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Fast Aerodynamic Establishment of a Constellation of CubeSats

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Abstract
The lack of long-duration propulsion has seen CubeSat constellation operators resort to aerodynamic accelerations to establish their constellations. By utilising a discrete set of maximum and minimum drag, current algorithms have demonstrated a great deal of competency in establishing constellations. Built upon these methods, a new algorithm is proposed for constellation establishment that makes use of intermediate drag accelerations - not just maximum and minimum drag. In doing so, the new algorithm reduces the maximum distance travelled by satellites within the constellations. Orbit propagations indicate that a constellation of CubeSats can be established 40% faster than legacy methods.

1. Introduction

The compactness and cost-effectiveness of CubeSats has dramatically increased the accessibility of space. Resultantly, there is a growing group of organisations who utilise CubeSats for their constellations. One such entity is Planet – an operator of constellations of over 100 CubeSats that provide up-to-date, cloud free imagery of the entire Earth. However, the use of CubeSats does not come without compromise. The limited volume, mass and power available to CubeSats restricts their operational utility. Most pertinent is the impracticability of long-duration propulsion for constellation manoeuvring. This is particularly problematic when CubeSats are released from a single launch vehicle and must disperse to establish the constellation. Varying the along-track launch velocity of each spacecraft from a single launch position has shown to create enough relative mean motion to separate spacecraft [1]. In this case, it was assumed that the variation in along-track velocity was caused by special launch pods or by rotating the launch vehicle to change the along-track velocity component [1].

However, as secondary payload, many CubeSat constellation operators have little control over the launch velocity of the CubeSats. This results in CubeSats typically being launched, in a localised bunch. In this instance, manoeuvring is required after launch to disperse the satellites to the correct relative position within the constellation [2]. Furthermore, for many constellation operators, the precise positioning of satellites is critical to their service offering. In the case of Planet, if the satellites are not spaced properly then parts of the Earth will not be imaged.

Operators have used differential drag in Low Earth Orbit (LEO) to create the relative motion required for constellation establishment [2]. Given the small magnitude of differential drag, and the large distances involved, constellation establishment takes in the order of months to complete [2]. This represents significant downtime and a large opportunity cost for the stakeholders. Therefore, manoeuvring algorithms that minimise the time taken to establish a constellation are of importance to constellation operators.

This paper takes a more encompassing view of aerodynamics on a spacecraft to produce a quicker differential drag based establishment algorithm for coplanar constellations of equispaced satellites such as those flown by Planet. Furthermore, orbit propagations of the new algorithm are conducted to compare its constellation establishment time with the method successfully implemented by Planet [2].

2. Background

2.1 Manoeuvring Spacecraft using Aerodynamics

As spacecraft orbit through the rarefied atmosphere in LEO, the particles of the atmosphere enact an acceleration on the spacecraft that can be decomposed into lift and drag. The lift is taken as the component that acts perpendicular to

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the velocity of the spacecraft relative to the atmosphere and the drag is the component that acts opposite the same velocity. The drag acceleration experienced by a spacecraft can be expressed by equation (1).

$$a_{drag} = -\frac{1}{2}\rho v^2 A C_D \tag{1}$$

Where a_{drag} is the drag acceleration, ρ is the atmospheric density, v is the velocity of the spacecraft relative to the atmosphere, A is the reference area of the satellite, and C_D is the drag coefficient. The drag coefficient accounts for the spacecraft's shape, particle-surface interaction, and angle from the relative velocity of the atmosphere (angle of attack) [3, 4, 5, 6]. Of all parameters is equation (1), the drag coefficient is used to change the drag acceleration by altering the angle of attack of the spacecraft. The variation of the drag coefficient of a flat plate over changing angle of attack is demonstrated by a physics based analytical model developed by Sentman et. al. [5, 6] and shown in Figure *1*.

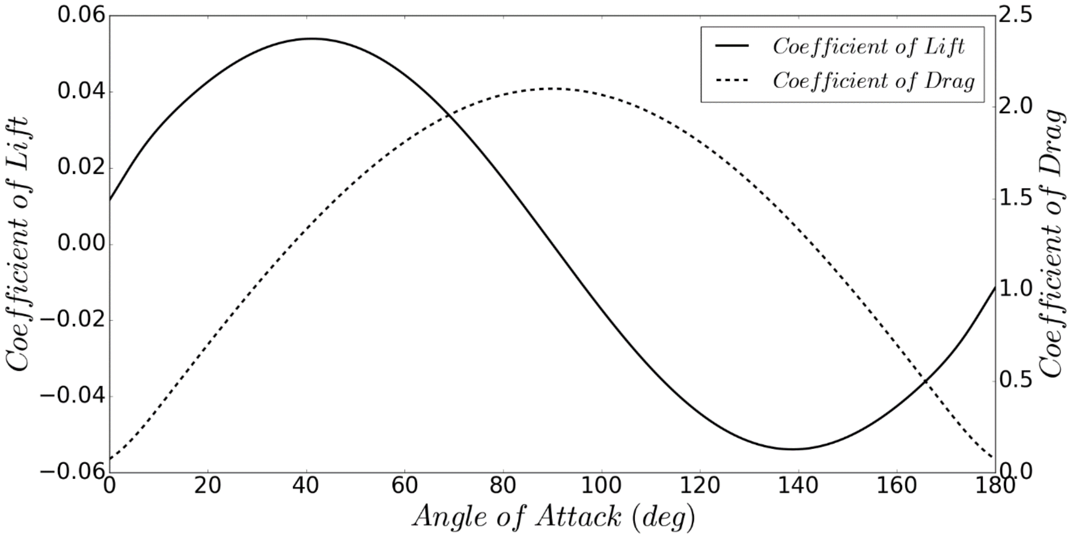

Figure 1: Variation in drag and lift with angle of attack

The aerodynamics of a CubeSat with relatively large solar panels, such as those used by Planet shown in *Figure 2*, will be dominated by the aerodynamics of the flat plate like solar panels. Therefore, the nature of the drag and lift coefficient on a CubeSat with large solar panels can be approximated by that in *Figure 1*.

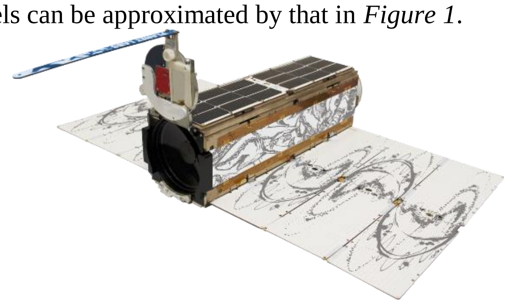

Figure 2: A CubeSat used within Planet's constellations [7]

As *Figure 1* shows, the drag coefficient is maximum when the plate is angled at 90 degrees to the relative wind velocity, the drag coefficient is minimum when the plate is aligned with the relative wind velocity, and any orientation in between produces an intermediate value of drag. Figure 3 depicts what the orientation of a CubeSat looks like for different drag accelerations.

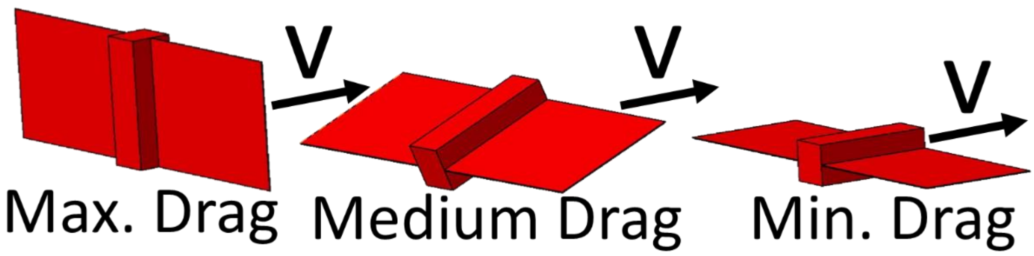

Figure 3: Demonstration of maximum drag, medium drag, and minimum drag

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In the context of spacecraft constellations, relative motion between satellites can be actuated by a difference in the drag acceleration, called differential drag. For identical spacecraft orbiting in an identical environment, differential drag is caused by a difference in the angle of attack. Historic constellation establishment and formation flying algorithms have only considered the differential drag caused by the difference in maximum and minimum drag [2, 8, 9, 10]. This creates the set of ternary drag states shown in Figure *4*: maximum differential drag, no differential drag and reversed maximum differential drag.

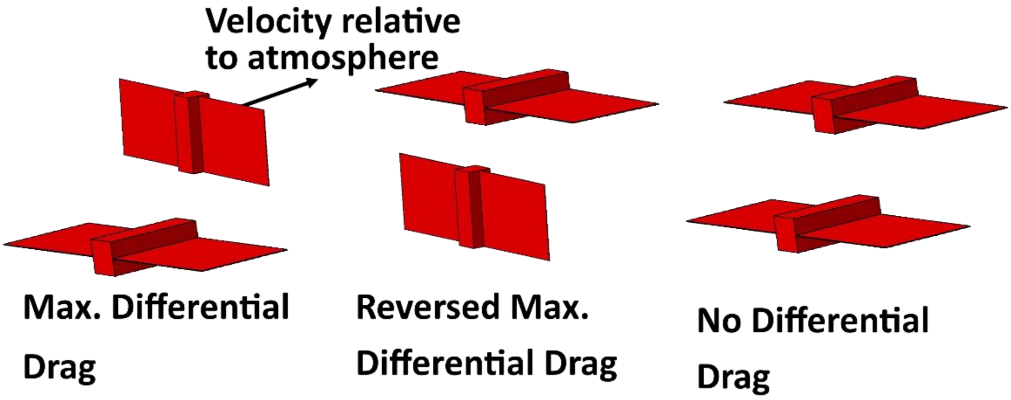

Figure 4: The set of ternary differential drag states commonly assumed in formation control algorithms

However, considering Figure *1*, differential drag can be achieved using any attitude that does not result in the same drag coefficient. While the ternary differential drag set encompasses the strongest differential drag accelerations, it is unnecessarily limiting. Realistically, any differential drag configuration should be considered if it results in more optimal manoeuvring. Differential drag associated with intermediate angles of attack will form the basis for the more optimal constellation establishment algorithms presented in this paper.

2.2 Legacy Constellation Establishment Algorithm

This paper seeks to improve the establishment time of coplanar constellations of satellites using aerodynamic accelerations. An algorithm utilised effectively to establish these kinds of constellations is that published by Planet (formerly Planet Labs) [2]. Planet used this algorithm to establish their Flock 1C constellation pictured in *Figure 5*. Given its implementation in the real world, this algorithm will be used as a baseline for comparison to the new algorithm presented in this paper.

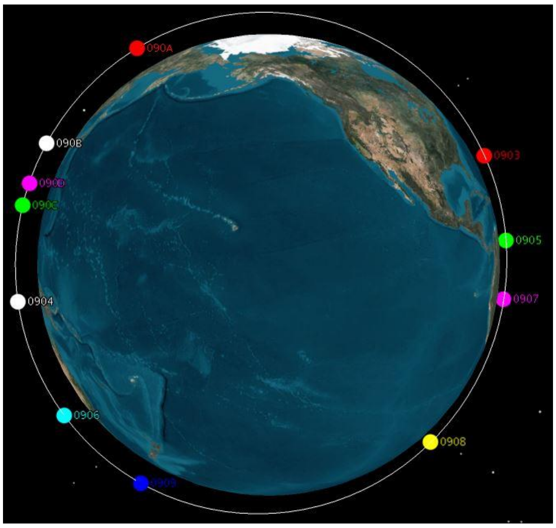

Figure 5: Demonstration of the position of Planet's Flock 1C satellites

Succinctly, the algorithm utilised by Planet is as follows:

1. Directly after launch the satellites are left to disperse due to subtly different launch velocities, or are commanded to disperse using differential drag manoeuvres.

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2. The spacecraft with the smallest semi-major axis is designated as the leader. All other spacecraft are assigned into slots, where each slot is an equispaced relative angular position compared to a leader. The slot's relative angular position remains constant throughout the leader's orbit. Slots are assigned all other spacecraft based on what results in the quickest establishment time.
3. The leader spacecraft attains minimum drag throughout manoeuvring. All other spacecraft nominally attain minimum drag as they drift behind the leader due to their naturally different mean motion.

After the assignment of slots to the spacecraft, the following algorithm is used to allocate high drag windows (periods of maximum drag) to each non-leader spacecraft:

1. Compute the mean angular distance of each satellite to the desired slot relative to the previous leader;
2. Compute the mean angular velocity of each satellite relative to the previous leader;
3. Compute the mean angular acceleration in high drag and low drag configuration;
4. Assign the new leader to be the satellite with the lowest semi-major axis;
5. For all other satellites:
    a. Calculate the relative mean angular distance and relative mean motion compared to the new leader;
    b. Find the time required to nullify the relative mean motion using differential drag;
    c. Determine the angle travelled during the nullification of the relative mean motion;
    d. Work out the "wait time" after which the differential drag manoeuvre will result in the desired slot.
    e. Create the high drag window.

In effect, this algorithm calls for the leader and all other spacecraft to nominally attain low drag when they are not generating power or downlinking data. Resultantly, no differential drag is used to accelerate the relative mean motion of the satellites beyond the subtle difference in their launch mean motion.

Furthermore, Planet have adhered to the common practice of only employing minimum and maximum drag states. While the differential drag is strongest between maximum and minimum drag, limiting the manoeuvring to only these two states results in particular traits. For instance, in Planet's algorithm, the leader is the lowest, fastest spacecraft – spacecraft 090C in Figure 6. All other spacecraft fall behind the leader, that is, relative motion is only in one direction. This results in some spacecraft having to travel very large relative distances. For example, with reference to Figure 6, spacecraft 090B must fall behind 300° in order to achieve a 60° lead angle – it takes the longer route. There is scope to build upon Planet's algorithm by allowing spacecraft to travel ahead of the leader to achieve a lead angle rather than falling behind more than 180° relative mean argument of latitude.

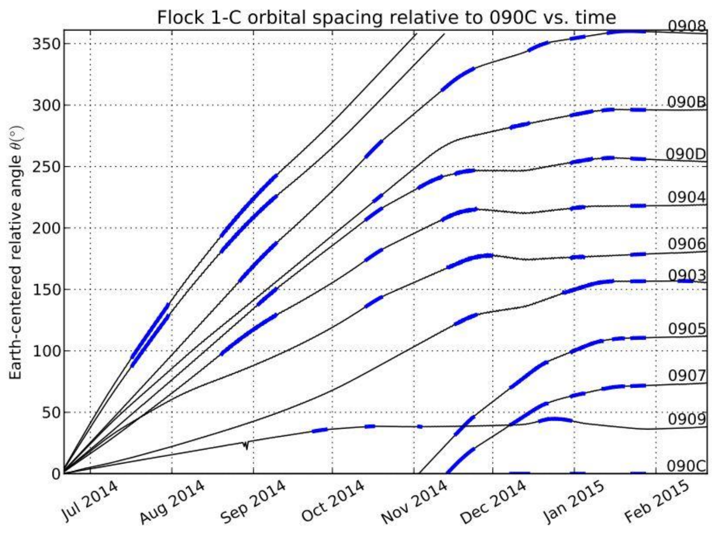

Figure 6: Actual Planet Flock 1-C position relative to the leader, 090C, measured using ranging data [2]

3. More Optimal Constellation Establishment Algorithm

3.1 Constellation Establishment Algorithm

In attempting to improve the speed of constellation establishment, emphasis will be placed on achieving bidirectional motion. That is, relative motion backwards and forwards of the leader spacecraft. This focus has resulted in the following algorithm for constellation establishment:

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1. Initial Launch

The spacecraft with the median semi-major axis is assigned the leader - the green spacecraft in Figure 7. The leader maintains a medium drag acceleration throughout manoeuvring, allowing all other spacecraft to attain a higher or lower drag acceleration independently.

The half of the constellation with smaller semi-major axes (higher mean motion) attain a maximum drag state. The high drag increases their mean motion causing the spacecraft to accelerate ahead of the leader. These spacecraft are therefore designated the “advancers”.

The half of the constellation with larger semi-major axes (slower mean motion) realise minimum drag. This minimises the increase in mean motion due to orbit decay. Subsequently, they fall behind the leader at an accelerating rate. These spacecraft are called “laggers”.

Slots are assigned to the spacecraft based on the magnitude of their semi-major axis relative to the leader. Spacecraft with a semi-major axis near the leaders are assigned close slots; these are the orange and blue spacecraft in Figure 7. Spacecraft with a greater relative semi-major axis (larger relative mean motion), the red and purple spacecraft in Figure 7, are assigned to further slots as their higher relative speed will minimise the time taken to intercept their distant slot.

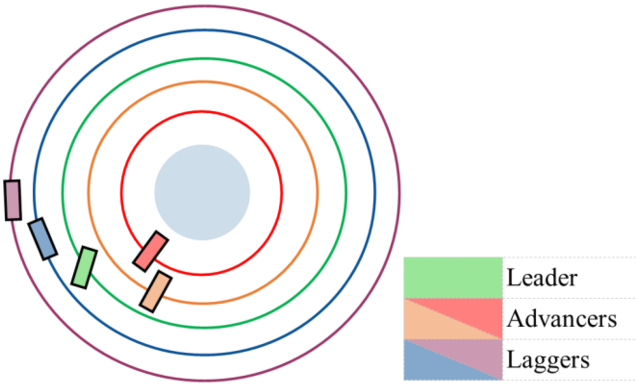

Figure 7: Spacecraft attain their drag state after initial launch

2. Drag Switching

As an advancer approaches its designated slot, it switches to minimum drag, the orange spacecraft in Figure 8. In doing this, its increase in mean motion due to orbit decay is slower than the leader. When timed perfectly, the relative mean motion is nullified just as the advancer arrives in its slot.

Independently, the inverse occurs for a lagger approaching its slot, it switches to maximum drag, the blue spacecraft in Figure 8, accelerating its relative mean motion towards that of the leader. The mean motion is zeroed as the lagger arrives in its slot.

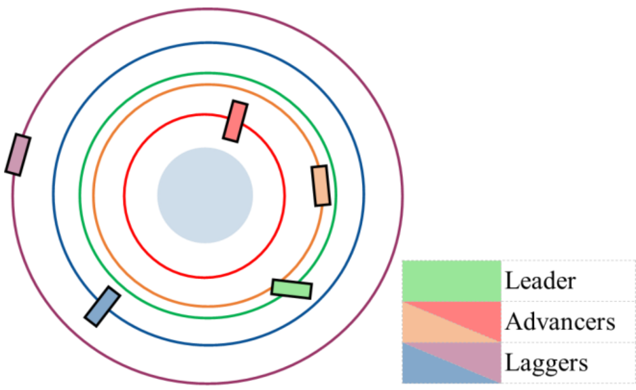

Figure 8: Advancers and laggers independently switch their drag state to converge upon their slot

During this process some spacecraft will arrive in their slot before others. In this instance, the arriving spacecraft attain the same intermediate drag as the leader, resulting in no differential drag, and stabilising their relative position as shown by the orange and blue spacecraft in *Figure 9*.

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Meanwhile, the spacecraft not yet in their slots can continue to manoeuvre independent of all stabilised spacecraft, eventually reversing their drag state, and entering their slots as shown in *Figure 10*.

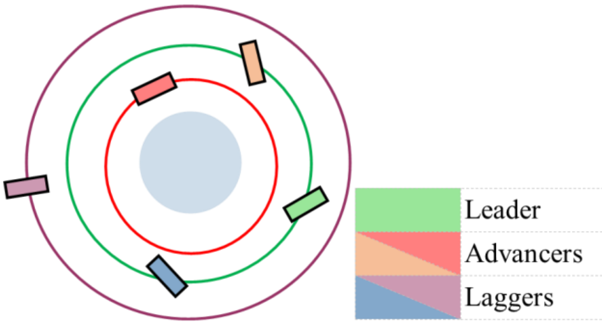

Figure 9: Arrived spacecraft attain the same medium drag as the leader to stabilise their relative motion

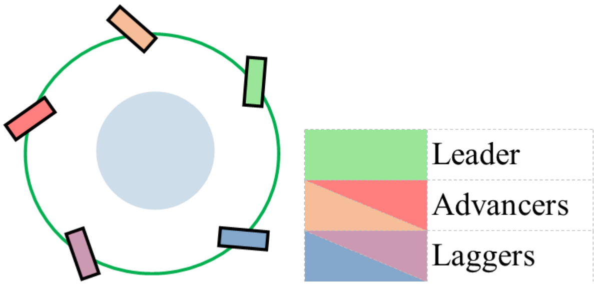

Figure 10: The constellation is established when the last spacecraft arrives in its slot

By considering intermediate drag, this new algorithm has achieved bidirectional relative motion - half of the constellation advance ahead of the leader and the rest of the constellation fall behind simultaneously. Therefore, the largest relative angular distance that needs to be travelled is 180° - less than what is required of Planet's algorithm. Furthermore, differential drag is used to accelerate the motion relative to the leader instead of relying on the natural drift after launch. However, the new algorithm compromises on the weaker strength of the differential drag created between maximum/minimum drag and medium drag. Therefore, any improvements are not obvious and simulations are required to validate any enhancement in establishment time.

3.2 Practical Considerations

While it is convenient to formulate establishment algorithms for satellites operating in an ideal world, some practical considerations also have to be made. Firstly, the operation of the constellation sometimes necessitate that the satellites point at the Earth (the nadir direction). This could be for remote sensing, downlinking data, or communications purposes. By rotating the drag surface about the nadir axis, as shown in *Figure 11*, it is possible to change drag accelerations while always pointing at nadir. Thus, the new algorithm is compatible with this constraint.

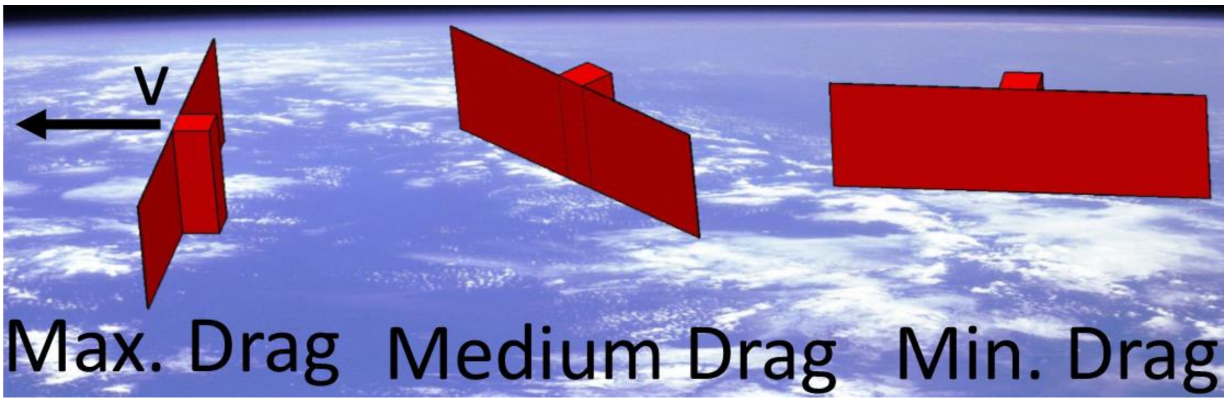

Figure 11: Spacecraft change drag acceleration without turning away from the Earth

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Optimal solar power generation requires the solar panels to be perpendicular to the incoming solar radiation. The attitude required for power generation may result in adverse drag accelerations and compromise the manoeuvring required of the new constellation establishment algorithms. If power generation is required, it is possible to pause manoeuvring, recharge then recommence manoeuvring. While the pause in manoeuvring will delay constellation establishment, it may be a necessary trade-off and will not compromise the overall ability to establish the constellation. Additionally, it must be noted that power generation and data downlinking was performed by Flock 1C and likely extended the constellation establishment time beyond what could be achieved by Planet's algorithm alone.

It is difficult to perfectly predict when the drag acceleration should be switched to stabilise the relative motion with the leader. Numerical orbit propagators provide a tool to estimate when the drag acceleration should be switched, however, the inaccuracies in the model, particularly the inaccuracy in space weather forecasting, mean that the final slot achieved in real life may differ from what was predicted. More sophisticated adaptive control methods may be necessary to guide spacecraft to their slots amongst environmental uncertainties.

4. Simulations

4.1 Constellation Establishment

To test the performance of the new algorithm, simulations were conducted in NASA's General Mission Analysis Tool R2016a (GMAT), a high fidelity orbital propagator. In the new algorithm, the longest possible completion time is that of a spacecraft that has to travel to the longest possible relative angular distance. Therefore, an advancer was simulated with a slot assigned to be 180° relative argument of latitude. A lagger was also simulated to demonstrate the ability to move fore and aft of the leader simultaneously. In this case, the lagger was assigned to a slot at -70° relative argument of latitude.

The maximum and minimum drag surface area of the spacecraft were taken to be the same as a Planet CubeSat [2], shown in *Table 1*. GMAT does not calculate the drag acceleration based on spacecraft angle of attack. Therefore, the medium drag acceleration was created by setting the drag surface area to the average of the maximum and minimum drag surface area. In all drag states the coefficient of drag was constant. For the most valid comparison to Planet's constellation establishment, the initial orbit was set to the same orbit as spacecraft 090C from Flock 1C, the leader in [2], by reading its state from Planet's online ephemeris [11]. The simulation date was set to a similar date to the launch of Flock 1C so that the space weather modelled within GMAT was representative of the actual space weather experienced by Flock 1C.

A list of conditions used in the simulations can be found in the following table:

Table 1: Assumptions used during simulations

Parameter	Value
Gregorian UTC epoch	26 Aug 2014 11:30:43.000
Area for maximum drag	0.195 m^2
Area for minimum drag	0.02 m^2
Area for medium drag	0.116 m^2
Drag coefficient	2.2
Integrator	RungeKutta89
Initial step size	1
Gravity model	EGM96: degree 20; order 20
Atmospheric model	MSIS90
Mass	4
Position X J2000	4644.456 km
Position Y J2000	-4254.844 km
Position Z J2000	3027.555 km
Velocity X J2000	1.606779 km/s
Velocity Y J2000	-3.060554 km/s
Velocity Z J2000	-6.717327 km/s

An iterative process was used to determine the required time of the advancer and lagger to intercept their slot and switch their drag. There is scope to develop a way of predicting the time to switch drag in future work.

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4.2 Sensitivity Analysis

In reality, the initial conditions of a constellation of spacecraft after launch are not identical. There will be subtle differences in their initial state due to differences in their launch time and velocity. The sensitivity of the maximum establishment time to the difference in initial semi-major axis between the advancer and leader was tested. Here, the semi-major axis of the advancer was subtly changed by subtracting a small difference in its initial along-track velocity. The difference in the along-track velocity was assumed to be a proportion of a typical launch velocity of 1.5 m/s [1]. In the extreme case, the entire launch velocity is applied to the advancer, representing a deliberate effort to minimise the establishment time [1]. In all cases, the leader's initial conditions were unchanged.

Table 2: The difference in initial semi-major axis and resulting initial conditions used for the advancer

Difference in along-track velocity (m/s)	Velocity X J2000 (km/s)	Velocity Y J2000 (km/s)	Velocity Z J2000 (km/s)	Difference in semi-major axis (km)
-0.05	1.606769	-3.060534	-6.717282	-0.0927
-0.1	1.606758	-3.060514	-6.717238	-0.1854
-1.5	1.277898	-2.755615	-6.914000	-2.7800

5. Results

From the simulation of the advancer, lagger and leader, the relative mean argument of latitude (angle between the spacecraft) is plotted in Figure 12. In total, it took 133 days for the advancer to achieve an 180° relative mean argument of latitude. This compares to over 220 days of manoeuvring reported by Planet to achieve its constellation, shown in Figure 6.

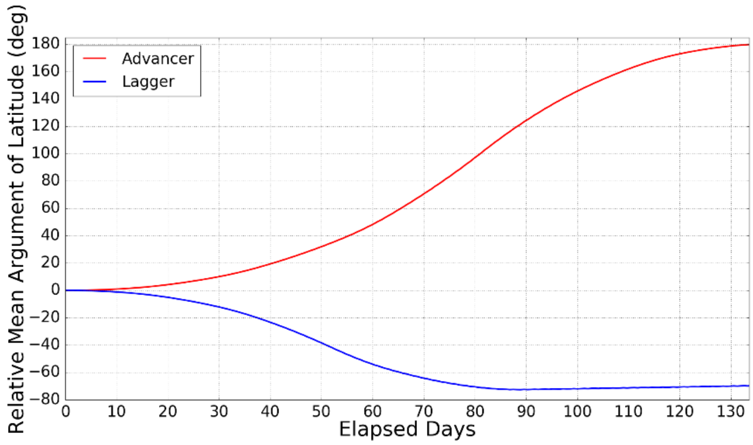

Figure 12: Simulated relative mean motion of an advancer and lagger relative to a leader spacecraft

Figure 12 also demonstrates how the relative mean argument of latitude of the lagger can intercept and stabilise itself in its slot simultaneously and independently of the advancer.

The result in *Figure 12*, however, assumes that the advancer and leader start at the exact same position and velocity. When the initial semi-major axis of the advancer was reduced, the completion time of constellation establishment changed significantly as can be seen in Figure *13* and Table 3.

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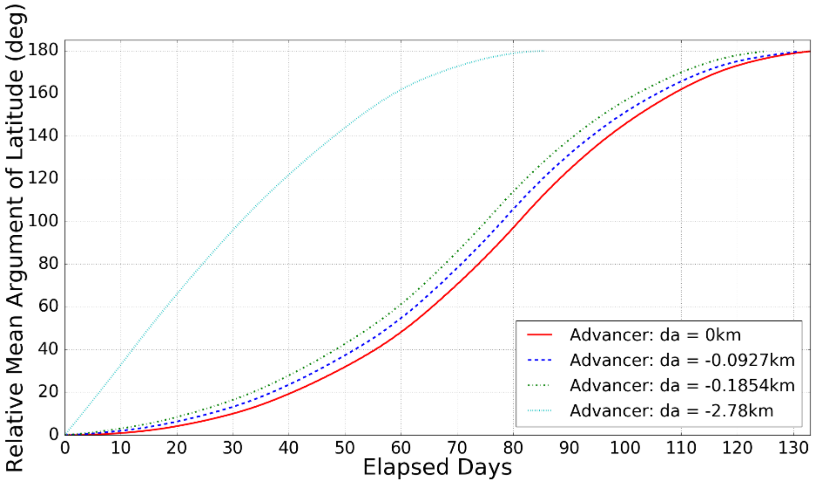

Figure 13: Difference in establishment time with subtle differences in semi-major axis (da)

Table 3: Time required to achieve an 180° relative argument of latitude for different initial relative semi-major axes

Case	Initial Difference in Semi-Major Axis (km)	Constellation Establishment Completion Time (days)
Reference	0	133
1	-0.0927	130
2	-0.1854	125
3	-2.7800	86

The difference in semi-major axis presented in Table 3 represent differences in along-track launch velocity caused by varying launch velocity magnitudes or launch angles from the launch vehicle. In cases 1 and 2, the difference in along-track launch velocity was subtle, less than 7% of the maximum launch velocity, however, the constellation was established up to eight days before the reference case, representing a significant benefit to operators, and indicating a large sensitivity to differences in initial launch velocity amongst the spacecraft.

Case 3, represents the instance when the entire launch velocity is applied in the along-track direction of the advancer and perpendicular to that direction for the leader as described in [1]. The resulting large initial relative mean motion results in very fast constellation establishment times, in this case 86 days, 40% of the time required to establish Flock 1c. The time savings presented in these simulations, even for the most conservative cases, have the potential to significantly reduce the cost associated with waiting for constellations to be established.

6. Conclusion

CubeSats are increasingly being adopted for commercial and scientific constellation operations. With no end to this trend in sight, it is advantageous to establish formations as quickly and efficiently as possible to minimise operational and opportunity costs. A new algorithm for constellation establishment using differential drag was proposed with the goal of decreasing the time required to establish a coplanar constellation of equispaced satellites. By considering the previously overlooked aerodynamics on a spacecraft at intermediate angles of attack, the new algorithm allows spacecraft within a constellation to manoeuvre fore and aft of a leader spacecraft. In doing so, the distance travelled by the spacecraft is reduced compared to legacy algorithms.

Orbit propagations of the constellation establishment algorithm presented in this paper indicated that the new algorithm can increase the speed of constellation establishment by approximately 40% on legacy algorithms in the most conservative case. When either natural or deliberate differences in the initial semi-major axis are taken into account the new algorithm establishes constellations up to 60% faster than legacy algorithms.

Improvements of this order stand to markedly reduce downtime during constellation establishment, and thus, cut-down the costs incurred by establishing a constellation of CubeSats.

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