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A	Initial Draft (Date: 8 Feb 2016)	By: Brian Cooper
B	Minor corrections and letterhead updated (Date: 18 Jan 2017)	By: Brian Cooper
C	Modified drag results for Corvus-HD (Date: 14 April 2017)	By: Brian Cooper

ATTACHMENT F

Astro Digital US, Inc.

ASTRO DIGITAL	TITLE: **Differential Drag Collision Avoidance Analysis**	REV. C Export Control: **EAR 99**

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1. Introduction

This document presents the investigation into using differential drag as a method of collision avoidance for low earth orbiting (LEO) small spacecraft. Small satellites, especially CubeSats/Nano-Satellites, provide the most likely platform to make use of this method due to their characteristically high surface-area-to-mass ratio, as well as volume constraints that can preclude the use of an on-board propulsion system. The differential drag analysis was performed by Astro Digital, and an analysis on the comparative effectiveness of an on-board propulsion system was performed by Phase Four, Inc. This paper was written to build on the subject of differential drag control for small satellites discussed by Planet Labs, Inc. (See Reference 2). The Planet Labs paper concluded that differential drag is an effective method of phasing and station keeping for large constellations of small satellites in orbits as high as 600 km altitude.

All satellite operators are familiar with the conjunction warnings issued by the Joint Space Operations Command (JSpOC), which provide a time and miss distance for close approaches between operational satellites and other orbital objects. These warnings are typically provided around 2 days prior to a potential conjunction, with the intent of helping satellite operators avoid potential collision events if possible. Small satellite operators without on-board propulsion on their spacecraft typically cannot take action on these warnings, but differential drag could potentially provide a method for spacecraft with 3-axis attitude control. This study evaluates the effectiveness of differential drag for collision avoidance on small spacecraft of varying form factors and mass. In all studies, the goal of the maneuver is to change the location of the spacecraft at the time of the potential collision by at least 1 kilometer. This distance was chosen to ensure that the spacecraft is outside the uncertainty margin typical of JSpOC's radar-based measurements.

2. Conjunction Warning Rate

Astro Digital operates Perseus-M1 and Perseus-M2 (Callsign: WH2XCA, LN: 0032-EX-PL-2015), two 6U CubeSats which are used for maritime traffic monitoring and on-orbit technology demonstration. These two satellites were launched into 620 km altitude sun synchronous polar orbits on 18 June 2014. At this altitude, these satellites provide an excellent real-world case study to determine how many potential conjunction warnings future small satellite constellations will receive. After analyzing every conjunction warning sent to Astro Digital by JSpOC over a period of 19 months, the following values were calculated:

a. Encounters per spacecraft per year, <300 meter miss: **1.89**
b. Encounters per spacecraft per year, <500 meter miss: **3.78**
c. Total encounters per spacecraft per year, <1 km miss: **7.87**

Of all 25 encounters analyzed, only 1 was with an active maneuverable spacecraft. These statistics align with the fact that there are 21,000 pieces of tracked space debris and only 1,100 active satellites in orbit. The takeaway from this is that the primary threat to any active satellite will always be space junk, not other active and maneuverable satellites. The Iridium-Cosmos collision of 2009 was an example of an active maneuverable satellite being destroyed by a completely deactivated object. There has never been an accidental orbital-velocity collision between two active satellites, so it is good to remember that uncontrollable space debris represent the largest collision threat to any space mission. One consequence of this is that the typical small satellite operator will almost exclusively need to maneuver on their own if they wish to avoid a potential collision (as opposed to letting the other object perform the maneuver).

Some satellite operators may choose to avoid every potential collision, or only collisions that are under a certain threshold miss distance. For reference, the Iridium-Cosmos satellite collision had a predicted miss distance of ~500 meters. For this reason, all miss distance predictions under 500 meters will be used as potential “maneuver-requiring events” for this paper.

3. Propulsive Collision Avoidance

Propulsion analysis was performed by Phase Four, Inc. for two separate spacecraft cases, using the CubeSat Ambipolar Thruster (CAT) electric propulsion system. The details of Phase Four's analysis inputs and methods are provided below. This analysis provides a comparison to the effectiveness of differential drag for collision avoidance. As expected, it is shown that higher spacecraft mass is associated with longer burn times and greater fuel expenditure to perform the same maneuver when the propulsion system design is held constant.

1. Corvus-BC Satellite Details:
   a. Satellite mass: 11.5 kg
   b. Average drag area: 0.087 m^2
2. Corvus-HD Satellite Details
   a. Satellite mass: 21.5 kg
   b. Average drag area: 0.134 m^2
3. Phase Four Cubesat Ambipolar Thruster (CAT) Propulsion System Details:
   a. Propellant: Xenon
   b. Propellant mass: 150 grams
   c. Propulsion input power: 30 Watts
   d. Thrust (theoretical): 1.66 mN
   e. I_{sp} (theoretical): 500 s
4. Analysis Methodology:
   a. The analysis was performed utilizing the Astrogator propagator in STK 10.
   b. Two identical satellites were placed in a 600 km, 90° inclination orbit. Results will be substantially similar for a sun synchronous orbit.
   c. The first satellite maintained a circular orbit at 600 km, and served as a reference for the second, maneuvering satellite.
   d. One orbit before the "collision," the avoidance maneuver sequence begins. The satellite propagates to a true anomaly that will allow the burn to center around the point exactly 180° phase from the "collision" point.
   e. Once the burn completes, the satellite will propagate past the "collision" point by greater than 1 km
5. Analysis Results (Corvus-BC, 11.5 kg):
   a. Time required to respond to collision avoidance warning: **53 min**
   b. Burn Duration: 500 s (8.3 min)
   c. Delta-V Required: 7.155×10^{-2} m/s
   d. Propellant Mass Required: 0.169 g
   e. Separation distance from "collision": 1032 m
6. Analysis Results (Corvus-HD, 21.5 kg):
   a. Time required to respond to collision avoidance warning: **57 min**
   b. Burn Duration: 1000 s (16.6 min)
   c. Delta-V Required: 7.667×10^{-2} m/s
   d. Propellant Mass Required: 0.339 g
   e. Separation distance from "collision": 1061 m

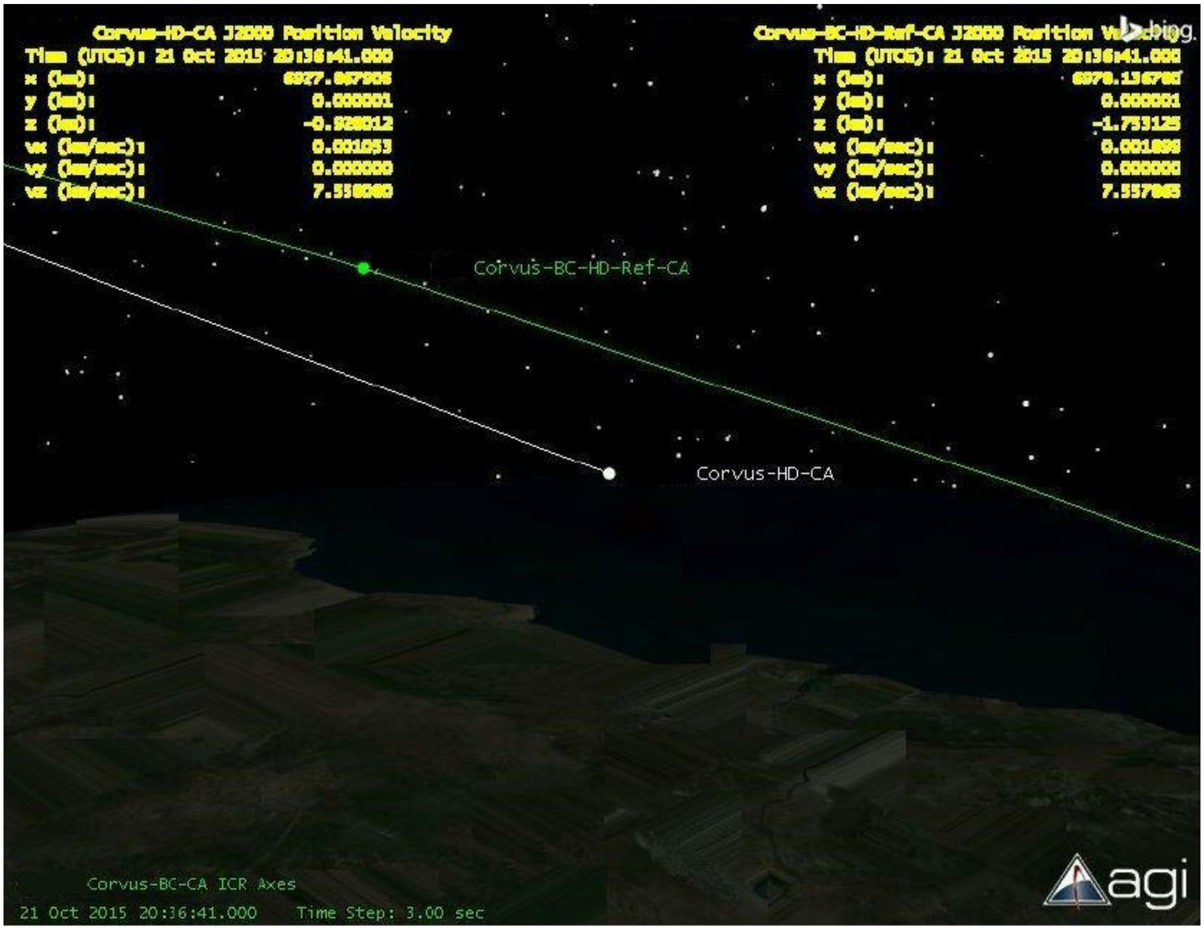

Figure 1. Miss distance of Corvus-HD after performing a propulsive avoidance maneuver. The "non-maneuvering Corvus-HD" position is shown in green, and maneuvering Corvus-HD in white.

This maneuver profile serves as a worst-case scenario from a burn time, required velocity change, and operational interruption standpoint since the maneuver is performed with the minimum time prior to the potential collision. If a satellite operator had more warning to perform the maneuver, all of these values would be correspondingly reduced.

4. Differential Drag Collision Avoidance

Differential drag analysis was performed for 5 separate spacecraft cases to capture the wide range of effectiveness with changing form factors and masses. Corvus-BC, Corvus-HD, a Planet Labs Dove, a generic 3U, and a generic 1U were all evaluated. It is shown that differential drag effectiveness typically decreases as spacecraft mass increases, but highly irregular form factors can also greatly improve differential drag effectiveness. A drag coefficient of 2.2 was used for all satellites in this study.

1. Corvus-BC Satellite Details:
    a. Satellite mass: 11.5 kg
    b. Average drag area: 0.124 m^2
    c. Maximum drag area: 0.142 m^2
    d. Minimum drag area: 0.024 m^2
    e. Average Ballistic Coefficient: 42.15 kg/m^2
2. Corvus-HD Satellite Details:
    a. Satellite mass: 21.5 kg
    b. Average drag area: 0.260 m^2
    c. Maximum drag area: 0.345 m^2
    d. Minimum drag area: 0.062 m^2
    e. Average Ballistic Coefficient: 37.59 kg/m^2
3. Planet Labs Dove Satellite Details:
    a. Satellite mass: 5.5 kg
    b. Average drag area: 0.127 m^2
    c. Maximum drag area: 0.195 m^2
    d. Minimum drag area: 0.022 m^2
    e. Average Ballistic Coefficient: 19.69 kg/m^2
4. Generic 3U Satellite Details:
    a. Satellite mass: 4.8 kg
    b. Average drag area: 0.038 m^2
    c. Maximum drag area: 0.050 m^2
    d. Minimum drag area: 0.014 m^2
    e. Average Ballistic Coefficient: 57.41 kg/m^2
5. Generic 1U Satellite Details:
    a. Satellite mass: 1.6 kg
    b. Average drag area: 0.020 m^2
    c. Maximum drag area: 0.025 m^2
    d. Minimum drag area: 0.014 m^2
    e. Average Ballistic Coefficient: 36.36 kg/m^2

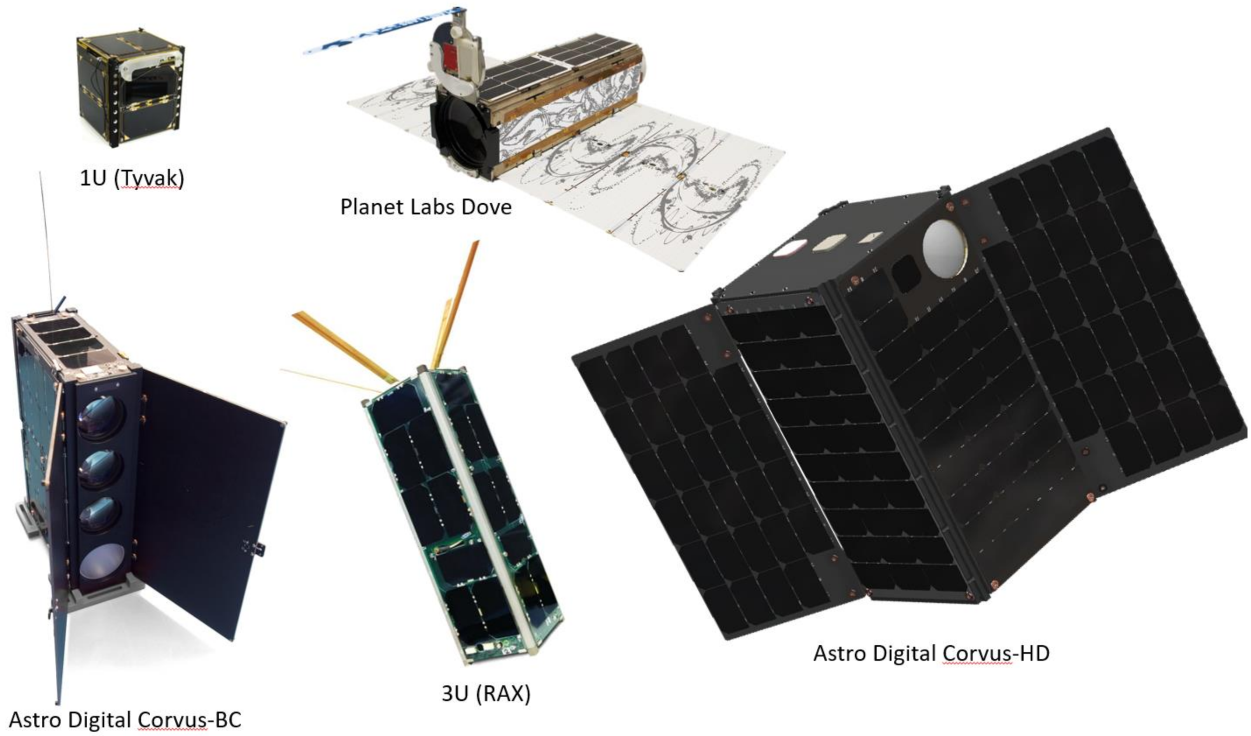

Figure 2. Images of satellites used for differential drag case study (sizes are approximately to scale)

Each of these spacecraft form factors were analyzed using OrbitMech, an open source Python orbital mechanics library developed at Astro Digital. The SciPy Ordinary Differential Equations solver *odeint* was used to numerically integrate the position of a representative "average tumbling area" satellite and then compared with the final location of a "max drag" and "min drag" satellite. The results below show the gradually increasing separation between these satellites due to differential drag acceleration.

As stated before, the goal for all maneuvers in this study is to change the satellite's predicted position at the time of the potential collision by 1 km. This does not take into account the predicted position of the second space object, so there are cases that the optimal differential drag maneuver could actually move the maneuvering satellite closer to a potential collision. By its nature, differential drag only allows maneuvers in two directions relative to a hypothetical non-maneuvering satellite, so a satellite operator would need to consider whether a low-drag or high-drag maneuver would be the most effective in each specific case. The second object's position at the time of closest approach is provided in every JSpOC conjunction warning, so this is a decision that can be made at the time the warning is issued.

1. Corvus-BC Results

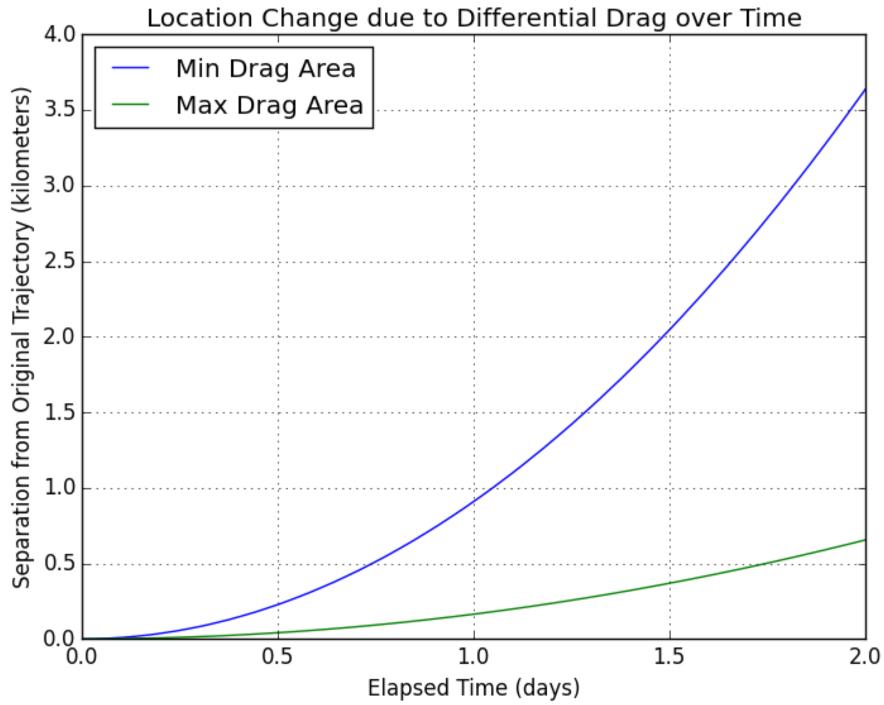

Figure 3. Differential Drag Separation of Corvus-BC Spacecraft

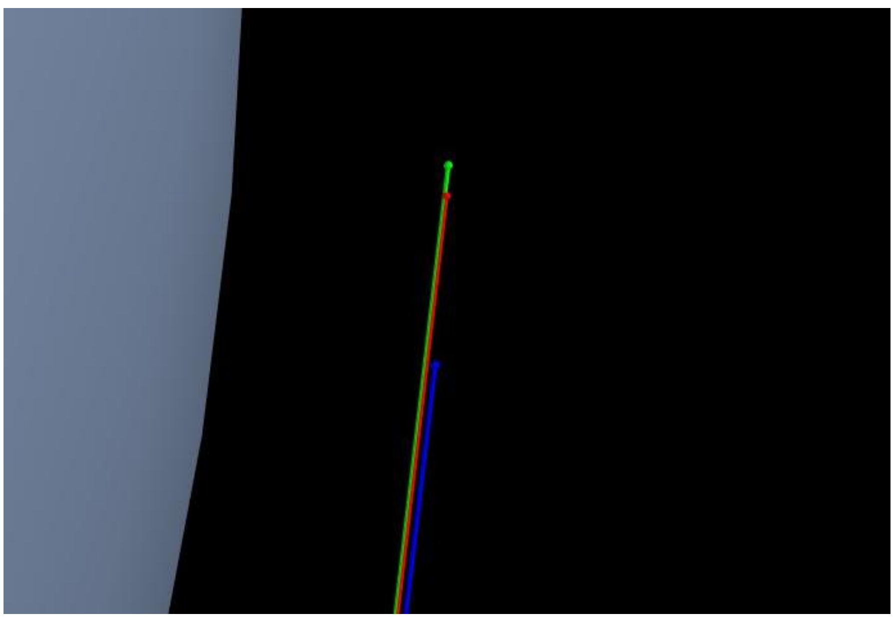

Figure 4. Visualization of final Corvus-BC separation after 2 days. Red is reference position, green is max drag, blue is min drag. The Earth is shown in pale blue to the left.

2. Corvus-HD Results

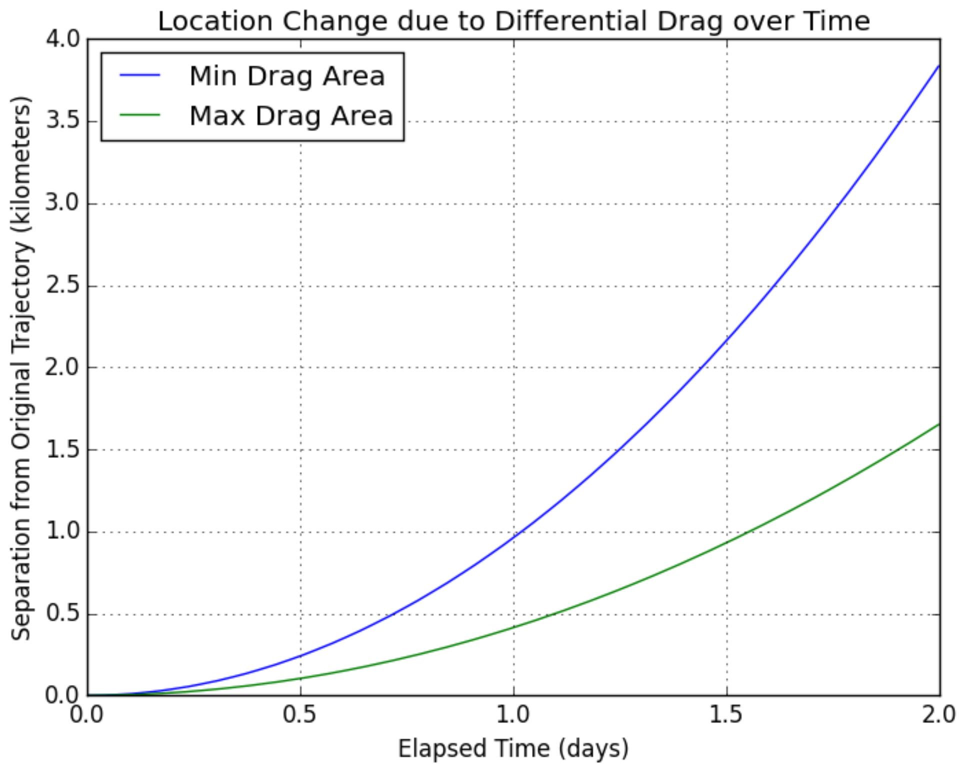

Figure 5. Differential Drag Separation of Corvus-HD Spacecraft

3. Planet Labs Dove Spacecraft Results

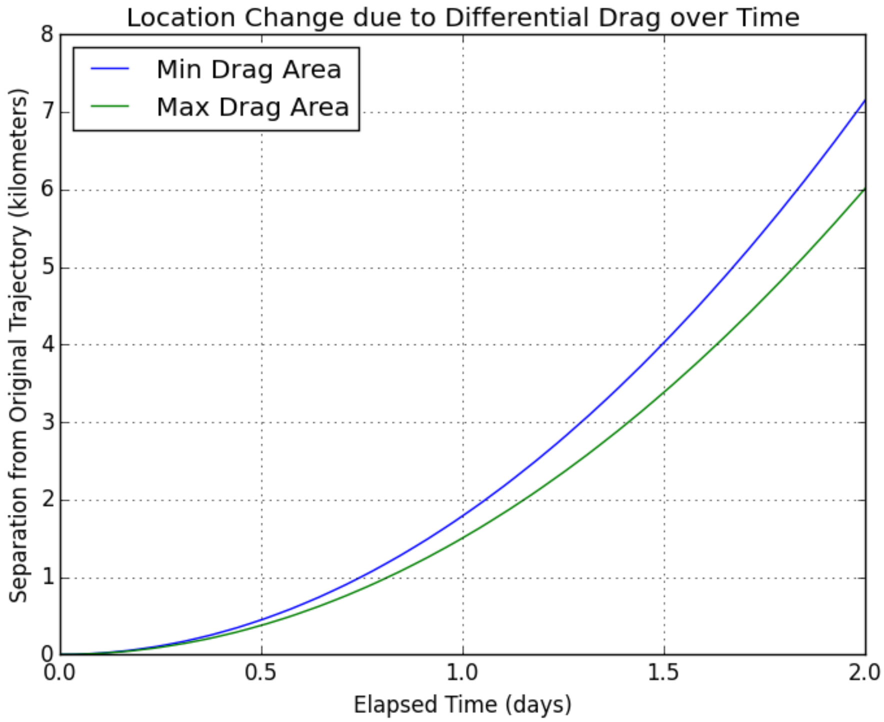

Figure 6. Differential Drag Separation of Planet Labs Dove Spacecraft

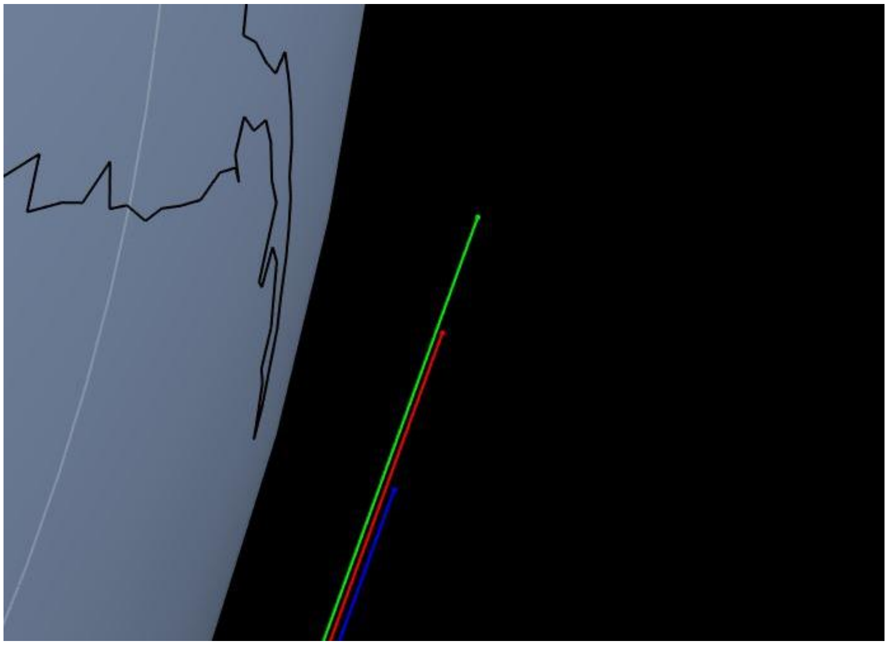

Figure 7. Visualization of final Dove separation after 2 days. Red is reference position, green is max drag, blue is min drag. The Earth is shown in pale blue to the left.

4. Generic 3U Spacecraft Results

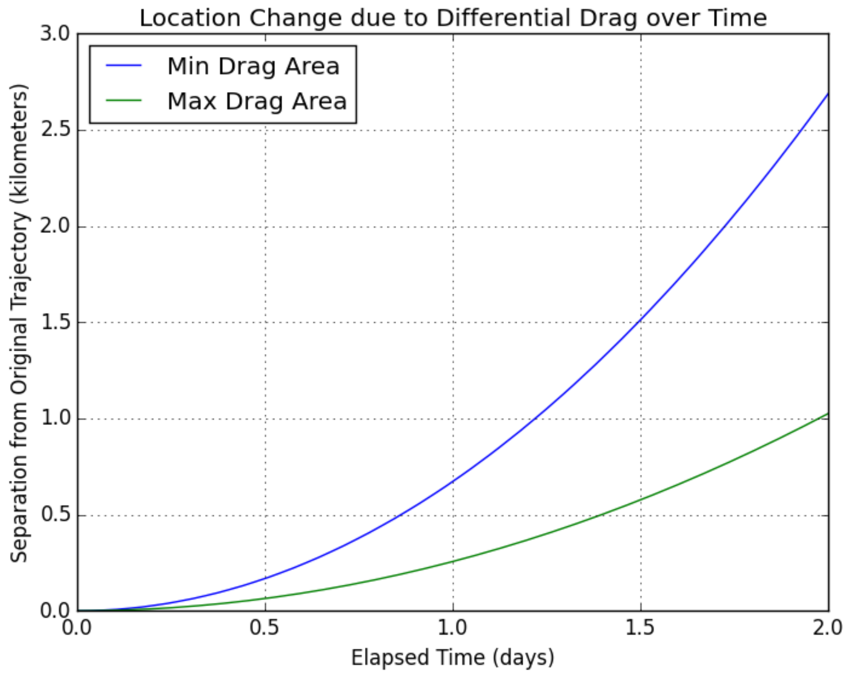

Figure 8. Differential Drag Separation of Generic 3U Spacecraft.

5. Generic 1U Spacecraft Results

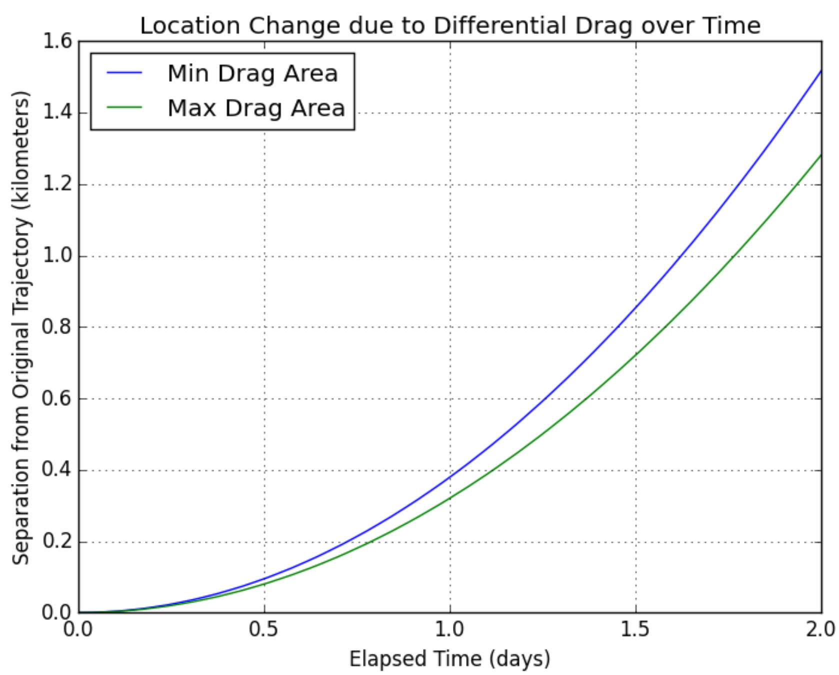

Figure 9. Differential Drag Separation of Generic 1U Spacecraft.

6. Combined Results Analysis

The two main parameters that determine the effectiveness of differential drag for a spacecraft at a given orbit are mass and surface area variation between axes. Large amounts of surface area variation can very easily make up for a higher mass, as demonstrated by the effectiveness of Corvus-BC and Dove over the generic 1U in Figure 11. This figure shows the approximate acceleration difference in nanometers/s^2 from the reference non-maneuvering satellite, as well as the time in minimum drag mode it would take to shift the satellite's orbit by 1 km. The minimum drag mode was shown to be the fastest method of modifying an orbit for all spacecraft form factors due to the larger drag area difference compared to the "uncontrolled" reference mode. All spacecraft in this study theoretically have the ability to successfully avoid a potential collision with 2 days warning given, since the maximum required time to maneuver 1 km is 1.65 days. However, real world constraints may make the maneuver infeasible (planning time, timely uplink of maneuver commands, undesirable operations disruption, etc.).

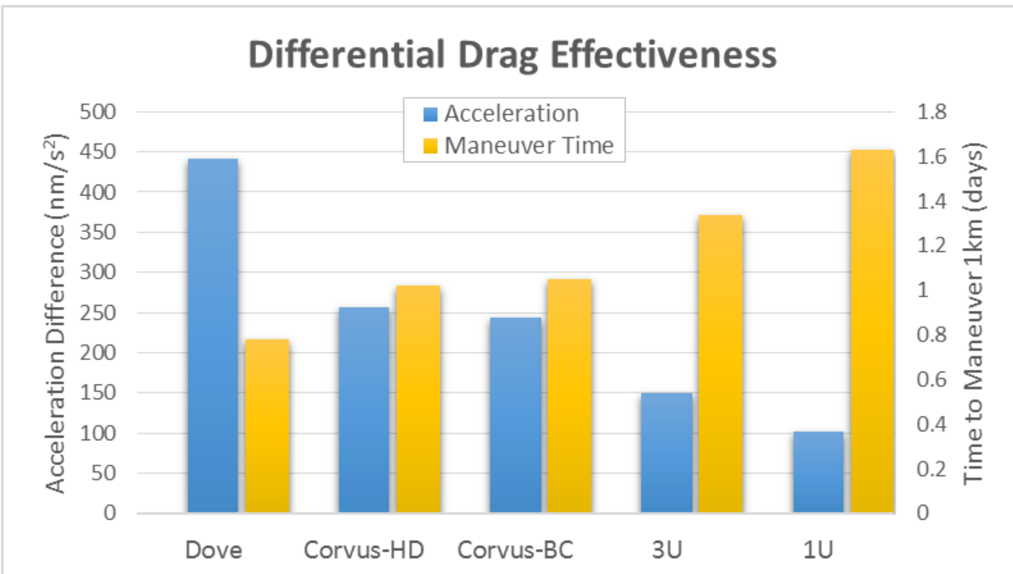

Figure 10. Comparison of Differential Drag Accelerations for Different Spacecraft.

All of the comparison analyses were performed for a 600 km altitude orbit, but differential drag effectiveness increases greatly with decreasing altitude. The amount of debris present (and thus potential collisions) drops off drastically below 600 km, so 600 km was chosen as the most representative altitude for potential use of differential drag collision avoidance. Figure 13 demonstrates the increasing effectiveness of differential drag control with decreasing altitude for Corvus-BC and Dove. The maximum achievable acceleration difference due to differential drag increases exponentially with decreasing altitude, which drastically improves maneuvering response times. For reference, it would only take 6 hours of differential drag control for Corvus-BC to avoid a potential collision at an altitude of 425 km, which is the approximate altitude of the International Space Station.

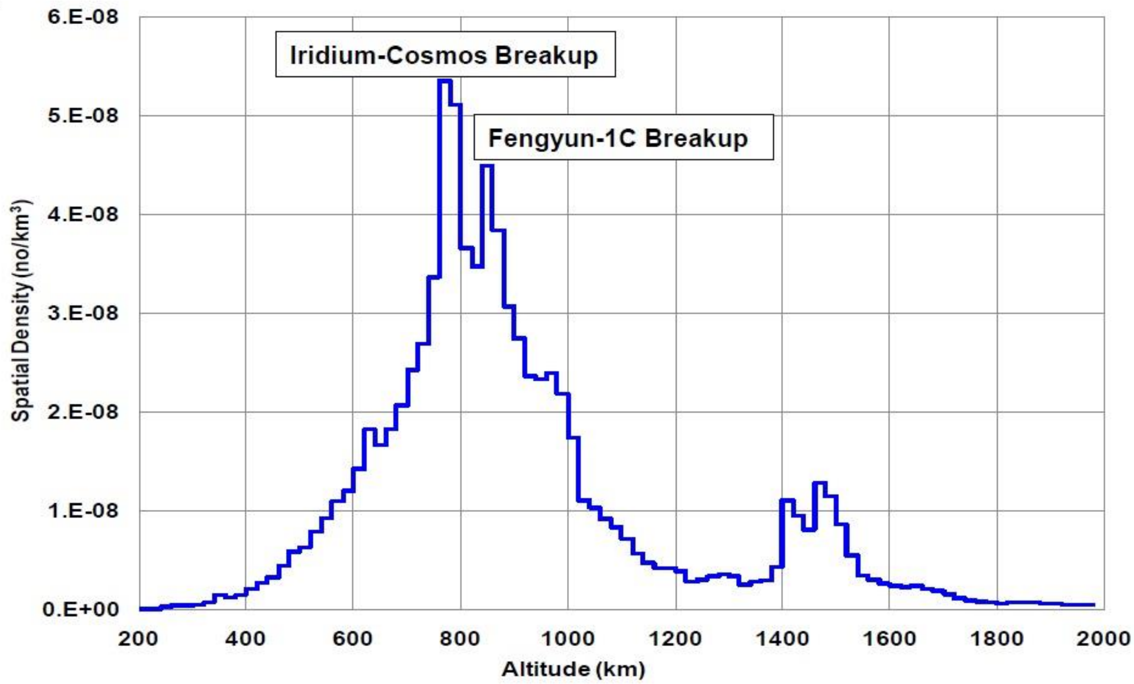

Figure 11. Spatial density of LEO space debris by altitude (Credit: UN Office for Outer Space Affairs)

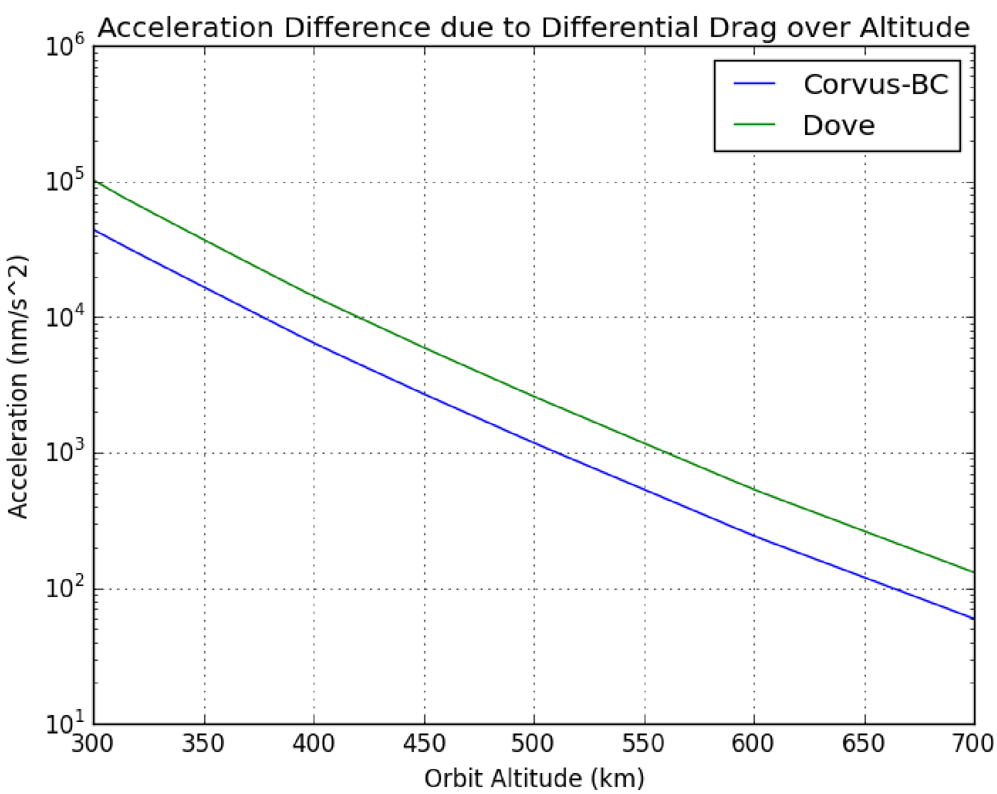

Figure 12. Spacecraft Differential Drag Acceleration over Altitude

5. Operational Interruption

This segment will compare the operational interruption to perform collision avoidance maneuvers for every conjunction with a miss distance under 500 meters. From Section 2 above, there are approximately 3.78 conjunctions per year at this miss distance or less. This analysis was performed for the Corvus-BC constellation, which consists of 10 Corvus-BC satellites, as well as hypothetical Dove constellations of 10 and 100 satellites. The metric to be used for comparison is how many satellite-days per year are occupied by collision avoidance maneuvers. As an example, a 10 satellite constellation has a total of 3650 satellite-days of operations available per year.

The Phase Four CAT propulsion system requires at least 30 Watts and a burn time of up to 16 minutes to successfully perform the avoidance maneuver half of an orbit prior to the conjunction. Assuming the satellite is operating in a constellation that requires relatively consistent orbital phasing, a re-synchronization burn would be required of equal duration which could occur as soon as the orbit afterwards. Due to the high power requirements associated with electric propulsion, a satellite operator can expect to lose 2 orbits worth of data from one satellite in the constellation every time a conjunction is predicted for a satellite. This would result in a total operational loss to collision avoidance maneuvers of **5.1 satellite-days per year (0.1%).**

Differential drag collision avoidance causes a much larger interruption to spacecraft operations. In order to maintain a constellation, it is generally required that all satellites in the constellation maintain the same approximate spacing (phasing) between each other. Since a differential drag maneuver irreversibly places a satellite into a new orbit with a slightly different orbital period from the rest of the constellation, something more must be done to “re-phase” the satellite into the constellation after a collision is avoided. One method of maintaining phasing would be to have all satellites perform identical differential drag maneuvers simultaneously whenever any single satellite needed to perform a collision avoidance maneuver. In this way, every satellite would relocate to a new orbit, but they would all be in the *same* new orbit. This method will be referred to as **Simultaneous Constellation Maneuvering (SCM).**

A Corvus-BC spacecraft would require 1.0 day of differential drag maneuvering to avoid a potential collision. Since the geometrical constraints of performing differential drag control preclude performing sun pointing for power collection, image gathering, and data downlink, this would result in an entire day of data from the satellite effectively being lost. With SCM, since all satellites must perform the same maneuver, one day of data from the full constellation would be lost. The entire constellation would be effectively out of commission an average of 37.8 days per year. This results in a total operational loss of **378 satellite-days per year (10.4%).**

Although the Corvus-BC constellation will be operated at an altitude of 600 km, other satellite constellations are planned to operate at altitudes as low as 450 km (such as Planet Labs). This provides the dual benefit of increasing the effectiveness of differential drag control, as well as reducing the number of potential collisions by a factor of approximately 4 (per Figure 12 above). The time to perform a 1 km differential drag avoidance maneuver for a Planet Labs Dove would be 0.24 days, and the number of potential collisions with miss distances under 500 meters would be 0.945 per year. These two factors (along with the high effectiveness of differential drag for Dove) serve to make this a “best case scenario” for SCM differential drag collision avoidance. If there were **10 satellites** in the Planet Labs constellation, it would experience an operational loss to SCM collision avoidance of **22.7 satellite-days per year (0.6%)**. With Planet Labs' full constellation of **100 satellites**, however, the total operational loss would be **2270 satellite-days per year (6.2%)** out of a constellation total of 36500 satellite-days per year. As more satellites are added to a constellation, the total collision avoidance requirement for the constellation increases, since every satellite must maneuver every time any single spacecraft experiences a potential collision event.

To avoid the rapidly decreasing efficiency with increasing constellation size of using SCM to avoid collisions, a satellite operator could potentially maneuver just the satellite that is involved with the collision warning. This can be accomplished by:

1) Commanding the threatened satellite to enter a low drag mode initially,
2) Then entering a high drag mode after the collision has been avoided in order to return back towards its designated constellation slot,
3) Entering a low drag mode to resynchronize its orbital period with the rest of the constellation,
4) Finally, resuming operations in the constellation.

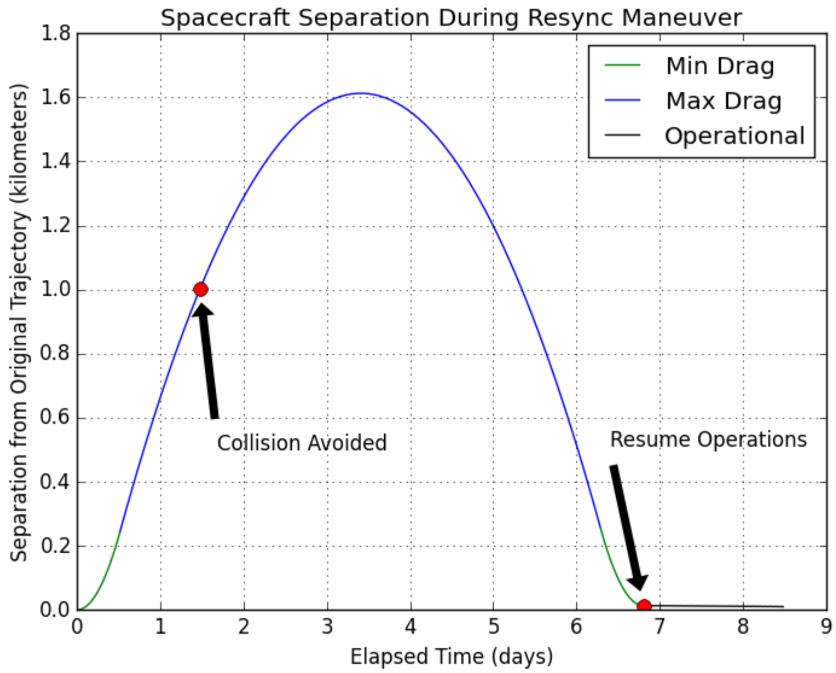

Figure 13. Corvus-BC Avoid and Resync Maneuver in 600 km Orbit

This collision avoidance method will be referred to as **Single Satellite Maneuvering (SSM).** An example of SSM for a Corvus-BC satellite in a 600 km orbit is shown in Figure 14. It is assumed that the satellite operator received a warning 2 days prior to the conjunction, and then commanded the satellite to begin its evasive maneuver 1.5 days prior to the collision. Since Corvus-BC has a greater difference between its minimum drag and average drag modes (as compared to the difference between its maximum drag and average drag modes), the minimum drag evasive maneuver is relatively quick, but the resynchronization maneuver afterwards takes much longer. Starting as early as possible on the evasive maneuver reduces the time required for the resynchronization maneuver because the satellite does not have to accelerate in the low drag mode for quite as long initially. As an example, a maneuver that begins 1 day prior to the conjunction would result in a loss of 12.5 days of operations (compared to only **6.8 days** for the maneuver shown).

A similar SSM maneuver for a Dove in a 600 km orbit is shown in Figure 15. The Dove has a more equal acceleration ability in both high drag and low drag modes, so the resynchronization maneuver takes less time relative to Corvus-BC. The Dove is in low drag mode for 0.55 days, enters a high drag mode to get a head start on resynchronizing, avoids the potential collision at 0.9 days, and resumes operations after a total of **2.4 days**. Although it would take less than a day for a single Dove to avoid a collision with SCM, the SSM method begins to pay off quickly in total operational satellite-days lost as the constellation grows.

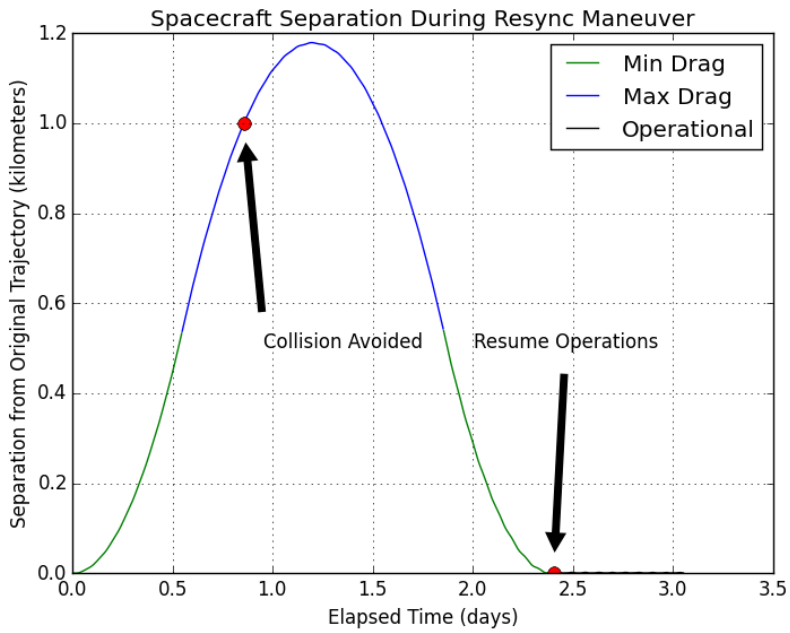

Figure 14. Dove Avoid and Resync Maneuver in 600 km Orbit

All of these scenarios are shown in Figure 16, along with a few others. For many satellite operators, losing upwards of 5% of the potential data from a constellation would be unacceptable from a business standpoint, which could prevent the implementation of differential drag collision avoidance in many of these cases. A trade will need to be made between adding more satellites to the constellation to account for this loss, dedicating money and effort to integrating a propulsion system, or accepting the increased risk of not avoiding collisions in the first place.

The case studies show that an on-board propulsion system is superior to differential drag control in every case, and doesn't suffer from the scaling problems associated with maintaining a large constellation with SCM differential drag. This comes with the obvious caveat that there are costs and engineering challenges associated with implementing a propulsion system in a small satellite. Additionally, for satellite operators that gather data which is expected to be continually updated, any constellation-wide downtime at all may be deemed unacceptable as well.

Spacecraft	Altitude	Maneuver Method	Conjunctions per Spacecraft per Year	Time to Maneuver	Number of Spacecraft in Constellation	Total Constellation Operational Time per Year	Operational Time Lost per Year	Operational Time Loss
Any	600 km	Propulsion	3.78	0.13 days	10 Spacecraft	3650 sat-days	5.1 sat-days	0.1%
Any	600 km	Propulsion	3.78	0.13 days	Any			0.1%
Any	450 km	Propulsion	0.95	0.13 days	10 Spacecraft	3650 sat-days	1.2 sat-days	0.03%
Any	450 km	Propulsion	0.95	0.13 days	Any			0.03%
Corvus-BC	600 km	SCM (Diff Drag)	3.78	1.04 days	1 Spacecraft	365 sat-days	3.9 sat-days	1.1%
Corvus-BC	600 km	SCM (Diff Drag)	3.78	1.04 days	10 Spacecraft	3650 sat-days	378 sat-days	10.4%
Corvus-BC	450 km	SCM (Diff Drag)	0.95	0.31 days	10 Spacecraft	3650 sat-days	29.5 sat-days	0.8%
Dove	600 km	SCM (Diff Drag)	3.78	0.78 days	10 Spacecraft	3650 sat-days	294 sat-days	8.0%
Dove	600 km	SCM (Diff Drag)	3.78	0.78 days	100 Spacecraft	36500 sat-days	29400 sat-day	80.8%
Dove	450 km	SCM (Diff Drag)	0.95	0.24 days	10 Spacecraft	3650 sat-days	22.7 sat-days	0.6%
Dove	450 km	SCM (Diff Drag)	0.95	0.24 days	100 Spacecraft	36500 sat-days	2270 sat-days	6.2%
Corvus-BC	600 km	SSM (Diff Drag)	3.78	6.80 days	Any			7.0%
Corvus-BC	450 km	SSM (Diff Drag)	0.95	1.70 days	Any			0.4%
Dove	600 km	SSM (Diff Drag)	3.78	2.40 days	Any			2.5%
Dove	450 km	SSM (Diff Drag)	0.95	0.78 days	Any			0.2%

Figure 15. Collision avoidance case studies. Related parameters are highlighted to show the changed variables for each specific case study.

A "break-even" point exists between SCM and SSM differential drag control as the constellation grows larger. For Corvus-BC, SCM and SSM are equally effective for a constellation of 6 satellites. With more than 6 satellites, SCM quickly becomes less effective overall. For Dove, the break-even point is around 3 satellites.

To answer a question that tends to come up with differential drag: how much orbital lifetime will be lost due to "artificially" modifying the satellite's drag profile? Since the most effective way to quickly modify a satellite's orbit with differential drag is generally by entering a low drag mode, this actually adds to the satellite's overall orbital lifetime. The satellite will remain in a higher orbit longer than if it had continued executing operations as normal. In the case of SSM, the satellite resynchronizes to the exact location it would have been in if no maneuvers were performed, so no orbital lifetime is lost.

6. Atmospheric Models

An important point to note in any discussion about the effect of atmospheric drag on spacecraft orbits is that the Earth's upper atmosphere varies greatly depending on a number of factors, the most important of which is the current solar activity level. All analyses in this paper were performed with the U.S. Standard Atmosphere, which is most accurate during moderate solar activity at a latitude of 45° north. However, the mean density of the atmosphere is known to change by approximately **2 orders of magnitude** between maximum and minimum solar cycles. Acceleration due to differential drag varies linearly with atmospheric density, so all operational time losses could be 10 times less or 10 times more depending on the current solar activity at the time of the maneuver. This variability in the effectiveness of differential drag collision avoidance could potentially dissuade some satellite operators from considering it as a truly viable avoidance method.

7. Conclusion

Differential drag was studied as a method of collision avoidance for small satellites and compared to the use of a representative propulsion system. It was found that form factors that had large surface area differences between axes resulted in the most differential drag control authority. Additionally, differential drag control authority decreases with increasing spacecraft mass, holding all other variables constant. As the atmosphere becomes thicker at lower orbital altitudes, the control authority increases quickly. The effect on spacecraft constellation operations of using differential drag for collision avoidance was studied, and it was found that a propulsion system generally results in much less constellation downtime. In some cases, the downtime requirements to implement constellation-wide SCM (Simultaneous Constellation Maneuvering) differential drag collision avoidance would result in an unacceptable loss of data-gathering ability, which could dissuade satellite operators from using these methods. SSM results in less overall operation loss for large constellations, but propulsion is still more effective in every case.

SCM differential drag collision avoidance is most promising for satellite's with a very irregular form factor, and a constellation size preferably well below 10 satellites. As constellation size grows, SSM differential drag collision avoidance can be useful for satellites with a large difference between both their minimum-to-average surface areas and maximum-to-average surface areas. Otherwise, satellite designers may need to consider propulsion as a more effective option to prevent high levels of constellation downtime if collision avoidance is a requirement.

8. References

1) Layson, H. and Halpern, S., “CubeSat Ambipolar Thruster Aquila Case Studies,” Phase Four, Inc., P4_AQUILA_R_2015_001
2) Foster, C., Hallam, H., and Mason, J., “Orbit Determination and Differential-Drag Control of Planet Labs CubeSat Constellations,” Planet Labs, Inc., AAS 15-524, Sep. 2015