce the drag experienced. However, this comes at the cost of internal volume and potential mounting area at the rear of the satellite, such as for the propulsion system or launch adaptor. For bodies similar in aspect ratio to the 0.5m (1:1) and 1.0m (2:1) bodies, tapering the rear of the satellite is unlikely to provide sufficient benefit. For instance the 0.5m (1:1) body only had a potential (unconstrained) improvement in drag of 4% which means that the savings in fuel would likely be insufficient to offset loss of internal volume. This is because these bodies are dominated by the pressure drag on the front surfaces, so reducing the shear drag on the upper and lower surfaces have limited impact on the overall drag. For the longer bodies such as 2.0m (4:1) and 4.0m (8:1), some form of tail cone can help to reduce the drag. It is likely that it would be necessary to find a compromise between the various parameters to achieve the best possible reduction in drag, particularly if the tail is paired with an appropriate nose cone.

4. Conclusions

This paper has presented work to identify whether tapering the front (nose) and rear (tail) of the satellite can reduce drag while operating in VLEO. The results presented were calculated using a surrogate model which drew on a number of DSMC simulations.

It was seen that in both the case of the nose and tail, the best improvements in drag reduction were achieved using the lowest available cone angle with no nose or tail radius. Though it should be noted that in general varying the properties of the nose geometry had a greater effect on the drag than that of the tail geometry.

Since tapering as much as possible removes a large amount of the spacecraft volume, possible geometric constraints and their effects such as minimising the loss of internal volume and maximising cone length were discussed. For instance, when the cone length was less than half the height of the body, the minimum drag was achieved when the cone angle was 40-45°and the nose radius was none zero. If the cone length was greater than half the height of the body, the minimum drag was achieved at the smallest available nose cone angle with a nose cone radius of zero.

For the tail geometry it was shown that for the longer bodies, reasonable reductions in drag could be achieved even with a large tail radius. This was as a result of the fewer particle-surface interaction taking place as the tapered surfaces were shaded by the front of the body. It was also demonstrated that when the tail radius was small, the drag coefficient was roughly proportional to the tail length. In general this meant the longer the tail the lower the drag the satellite test body experienced. By comparison for the shorter bodies, while there was an improvement in the drag as a result of tapering the rear of the satellite, it was seen that the improvement was small and would possibly not offset the loss of internal volume.

5. Further Work

The work presented here focused on bodies of fixed frontal area. Future work will include optimising the shape for a fixed volume assuming the length, height, and nose and tail geometries vary. Additionally, this work has focused on the drag of the satellite, as this limits the operational life. However, since drag has increased as a result of the higher density in VLEO, so too do the aerodynamic moments on the spacecraft which affect its stability. Part of the next stage

DOI: 10.13009/EUCASS2017-449

of work will therefore focus on what impact the shape has on the platform's orientational stability.

6. Acknowledgements

The authors would like to thank Professor Chris Allen and Andrew Bacon from Thales Alenia Space UK. The views expressed in this paper do not represent those of Thales Alenia Space UK. The work performed here was funded under EPSRC grant number 15220191.

References

[1] D. G. Fearn. "Economical remote sensing from a low altitude with continuous drag compensation". In: *Acta Astronautica* 56.5 (2005), pp. 555–572.

[2] A. Green. "An Ultra Low Altitude Synthetic Aperture Radar Micro-Satellite". MA thesis. University of Bristol, 2011.

[3] A. Grasso. "Feasibility Study of an Ultra-Low Altitude Hyperspectral Micro-Satellite". MA thesis. University of Bristol, 2011.

[4] J. Virgili Llop et al. "Very Low Earth Orbit mission concepts for Earth Observation: Benefits and challenges". In: *12th Reinventing Space Conference* January 2016 (2014), pp. 1–18.

[5] GOCE flight control team (HSO-OEG). *GO-RP-ESC-FS-6268: GOCE End-of-mission operations report*. Tech. rep. 2014, pp. 1–193.

[6] ESA. *SLATS (Super Low Altitude Test Satellite)*. 2017. URL: `https://directory.eoportal.org/web/eoportal/satellite-missions/s/slats` (visited on 05/26/2017).

[7] J. A. Walsh and L. Berthoud. "Is it possible to integrate Electric Propulsion thrusters on Very-Low Earth Orbit Microsatellites ?" In: *Space Propulsion 2016*. May. Rome, 2016.

[8] L. Sentman. *Free molecule flow theory and its application to the determination of aerodynamic forces*. Tech. rep. 1961.

[9] D. A. Vallado and D. Finkleman. "A Critical Assessment of Satellite Drag and Atmospheric Density Modeling". In: *Acta Astronautica* 95.1 (2014), pp. 141–165.

[10] G. A. Bird. *Molecular gas dynamics and the direct simulation of gas flows*. 2nd ed. Sydney: Oxford : Clarendon Press, 1994. ISBN: ISBN0198561954.

[11] Sandia National Laboratories. *SPARTA Direct Simulation Monte Carlo (DSMC) Simulator*. URL: `http://sparta.sandia.gov/` (visited on 05/29/2017).

[12] M. A. Gallis et al. "Direct simulation Monte Carlo: The quest for speed". In: *29th International Symposium on Rarefied Gas Dynamics*. Vol. 27. 2014. 2014, pp. 27–36.

[13] N. V. Queipo et al. "Surrogate-based analysis and optimization". In: *Progress in Aerospace Sciences* 41.1 (2005), pp. 1–28.

[14] K. Moe and M. M. Moe. "Gas-Surface Interactions in Low-Earth Orbit". In: *27th International Symposium on Rarefied Gas Dynamics*. 2010.