Deployment of CubeSat Constellations Utilizing Current Launch Opportunities

Jordi Puig-Suari, Guy Zohar
Aerospace Engineering Dept., Cal Poly State University
1 Grand Ave., San Luis Obispo, California, 92407; (805) 756-8750
jpuigsua@calpoly.edu

Kyle Leveque
SRI International
333 Ravenswood Ave., Menlo Park, California, 94025; (650) 859-2000

ABSTRACT

Large sensor constellations are being proposed as a natural application of CubeSat class spacecraft. Given their low cost and numerous launch opportunities large numbers of CubeSats can be easily deployed in orbit. However, the fact that CubeSats are launched as secondary payloads limits the options for their deployment in appropriate constellation geometries. This problem is further aggravated given the current lack of propulsive options for CubeSats. This paper explores the viability of deploying constellations of cubeSats with efficient geometries using current secondary launch opportunities. The only variables being considered are the deployment timing and direction for individual CubeSats in a single launch. The results indicate that simple deployment strategies can be utilized to provide appropriate CubeSat dispersion to create efficient constellation geometries.

INTRODUCTION

In 1999, the CubeSat standard [1,2] was developed by Stanford and Cal Poly as a low-lost education platform (Fig.1). In the early days of CubeSat program, these university spacecraft had very little capability and CubeSat missions were limited to education and in-space component testing. However, as the CubeSat community has evolved the capability of these small spacecraft has increased exponentially driven by the adoption of high performance commercial electronic components as well as the efforts of the scientific instrument developer community. Many government agencies are currently supporting the development of mission ready CubeSats including NSF, NASA, and DoD. Given their small cost and ease of launch many of the CubeSat missions being developed are viewed as precursors for constellation mission that would provide extended or global coverage [3,5]. However, while the number of launch opportunities for CubeSats has increased dramatically, the deployment of CubeSat constellations still presents some challenges for the

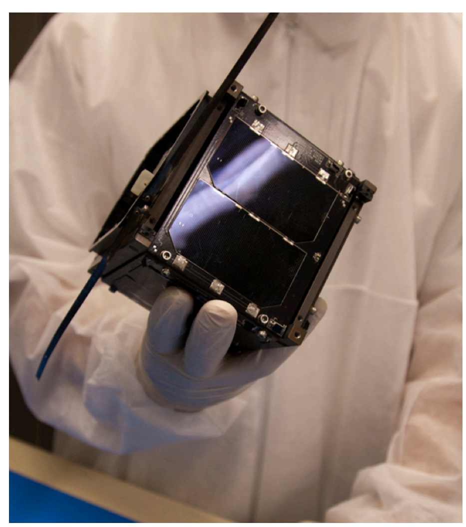

Figure 1: Cal Poly's CP 6, a typical CubeSat Class Spacecraft

CubeSat developers. A critical challenge is the need for propulsive maneuvers to accurately deploy a constellation. Propulsion systems for CubeSats are currently in development and expected to be available in the near future. However, the cost and mass associated with propulsive systems limits the potential use of this critical technology by many CubeSat missions. Therefore, this paper investigates the feasibility to deploy CubeSat constellations with minimal or no propulsion capabilities utilizing current launch capabilities.

CURRENT LAUNCH CAPABILITIES

Currently CubeSats are launched using a deployement system such as Cal Poly's Poly-Picosatellite Orbital Deployer (P-POD) [6]. The P-POD can carry three standard 1U CubeSats, a single 3U CubeSat or an combination of different size CubeSats. The P-POD is mounted on the launch vehicle (LV) (Fig. 2) and when commanded by the LV avionics it ejects the CubeSats using a spring-loaded mechanism. CubeSat accommodations are currently available in a large number of LVs and launch sites worldwide. In this paper, we will focus our analysis on US based CubeSat launch capabilities.

The P-POD deployers incorporate a standard deployment spring that generates deployment speeds in the order of 1.5m/s for standard mass CubeSats with variations in CubeSat resulting in proportional changes in deployment speed. In addition, when multiple CubeSats are deployed from a single P-POD small separation springs aid in the separation of the satellites in a single deployer. However, the dynamics of multiple

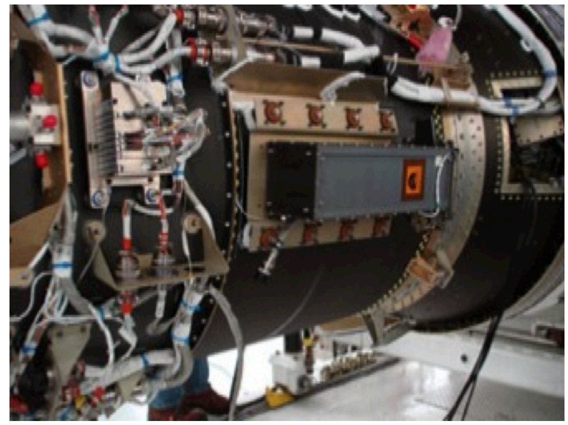

Figure 2: A P-POD Mounted on a Minotaur Launch Vehicle and ready for launch

deployments from a single P-POD are complex and it is difficult to accurately determine individual spacecraft deployment speeds. This paper will assume a homogeneous constellation of identical 3U spacecraft resulting in identical deployment speeds. Given current CubeSat development this is the most likely constellation scenario.

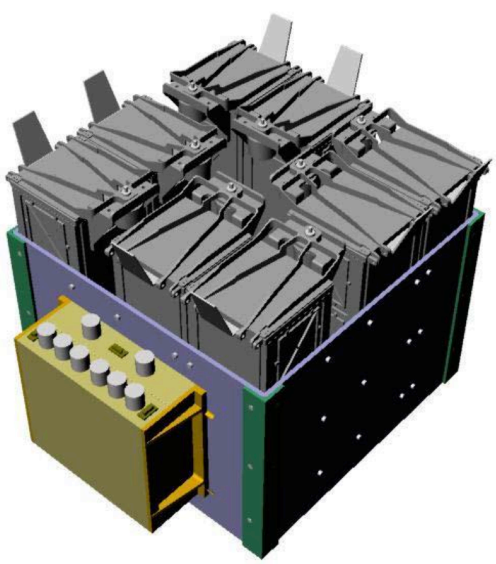

Figure 3: NPSCuL Model (credit Naval Postgraduate School)

In response to the high demand for CubeSat launch opportunities, the Naval Postgraduate School CubeSat Launcher (NPSCuL) was developed to facilitate the integration of multiple P-PODS into one system. The NPSCuL carrier can be integrated into multiple launch vehicles and holds eight P-PODs. The NPSCuL was first used on the Atlas V launch vehicle on the newly created Aft Bulkhead Carrier [7] plate for the NROL-36 launch. Future Atlas V launches will have NPSCuL capability and will drastically increase the launch capabilities for CubeSats. Currently, the NPSCuL carrier represents the largest number of P-PODs than can be launched in a single vehicle. This 8 P-POD capability will be used as the baseline for the constellation deployment studies in this paper.

The deployment control parameters being evaluated in this paper are limited to the time between P-POD deployments and the deployment direction.

DEPLOYMENT SIMULATION CAPABILITES

STK was the tool of choice to simulate deployment of CubeSats constellations. In order to verify the accuracy of the simulation, the NPP CubeSat launch was used as a test case and STK was used to predict that orbital position of RAX 2, one of the CubeSats in that launch over a long period of time. The initial results showed errors of up to 15deg in true anomaly over a 225 day period. These results were discouraging and required further analysis. The main problem was identified as the variations in the satellite's drag parameter B*, as

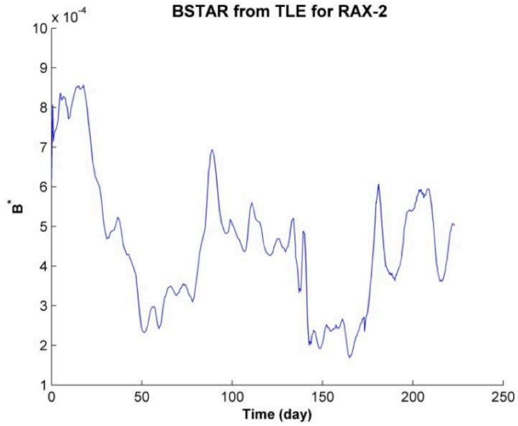

Figure 4: B* term for RAX2 CubeSat

reported in the spacecraft actual TLEs reported by NORAD (Fig. 4). This drag changes cannot be accurately modeled within STK. This error levels would limit the accuracy of long-term constellation deployment simulations. However, when the B* fluctuations for all of the spacecraft in the NPP launch are compared (Fig. 5), it is clear that B* fluctuations are due to atmospheric effects that act consistently across all spacecraft. Note that the initial discrepancies in the data are due to tracking errors in during the first days of the mission. Once, steady TLE's have been established variations in the B* value for all spacecraft are very consistent. Therefore, even if the simulations fail to accurately predict the absolute position of the deployed spacecraft, STK will accurately predict the relative position of the deployed spacecraft. This relative position is the critical parameter in the definition of the constellation characteristics.

EVALUATING DEPLOYMENT PERFORMANCE

In order to determine the effectiveness of a specific deployment strategy, a performance metric needed to be defined. While different missions may require different spacecraft distributions, in this work it assumed that the ideal spacecraft deployment distribution involves spacecraft equally spaced along the orbital path. With the worst possible distribution being all spacecraft clustered in a single point. In order to quantify how close a constellation is to the ideal distribution a clusterness parameter is defined as:

$$Custerness = \frac{\|\Sigma(\theta_{max} - \theta_N)\|}{(N-1)\theta_{max}} \qquad (1)$$

Where N is the number of satellites, θ_N is the true anomaly separation between satellites N and N+1, and θ_{max} is the true anomaly separation for a perfectly distributed constellation and is given as:

$$\theta_{max} = \frac{360}{N} \qquad (2)$$

The value of the clusterness is zero when the satellites are evenly distributed along the orbit and one when the satellites are located at the same point in the orbit.

It should be noted that without a method to control the velocity of the spacecraft the constellations will remain

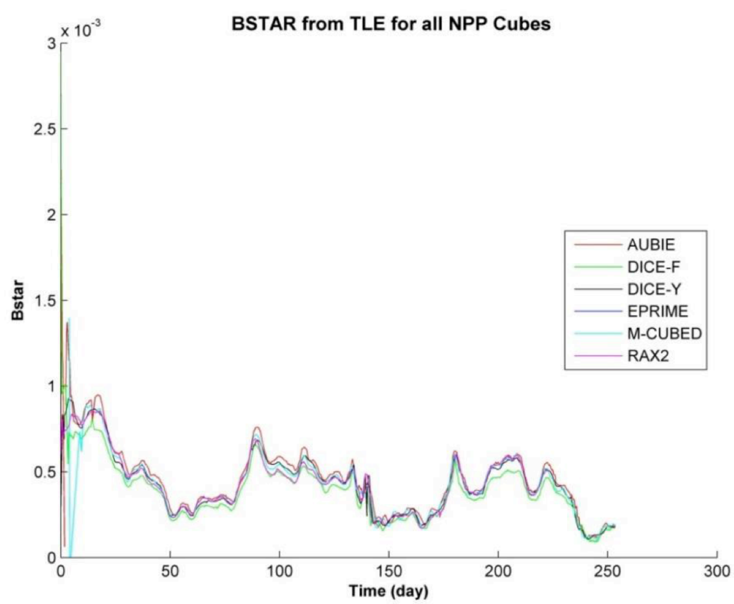

Figure 5: B* term for all NPP CubeSats

dynamic arrangements changing with time and therefore, the clusterness value will change over time.

Note that the simple deployment strategies presented here can be utilized to optimize other constellation requirements not based in an even distribution of the spacecraft.

DEPLOYMENT STRATEGIES

Currently, deployment maneuvers for CubeSats are very simple with the primary deployment objective being collision avoidance. In many cases, all the spacecraft will be deployed in the anti-velocity direction with a specified time interval between deployments. This deployment strategy results in very slow separation of the spacecraft in a single launch and presents some tracking and spacecraft identification challenges.

This is a predictable result since CubeSats deployed in the same direction with the same deployment mechanism will deploy with very similar separation velocities with respect to the LV. The Clohessy-Wiltshire (C-W) Equations of relative orbit motion indicate that producing a steady separation between two spacecraft requires a velocity differential in the orbit path direction or a change in orbit radius. The specific term in the equations is:

$$y(t) = -(6wx_0 - 3\dot{y}_0)t \qquad (3)$$

Where $y(t)$ is the relative position along the orbit path, x_0 is the difference in initial orbit radius, $\dot{y}_0$ is the initial difference in velocity along the orbit, and w is the orbital angular velocity.

The anti-velocity deployment strategy results in minimal speed and radius differences. The only separation between the spacecraft is due to the time delay between deployments. This initial separation increases very slowly due to second order orbital perturbations.

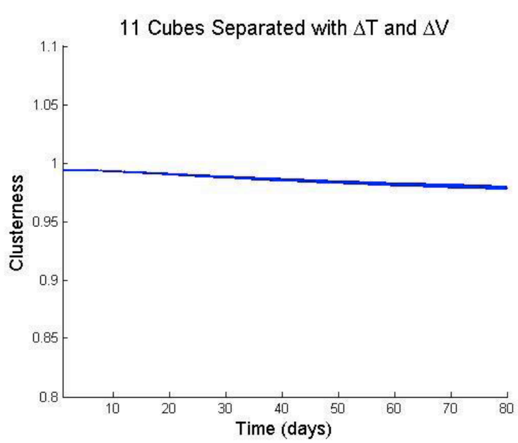

Figure 6: Clusterness for 11 Cubes with varying deployment time and ΔV = 1.5 m/s

The lack of separation in standard CubeSat deployment scenarios can also be described using our clusterness parameter. A simulation is performed of the L-36 deployment with 11 CubeSats deployed with identical velocities (1.5m/s) and with the separation times as follows:

CubeSat	Deployment Time (min)
1	0
2	1
3	2
4	5
5	10
6	15
7	30
8	60
9	90
10	120
11	180

The clusterness value for this simulation remains close to one for over 80 days (Fig. 6) indicating a vey small separation rate between spacecraft even with large deployment time variations between spacecraft.

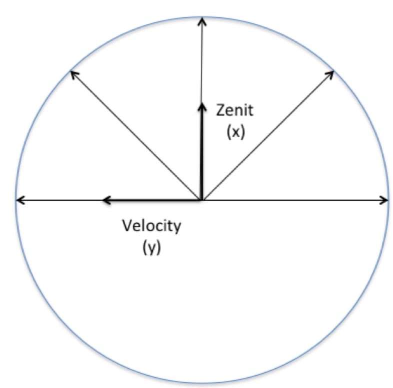

Figure 7: Radial Semi-Circular deployment

Clearly, looking at the CW equation, better separation rates can be obtained if the spacecraft are deployed with different deployment velocities along the orbit path. Many separation strategies were considered with varying levels of success. One of the most successful options is the deployment of the CubeSats in a radial semi-circular pattern on the orbit plane (Fig. 7). This deployment scheme can be accomplished by deploying the CubeSats while the upper stage is rotating in the orbit plane or by installing the P-PODs in a radial pattern on the launch vehicle. Note, that rotation maneuvers are not uncommon for upper stages and are used during payload deployments and orbit transfer maneuvers.

A specific semi-circular deployment distribution was simulated to show its potential to deploy a constellation. The analysis assumes a 500 x 550 orbit at a 51.6° inclination with an Argument of Perigee, RAAN, and True anomaly all set to zero. All propagations are initialized on 1 Jan 2012 01:00:00 UTC. The launch assumes an NPSCuL system with eight 3U CubeSats. The Satellites are assumed to weigh 4kg resulting in a separation speed of 1.44m/s. The CubeSats are deployed 3 minutes apart as the upper stage rotates at constant angular velocity through 180 degrees. This results in the following deployment parameters.

CubeSat	Deploy Time (min)	Angle from +Y (deg)	Sep. Velocity (m/s)		
			X	Y	Z
1	0	0	0	1.44	0
2	3	25.7	0.62	1.30	0
3	6	51.4	1.13	0.90	0
4	9	77.1	1.4	0.32	0
5	12	102.9	1.4	-0.32	0
6	15	128.6	1.13	-0.90	0
7	18	154.3	0.62	-1.30	0
8	21	180	0	-1.44	0

The motion of the spacecraft is simulated for 365 days and the clusterness parameter variations are shown in figure 8. The scheme results in the cubes in the constellation separating quickly and reaching a near minimum Clusterness value of 0.0513 after approximately 45 days. The developed constellation then oscillates above the near minimum value by breaking down and reforming periodically but does not reach a state significantly less clustered. The absolute minimum value over the year occurs at 203 days with a Clusterness value of 0.0513. A CubeSat developer is unlikely to wait 158 days for a small improvement in satellite distribution. Therefore, the constellation is considered deployed after the initial 45 day period.

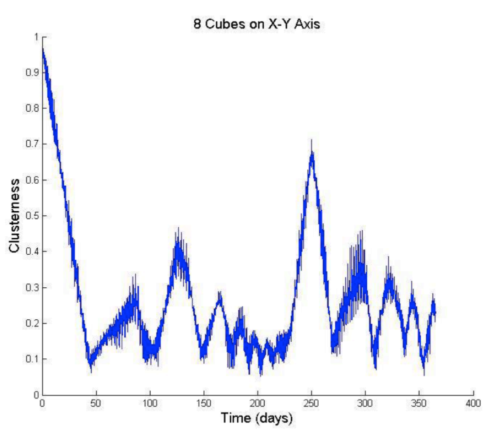

Figure 8: Clusternees for semi-circular deployment scheme

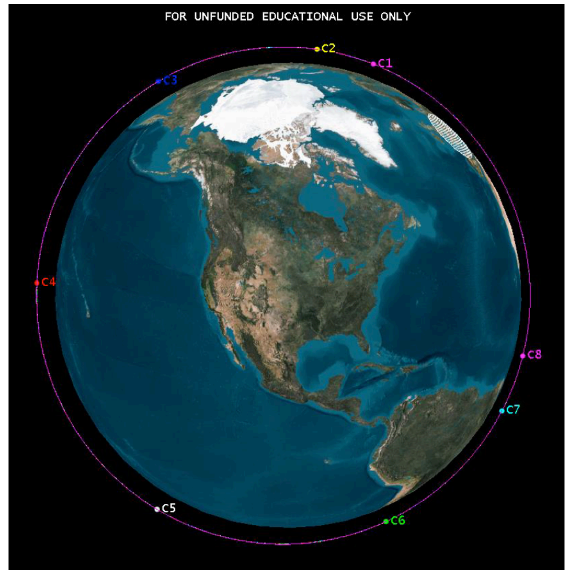

Figure 9: CubeSat location after 45 days semi-circular deployment scheme

Examining the constellation directly at its initial maximum separation on day 45 (Fig. 9) shows that the satellites are not evenly distributed as expected with a clusterness higher that zero. The CubeSats are distributed along the orbit in the order they were dispersed with the separation determined by the magnitude of their relative Y separation speed. Note that the dispersion of the satellites could be improved if the magnitudes of the relative Y speeds were adjusted to provide even separation speeds.

Equally distributed Y velocities result in the following deployment characteristics:

CubeSat	Deploy Time (min)	Angle from +Y (deg)	Sep. Velocity (m/s)		
			X	Y	Z
1	0	0.00	0.00	1.44	0
2	3	44.41	1.01	1.03	0
3	6	64.62	1.30	0.62	0
4	9	81.79	1.43	0.21	0
5	12	98.21	1.43	-0.21	0
6	15	115.38	1.30	-0.62	0
7	18	135.59	1.01	-1.03	0
8	21	180.00	0.00	-1.44	0

The clusterness plot shows a similar behavior to the semi-circular deployment (Fig. 10). The minimum

Clusterness value of the constellation is 0.02099 with the initial full deployment reaching a Clusterness value of 0.02967 after 44.93 days. The simulated position of each CubeSat in the constellation on day 45 is shown in Figure 11.

As expected a separation scheme based on equally distributed Y-vector separation velocities and applied to a semi-circle geometry produces a very well distributed constellation. However, the resulting distribution maneuver would be more complex for the upper stage when using an NPSCuL like system. Therefore the simple semi-circular radial distribution scheme will continue to be used as a baseline for this paper. Alternatively, a radial mounting scheme for the P-PODs could be developed. Such a mounting configuration for the Pegasus vehicle was proposed for SDL's HiDEF mission (Fig. 12) [3].

Next the effects of orbital altitude on this deployment strategy were analyzed for the simple semi-circular deployment scheme. The analysis was performed by maintaining constant orbit eccentricity and varying perigee from 400km to 650km The results are as follows:

Perigee Alt.	Deployment (days)	Clusterness
400	38.48	0.05388
455.6	44.1	0.05633
511.1	45.52	0.06062
566.7	47.16	0.05613
622.2	47.72	0.05742
650	48.83	0.05902

The results indicate that the behavior of the system remains fundamentally the same and the only significant change is the time required to reach the initial deployment state.

The deterioration of the constellation geometry after the

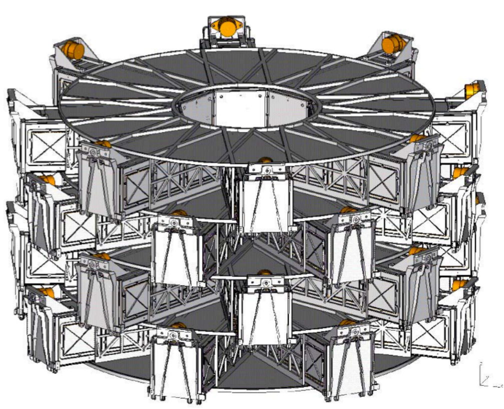

Figure 12: Radial P-POD mounting proposed for the HiDEF mission

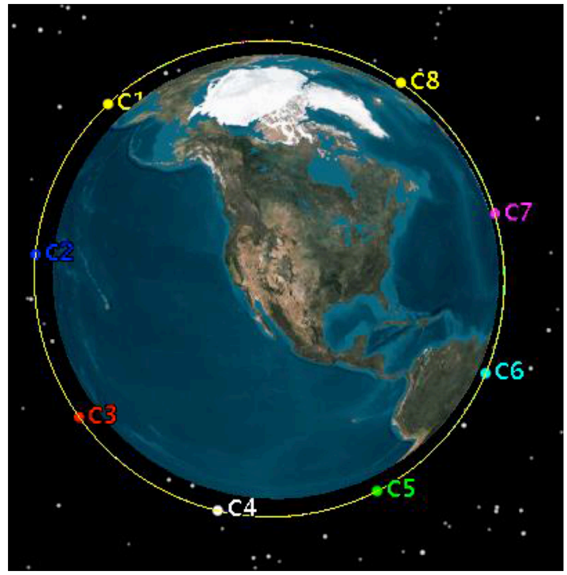

Figure 11: CubeSat location after 45 days for Equally distributed Y deployment scheme

45 day deployment period is not a desirable feature. Clearly a maneuver could be performed at that point to "freeze" the geometry. The maneuver would require the equalization of the orbit period for all the CubeSats. In the analysis an average orbital period was used as the target period to distribute the ΔV among al the spacecraft. For the simple semi-circular deployment the required maneuvers to "freeze" the constellation after 45 days are:

Cube #	Initial Orbital Velocity (km/s)	|ΔV| (m/s)
Target Orbit	7.5751 -	
1	7.5758	0.6708
2	7.5714	3.6947
3	7.5678	7.3733
4	7.5789	3.7989
5	7.5768	1.6953
6	7.5784	3.2434
7	7.5750	0.1663
8	7.5770	1.8370

The maximum maneuver required to "freeze" the constellation is 7.3m/s. This small value is clearly within reach of the simplest propulsion systems being developed for CubeSat class spacecraft [8], such as small cold gas systems. In addition, low ΔV maneuvers may be performed by non-propulsive means such as differential drag using attitude changes [9].

CONCLUSION

The results from this analysis indicate that the successful deployment of CubeSat constellations is feasible using current secondary launch capabilities with minor operational changes. High-coverage constellations can be deployed in less than 50 days without the use of CubeSat propulsion. Without active control the deployed CubeSats will provide a well-developed constellation for days or weeks around the 50 day high-coverage point. However, the ΔV requirements to maintaining the constellation geometry are minimal and well within the capabilities of current CubeSat technology.

REFERENCES

1. Puig-Suari, J., Schoos, J., Turner, C., Wagner, T., and Connolly, R., "CubeSat Developments at CalPoly: the Standard Deployer and PolySat," paper 4136-13, 45th Annual Meeting of International Society for Optical Engineering (SPIE), July-August 2000.
2. Heidt, H., Puig-Suari, J., Moore, A., Nakasuka, S., and Twiggs, R., "CubeSat: A new Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation", 14th Annual AIAA/USU Small Satellite Conference, Logan, Utah, August, 2000.
3. Whitmore, S., Bingham, B., and Young, Q., "Launch and deployment of the High-Latitude Dynamic E-Field (HiDEF) Explorer Satellite Constellation," 22nd Annual AIAA/USU Small Satellite Conference, Logan, Utah, August, 2008.
4. H., Arens-Fischer, W., Wolfsberger, W. Iglseder, "Small Satellite Constellations for Disaster Detection and Monitoring," Advanced Space Research, vol. 15, no. 11, pp. 79-85, 1995.
5. Bill Blackwell, "Nanosatellites for Earth Environmental Monitoring: the MicroMAS Project," in AIAA/USU Conference on Small Satellites, Logan, UT, 2012.
6. The CubeSat Program, Cal Poly SLO. (2009) CubeSat Design Specification, Rev. 12. [Online]. http://www.cubesat.org/images/developers/cds_rev12.p df
7. M. Willcox, "Atlas V Aft Bulkhead Carrier Rideshare System," in AIAA/USU Conference on Small Satellites, Logan, UT, 2012.
8. W.D. Williams, "Propulsion Solutions for CubeSats," in AIAA/USU Conference on Small Satellites, Logan, UT, 2012.
9. Y. Winetraub and R. Dr Tamir, "Using Differential Drag for management of Pico-Satellite Constellations," "Evolution Not Revolution" Nanosatellite Symposium, September 2008, Glasgow, Scotland.