

# An investigation into using differential drag for controlling a formation of CubeSats

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## Abstract

As the SSA system upgrades its existing capabilities and adds new ones, the potential offered by inexpensive CubeSat-based systems is growing more attractive. The potential benefits of using CubeSats increase if they are operated in groups to form ‘virtual’ satellites, which have the same functionality of a much larger satellite, but at a fraction of the cost. This paper will investigate the feasibility of using differential aerodynamic forces to control a formation of CubeSats in order to form a virtual satellite. Unfortunately, due to third body gravitational forces, solar radiation pressure, and other perturbing forces, the satellites will drift apart if no control mechanism is employed to maintain the formation. However, providing for a control mechanism is difficult. Using a rocket engine is expensive, increases mission risk, and requires fuel to be carried in the rather limited volume available in a typical CubeSat. However, passive techniques that take advantage of the differential aerodynamic forces experienced by two spacecraft can be used to exert a modest amount of control over the formation. Techniques for doing this have been discussed in the literature. These techniques rely on a simple drag plate, and only allow modest control of the formation in the plane defined by the spacecrafat's orbit. An alternative is to treat the drag plate as an aerodynamic control surface, much as is done with an aircraft. This technique allows the control surface to be oriented in a fully 3 dimensional fashion, allowing a greater range of control of the satellite formation. A challenge in treating the drag plate as a 3 dimensional control surface is that the equations of motion describing the relative motions of the satellites become fully coupled with their relative orientations. Thus, controlling the satellite formation by adjusting the relative orientations of the different satellites will require solving a fully coupled set of differential equations and devising a control law based on these equations.

This paper will derive the relative motion of a closely spaced formation of CubeSats, incorporating the aerodynamic drag and lift effects due to their relative orientations. A control law will be developed that allows the relative positions of the satellites to be controlled by adjusting the orientations of the satellites. A simulation of a group of 2 CubeSats in LEO will be performed to demonstrate the effectiveness of the method.

## 1. Introduction

This paper describes an investigation into using the differential aerodynamic forces experienced by a pair of CubeSats for conducting maneuvers in Low Earth Orbit (LEO). A CubeSat is a nanosatellite standard developed by California Polytechnic State University (Cal Poly) and Stanford University. The standard defines a CubeSat as being cube shaped, measuring 10 cm on a side and having a mass of about 1 kilogram. Larger versions exist, such as 2U and 3U designs that are the same width and length but have heights that are roughly 2 and 3 times the original standard. This class of small satellite is quickly gaining in popularity for scientific [1-3], commercial [4,5] and military applications [6], primarily due to the significant cost advantages when compared to larger satellites. CubeSats are inexpensive to produce and launch and are capable of performing many of the functions traditionally done by much larger satellites. A number of papers have advocated flying a group of small satellites in formation, which should make it possible to improve performance greatly (see ref's [7-9] for more details). However, this requires the capability of assembling the group of satellites into a formation, and then maintaining the formation for the duration of the mission. In principle, on-orbit assembly and formation keeping can be performed using rocket engines. In the case of CubeSats, this is proving to be difficult due to the challenge of designing propulsion systems that conform to the stringent mass, volume and power budgets of CubeSats, see [10, 11] for excellent reviews. In addition, one of the cost saving advantages of CubeSats is the possibility of getting a ‘free’ ride into space by taking advantage of the spare capacity available in a typical space launch. However, this usually requires the permissions of the owners of the primary satellites being lifted into orbit. This permission is unlikely in cases where the CubeSats introduce additional risk, such as is the case where a rocket engine is part of the CubeSat’s design.

Instead of relying on a rocket for propulsion, other forces can be used to provide control over the relative motion of the satellites. In [12-14] techniques are studied to provide control over the relative motion of a pair of satellites by taking advantage of the difference in drag experienced by the two satellites. A serious drawback to using differential drag is that it only allows control over the relative motion in the orbital plane of the target spacecraft. Out-of-plane motion cannot be controlled using differential drag [14]. However, aerodynamic lift acts in a direction orthogonal to drag and offers the potential of controlling the motion in the out-of-plane direction. Techniques using aerodynamic drag and lift have been developed for performing aeroassisted orbital maneuvers such as aerobraking and performing plane changes, see [15, 16] for examples. Thus, by combining the actions of differential drag and lift, it should be possible to perform formation flying maneuvers in all three translational degrees of freedom. However, aerodynamic lift is generally much weaker than drag, which will limit its applicability to controlling the relative motion of a group of CubeSats to lower altitudes.

The remainder of this work will introduce aerodynamic force models appropriate for satellites and how to use lift to perform maneuvers out-of-plane. There are many methods already developed using drag to control the in-plane motion, so this paper will assume the in-plane motion has been controlled, and the only remaining problem is how to control the out-of-plane motion. Thus, the main contribution of this work is a brief review of the effects of aerodynamic lift derived from satellite precision orbital analyses (POA's) and a description of a control algorithm that utilizes aerodynamic lift to control the out-of-plane motion of a pair of CubeSats.

## 2. Aerodynamic Force Models

The aerodynamic effects on satellite orbits tend to be dominated by drag. There are a number of reasons for this. First, satellites that are spinning/tumbling tend to have the effect of aerodynamic lift cancel out, yielding negligible effect on the orbit. Also, satellites with certain symmetrical shapes will tend to have the effect of the aerodynamic lift force cancel out. Lastly, as will be described next, the coefficient of lift tends to be much smaller than the coefficient of drag, again making the effect of lift negligible in most cases. To complicate things, the coefficient of lift is difficult to model as well as to measure at orbital altitudes. The lift coefficient can be estimated using physical models of the gas-surface interaction together with modeling assumptions, yielding different results depending on the assumptions made by the modeler. In the past, the aerodynamic coefficients of drag and lift have been computed for simple shapes at orbital altitudes using the hyperthermal approximation. The hyperthermal approximation assumes the incident gas molecules are all traveling in the same direction and that the thermal velocity of the gas molecules is negligible and thus is typically ignored. Under these assumptions, the ratio of the lift-to-drag coefficients is found to vary from 0.05 to a maximum of 2/3, depending on the level of accommodation present at the satellite's altitude [24]. The accommodation coefficient,  $\alpha$ , is a parameter that is used to capture some of the important aspects of the surface chemistry effects and is defined as

$$\alpha = \frac{E_{inc} - E_r}{E_{inc} - E_s}$$

where  $E_{inc}$  is the kinetic energy of the incident molecule,  $E_r$  the kinetic energy of the reflected molecule, and  $E_s$  is the kinetic energy the reflected particles had they been emitted with an energy due to the temperature of the satellite surface. In a sense,  $\alpha$  describes how much memory the gas molecule retains of its initial velocity after its interaction with the satellite surface. Values of 1 indicate complete accommodation, meaning the emitted particle has a kinetic energy that has completely adjusted to the thermal energy of the surface.

In a series of pioneering papers [18, 19] the aerodynamics at orbital altitudes was studied without making the hyperthermal approximation. Atmospheric temperatures at altitudes ranging from 120 km to 600 km can vary from 600 K to 1200 K over a typical solar cycle [21]. This gives rise to mean thermal velocities on the order of 1 - 2.5 km/s. When compared to orbital velocities of  $\approx 7.6$  km/s at altitudes of 500 km or so, the mean thermal velocity represents a sizable fraction of the orbital velocity. This suggests that the hyperthermal approximation is not appropriate at these altitudes and the aerodynamic effects would be better described using other theoretical tools. In [18], a variety of different models of the gas-surface interaction were studied in an effort to better understand the effects of lift and drag at orbital altitudes using satellite ranging data. The results of the study indicated that the particles striking the satellite surface tend to be accommodated and are re-emitted at low velocities ( $\sim 2$  km/s) in a

nearly specular fashion. This work was followed by a more detailed treatment by the same authors in [19]. In this paper, the aerodynamic drag and lift were treated using molecular free flow theory and did not rely on the hypervelocity assumption. Instead, the thermal velocities of the rarefied gas molecules are explicitly taken into account when computing the coefficients of lift and drag. This necessitates performing a complicated integration of the incident momentum flux over the satellite surface, and involves parameters derived from surface chemistry reactions between the atmosphere and the satellite surface. In [19], the coefficients of lift and drag for a flat plate were computed based on free molecular flow theory at orbital altitudes, yielding maximum lift-to-drag ratios ranging from approximately 0.17 to 0.38, depending on the exact mix of atomic oxygen and helium at the satellite's orbital altitude. These values are based on analysis of satellite laser ranging data on a number of LEO satellites. The accommodation coefficient is a convenient measure of the interaction between the incoming atmospheric molecule and the surface of the satellite. The accommodation coefficient is not well characterized at orbital altitudes. In [23], it is described how a small number of measurements have been made and seem to indicate that satellites quickly obtain a coating of atomic oxygen and its reaction products on all surfaces exposed to the rarefied atmosphere. This has improved the calculation of the drag and lift coefficients that are based on physical models of the momentum transfer between the rarefied atmosphere and the satellite surface, such as [18, 19, 20].

In [20], it is described how the CHAMP satellite is providing useful data to atmospheric scientists. The satellite was modeled as a collection of flat plates and the coefficients of lift and drag were computed using molecular free flow theory. The accelerometers on board the satellite measure the vector quantity of acceleration caused by non-gravitational sources. The effects of solar radiation, Earth's albedo and infrared radiation were modeled and removed in order to measure the drag and lift accelerations. This was done in order to better measure the properties of the thermosphere and it was found that including the effects of lift markedly improved the analysis results. Based on the molecular free flow treatment of lift and drag together with the high precision data collected on a number of satellites, it is evident that aerodynamic lift is significant at orbital altitudes and should be useful for conducting modest maneuvers at LEO.

Following the methods described in [20], the drag force can be expressed in the direction opposing the satellite's velocity,  $\vec{v}$ :

$$F_{drag} = ma_{drag} = -\frac{1}{2}\rho C_D A_{ref} |\vec{v}|^2 \quad \text{eq 1}$$

where  $\rho$  is the atmospheric density,  $m$  is the mass of the satellite,  $C_D$  is the coefficient of drag and  $A_{ref}$  is the reference area of the satellite. In order to simplify the expression for lift, it will be assumed that the satellite is outfitted with a flat drag plate much larger than the CubeSat itself, allowing the contribution of the CubeSat body to the drag and lift to be ignored. In this case, the lift force can be expressed in a direction that is perpendicular to  $\vec{v}$  and that depends on the orientation of the drag plate,  $\frac{\vec{F}_{lift}}{|\vec{F}_{lift}|} = (\hat{v} \times \hat{n}) \times \hat{v}$ :

$$F_{lift} = ma_{lift} = -\frac{1}{2}\rho C_L A_{ref} |\vec{v}|^2 \quad \text{eq 2}$$

where  $C_L$  is the coefficient of lift and  $\hat{n}$  is the normal vector of the plate's surface. Following the treatment in [20] and references contained therein, the drag and lift coefficients can be modeled for a simple flat plate using molecular free flow theory as:

$$C_D = 2 \left[ 1 + \frac{2}{3} \sqrt{1 + \alpha \left( \frac{T_w}{T_a} - 1 \right)} \cos \theta \right] \quad \text{eq 3}$$

$$C_L = \frac{4}{3} \sqrt{1 + \alpha \left( \frac{T_w}{T_a} - 1 \right)} \sin \theta, \quad \text{eq 4}$$

where  $\alpha$  is the accommodation coefficient,  $T_a$  is the temperature of the local atmosphere,  $T_w$  is the surface temperature of the plate, and  $\theta$  is the angle of the incident gas flow with respect to the plate. Assuming  $\theta = 45^\circ$  and  $\alpha = 0.95$ , a lift-to-drag ratio that is approximately 0.2 is obtained. The value of alpha will vary with altitude and material properties and values less than 0.95 would not be unreasonable. In these cases the lift-to-drag ratio will be higher.

In a manner similar to [12, 14], it will be assumed the satellite has available some sort of controllable drag plate. The drag plate can be deployed by one or both satellites in order to generate a positive or negative relative acceleration. The drag plate could be a large solar array for instance, or some sort of structure created specifically for maneuvering purposes. It will furthermore be assumed that the orientation of the drag plate can be controlled by the satellite and maintained in the controlled orientation for an indefinite period of time.

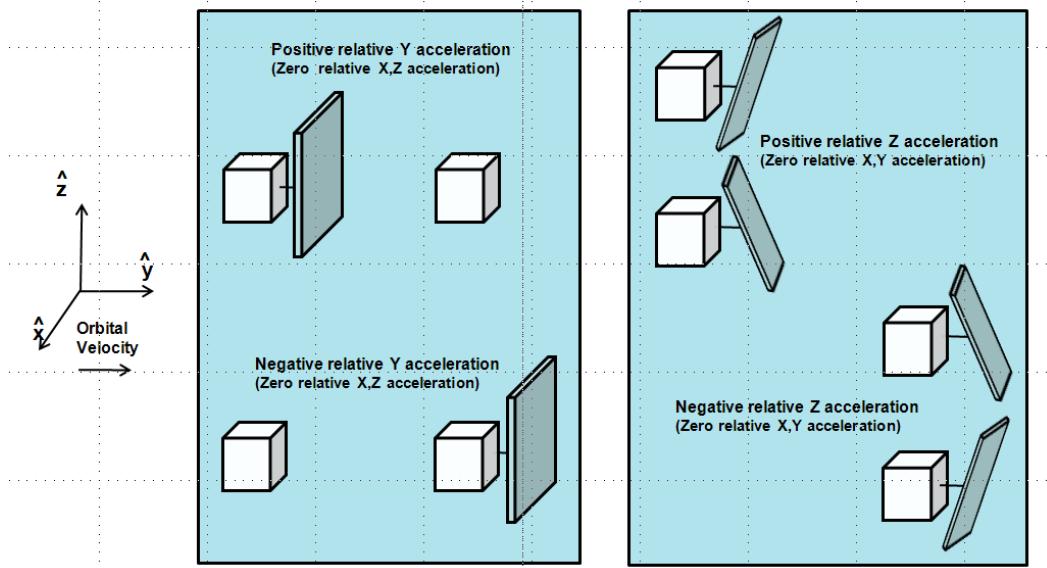


Fig. 1. Conceptual explanation of differential drag and lift control.

### 3. Dynamics

The relative motion between two objects orbiting the Earth can be described in the classical LVLH coordinate system (see fig. 2). The x axis points from the center of the Earth to the position of the reference satellite, the y axis points in the velocity direction, and the z coordinate is orthogonal to x and y. The motion of the chaser satellite relative to the reference satellite can be described using the well known Hill-Clohessy-Wiltshire equations:

$$\ddot{x} - 2\omega\dot{y} - 3\omega^2x = \Delta a_x \quad \text{eq. 5a}$$

$$\ddot{y} + 2\omega\dot{x} = \Delta a_y \quad \text{eq. 5b}$$

$$\ddot{z} + \omega^2z = \Delta a_z \quad \text{eq. 5c}$$

where  $\Delta a_i = a_i^2 - a_i^1$ ,  $i = x, y, z$ , is the differential acceleration and  $\omega$  is the circular orbit angular velocity. As is evident in the equations above, the motion in the x and y directions are coupled, and the motion in the z direction is independent of x or y. As described in section 2, differential drag accelerations,  $\Delta a_y$ , can be generated by deploying or retracting either the reference or chaser satellite's drag plate. Assuming the chaser satellite is trailing the reference satellite, positive relative accelerations in y can be obtained by controlling the chaser satellite to deploy its drag plate and the reference satellite to retract its plate. Negative accelerations can be generated by reversing the process. In order to simplify modeling the system, it will be assumed that no accelerations in the x direction are



Fig. 2. LVLH coordinate system.

present. The problem of controlling the motion in the x and y plane has been solved by [14], using an analytical control technique. In order to extend control to the out-of-plane direction, differential lift acceleration can be used. Differential accelerations in the z dimension can be generated by controlling both satellites to deploy their drag plates. Positive and negative accelerations in the z direction can be generated by controlling the relative orientations of the drag plates. In the upper right diagram in figure 1, a positive relative acceleration in the z direction is generated by controlling the outward normal of the lead CubeSat's plate such that it makes an angle of 45 degrees with the y axis,  $\hat{n}_1 = [0 \ 0.707 \ -0.707]$ . The trailing CubeSat is commanded to orient its control plate such that the normal vector takes the value  $\hat{n}_2 = [0 \ 0.707 \ 0.707]$ . In this way, both CubeSats experience equal drag accelerations (and hence zero relative drag) and equal but opposite lift accelerations in the z direction. Using equations 2 and 4, we get a positive net acceleration in the z direction of

$$a_z = \rho C_L \frac{A_{ref}}{m} v^2 \quad \text{eq. 6.}$$

In a similar manner, negative net accelerations in the z direction are generated by controlling the relative orientations as shown in the lower right diagram in fig. 1. The solution to eqn. 5c can be shown by direction substitution to be

$$z(t) = \left( z_0 - \frac{a_z}{(\omega c)^2} \right) \cos(\omega c t) + \frac{\dot{z}_0}{\omega c} \sin(\omega c t) + \frac{a_z}{(\omega c)^2} \quad \text{eq. 7}$$

where  $z_0$  and  $\dot{z}_0$  are the initial conditions, and  $a_z$  can take on positive and negative values described by eq 2, as well as zero (i.e. coasting). The relative velocity,  $\dot{z}$ , is the time derivative of  $z$ . Scaling the relative velocity by  $\frac{1}{\omega c}$ , the CubeSats move along circles in the  $(z, \frac{\dot{z}}{\omega c})$  plane, see fig 3. The circles will be centered at  $(\pm \frac{a_z}{(\omega c)^2}, 0)$  for cases

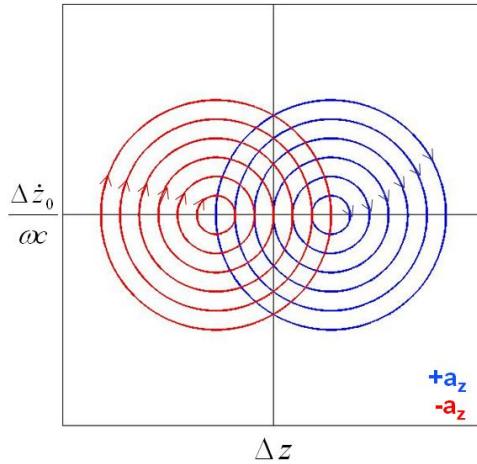


Figure 3 Notional example of relative motion between two CubeSats controlled using differential lift. Net negative (positive) accelerations causes the relative position and velocity to move along one of the red (blue) circles.

where a relative acceleration is present, or  $(0, 0)$  in cases where the CubeSats are coasting (no net accelerations present). A simple control algorithm can be developed to zero out the relative separation and velocity between two CubeSats by switching between the control curves in fig. 3 and is described in the following section.

#### 4. Control

A simple control algorithm can be developed that can be used to zero out the relative position and velocity between two CubeSats in the z dimension. Imagine a point in the upper left corner of figure 3 (negative relative position and positive relative velocity). If the relative velocity could be controlled to be zero, the point would be located at  $(-\Delta z_0, 0)$ . Next, the relative orientations of the two CubeSats would be commanded to generate a net negative acceleration. In this case the motion would be along one of the red circles. This acceleration would be maintained for exactly  $\frac{1}{2}$  an orbital period, where once again the relative velocity would be zero. However, the point is now at  $(\Delta z_0 - \frac{2a_z}{(\omega c)^2}, 0)$ , a little closer to the origin. The CubeSats are now commanded to reverse the relative acceleration, and thus will travel along one of the blue circles. After exactly  $\frac{1}{2}$  an orbital period, the point will be located at  $(-\Delta z_0 + \frac{4a_z}{(\omega c)^2}, 0)$ . In a single orbital period, the relative separation between the two CubeSats will have shrunk by an amount  $\frac{4a_z}{(\omega c)^2}$ . This process is continued until the relative position and velocity between the CubeSats is zeroed out. For arbitrary cases, it will be necessary to command the CubeSats to a point where the relative velocity is zero and the relative separation is an integer multiple of  $\frac{4a_z}{(\omega c)^2}$ . Once this is accomplished, the above sequence of commands is executed until the origin is reached.

In order to handle arbitrary cases, the following algorithm is presented:

- 1) Coast for  $T_1$  seconds
- 2) Apply acceleration for  $T_2$  seconds
- 3) Reverse acceleration, apply for  $T_2$  seconds
- 4) Execute N times:
  - a. Reverse acceleration, apply for  $\frac{1}{2}$  orbital period
  - b. Reverse acceleration, apply for  $\frac{1}{2}$  orbital period.

The initial coast time,  $T_1$ , intermediate time  $T_2$ , and the number of iterations N can be found by starting at the origin and working backwards. In principle the sequence of signs for the accelerations should be chosen to minimize the total travel time. However, the total travel time is dominated by step 4, and so the initial sign of the acceleration was arbitrarily chosen to be positive. This makes the algorithm suboptimal, but only by a small amount. The number of iterations, N, is found by computing the integer that is equal to or less than the initial radius,  $R_0 = \sqrt{z_0^2 + \left(\frac{z_0}{(\omega c)^2}\right)^2}$ , divided by the amount the relative separation decreases in a single orbital period,

$$N \leq \frac{R_0}{\frac{4|a_z|}{(\omega c)^2}}.$$

At this point in time, the relative position and velocity will be  $(\pm\Delta\dot{z}, 0)$ , and the radius will be  $R'$ . The initial sign in the sequence of accelerations was arbitrarily chosen to be positive; this then determines the initial sign of the acceleration in step 2. The time  $T_2$  is found by numerically solving for the time required to bring the radius  $R'$  to  $R_0$ ,

$$T_2^{min} = \min_{T_2} |R_0 - R'|,$$

where  $T_2$  is the travel time allowed for each section of the two part maneuver (steps 3) and 2) in the above algorithm). At this point in time, the relative position and velocity will be  $(\Delta z'', \Delta\dot{z}'')$  which will be at the same radius as the initial starting point. The remaining step required is to coast for a time  $T_1$  that is found by numerically solving the following equation,

$$T_1^{min} = \min_{T_1} \sqrt{(\Delta z'' - \Delta z_0)^2 + (\Delta\dot{z}'' - \Delta\dot{z}_0)^2}.$$

An example is shown in fig 4. The objective is to control the orientations of two CubeSats in order to zero out their relative position and velocities. The CubeSats were modeled as having a mass of 5 kg and a drag plate with an area of  $1 \text{ m}^2$ . The initial starting conditions are  $\Delta z_0 = 20 \text{ m}$  and  $\Delta \dot{z}_0 = 0.05 \text{ m/s}$ . The initial orbit was chosen to be circular and have an inclination of 51.45 degrees and an altitude of 500 km. The atmospheric density was considered to be constant for the duration of the maneuver, and had a value of  $\rho = 4.89 \times 10^{-13} \frac{\text{kg}}{\text{m}^3}$  [21]. The initial starting point is shown in the diagram with a square. The coast phase is shown in black solid line and continues until the point marked by the x is arrived at. A negative acceleration (red curve) is applied, followed by a positive acceleration (blue). This sequence of accelerations places the point at the left most 'x' lying along the  $\Delta \dot{z}$  axis. This point is an exact multiple of  $\frac{4 a_z}{(\omega c)^2}$ . A sequence of alternating negative and positive accelerations are applied until the point reaches the origin.

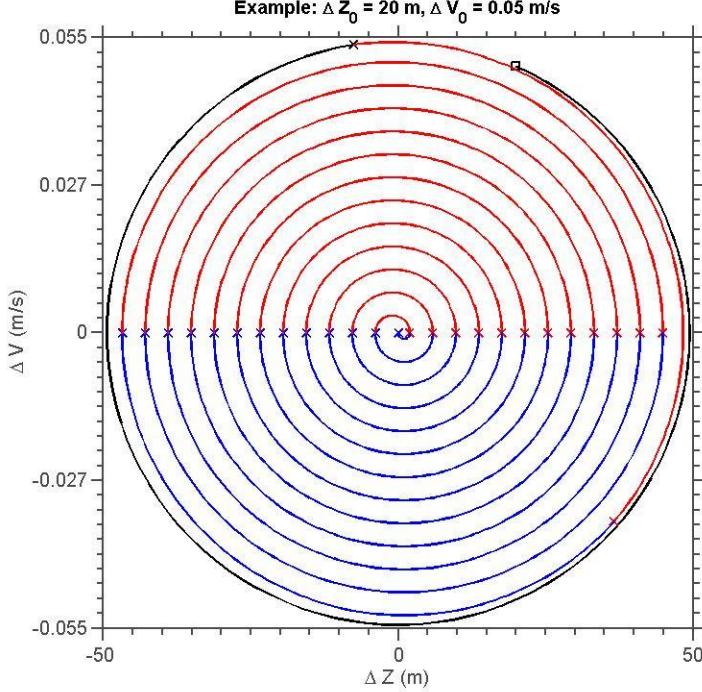


Figure 4 Example control problem. Red curves indicate negative accelerations, blue curves positive acceleration, and black curve no acceleration (coasting).

The above example illustrates the difficulty in utilizing aerodynamic drag for conducting satellite maneuvers. The initial starting conditions were quite modest, with the initial separation being 20 m and the difference in velocity being very small, 5 cm/s, and yet the maneuver took approximately 0.59 days to complete. An analysis was done to characterize the travel time required to zero out the relative position and motion between two CubeSats. The initial orbits were the same as described above. The initial separations and velocity differentials were varied independently, with  $\Delta z_0$  ranging from 0 to 1 km, and  $\Delta \dot{z}_0$  ranging from 0 to 1 m/s. The results are shown in fig. 5. For separations of 1 km and velocity differences of 1 m/s, the travel time required to zero out the differentials in position and velocity was approximately 20 days. This is a substantial amount of time and results in losses in altitude of approximately 21.3 km, based on the variation of the semimajor axis for one orbit due to drag (see [22] for details).

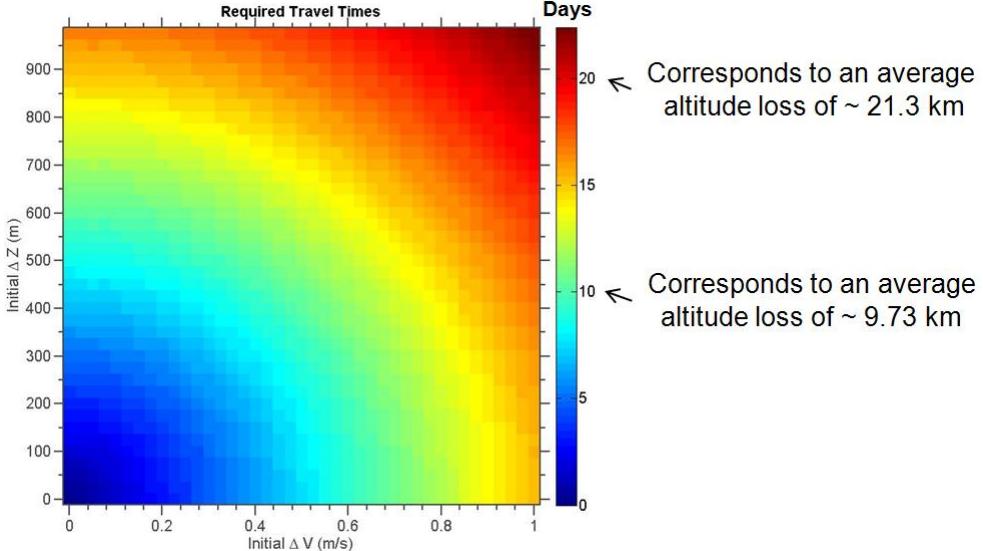


Figure 5 Travel times required for performing rendezvous in the z dimension.

## 5. Conclusions

Differential aerodynamic lift was introduced as a way to extend control over the out-of-plane motion of a pair of CubeSats. Used together with techniques using differential drag [14], this control technique allows the relative dynamics of two CubeSats to be completely controlled using only aerodynamic forces. This is an important result for CubeSats because controlling the out-of-plane motion was not possible using differential drag, and would have required the use of a rocket engine. An important caveat in this work is the value of the coefficient of lift. Under the hyperthermal approximation, the coefficient of lift is expected to be very small, only a few percent that of drag. This would virtually eliminate any benefit of using lift for controlling the relative motions in the out-of-plane dimension. However, the hyperthermal approximation was first applied to the treatment of lift and drag in 1964 [24], and there was not much experimental data to compare with theory. Moreover, lift tends to cancel out for a variety of conditions related to the satellite's motion and geometry, making it difficult to find cases where the effect of lift is present. However, as was pointed out in [18], by maintaining a fixed orientation for extended periods of time, it is possible to have the effects of aerodynamic lift essentially build up over time and generate measurable effects on the satellite orbit. Modern analyses which do not rely on the hyperthermal approximation and use molecular free flow theory to compute the coefficient of lift indicate much higher values of lift, with lift-to-drag ratios of approximately 0.17 – 0.38 for a flat plate at LEO. Moreover, these modern analyses have been compared with precision tracking data and accelerometer data on a number of satellites and compare favorably. Thus it seems that aerodynamic lift is significant at orbital altitudes and is strong enough to be used for performing modest maneuvers involving low mass CubeSats with large surface areas. Given the rather small number of studies on aerodynamic lift at orbital altitudes, a dedicated study of the effect would be beneficial and would help determine the utility of using lift for performing maneuvers.

## 6. ACKNOWLEDGEMENTS

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