The CubeSat Challenge:

A Review of CubeSat Dependencies and Requirements for Space Tracking Systems

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ABSTRACT

This paper investigates the challenges cubesats pose to space surveillance networks and the corresponding dependencies cubesat's have of external tracking systems during all phases of the mission. From deployment, through activation, operations to end of life, cubesats depend upon timely, accurate and consistent data from space surveillance networks to successfully execute the mission. Supplying this data has been a challenge for existing space surveillance sensors given the physical and electrical size of each cubesat and is further compounded by the numbers of cubesats deployed from any given launch. As the use of cubesats proliferates, this added tracking complexity of resolving clusters, correlating tracks and associating those tracks with the correct cubesat will only increase. The rapid growth of cubesats presents a significant challenge to the existing space surveillance infrastructure both computationally and also with respect to the resource management of individual sensors. The resulting variability in space surveillance supplied data provides a scheduling challenge to the cubesat operations team to successfully execute their mission given their limited mission life. Relevant examples of this integrated cubesat-space surveillance network dependency are provided from previous cubesat missions from the US Naval Research Laboratory and California Polytechnic Institute San Luis Obispo. Analysis of this data is also reviewed including two-line element accuracy, correlation and association metrics, along with overall timeline and schedule impacts to the mission from cubesats deployed from both US and Russian launch vehicles.

Acronym List

1U	1 Unit 10 x 10 x 10 cm cube
2U	2 Unit 10 x 10 x 20 cm volume
3U	3 Unit 10 x 10 x 30 cm volume
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NRL	Naval Research Laboratory
P-POD	Picosatellite Orbital Deployer
RCS	Radar Cross Section
RF	Radio Frequency
TLE	Two Line Element
TVAC	Thermal Vacuum
UHF	Ultra High Frequency
VHF	Very High Frequency

INTRODUCTION

Over the past decade, CubeSats have rapidly advanced in complexity and in sheer numbers to now comprise almost 10% of the active LEO catalog as depicted in Figure 1 [1]. Their exponential growth in numbers is further complicated by a continual drive to smaller and smaller form factors on the order of 10 cm x 10 cm (i.e. 1U). Their small physical and electrical size has placed additional requirements and difficulties for existing space tracking systems. A CubeSat's small size coupled with complex dynamics and the LEO debris environment represents a challenging resource and processing problem for existing space tracking sensors. Despite the problem CubeSats pose to space tracking systems, each CubeSat mission is

Figure 1: CubeSats represent nearly 10% of 2012 LEO population [1]

inherently dependent upon the same system to quickly generate accurate ephemerides to aid in the activation and operations of the CubeSat before the end of its limited life either through fault or deorbit.
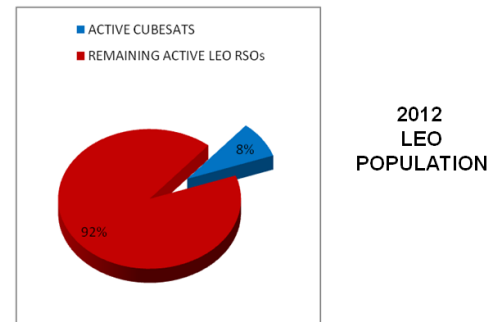
2.0 CUBESAT STATISTICS

Figure 2 illustrates the exponential increase in the number and success rate of CubeSats over the past 10 years [1]. This rapid growth has been aided by parallel advances in the deployment of CubeSats from multiple launch vehicles. This agnostic approach to enabling secondary payload launch opportunities has been led by the P-POD canister developed by the California Polytechnic University (CalPoly). Figure 3 depicts the corresponding increase in P-POD capacity over the same time frame allowing for more and more CubeSats to be launched by a single booster [2]. In conjunction with these advances in reliability and deployment mechanisms, the accelerating pace of miniaturization has provided extraordinary capabilities in processing, communications and control in the same time frame roughly following Moore's Law. As depicted in Figure 4 the preponderance of CubeSat configurations has gravitated towards
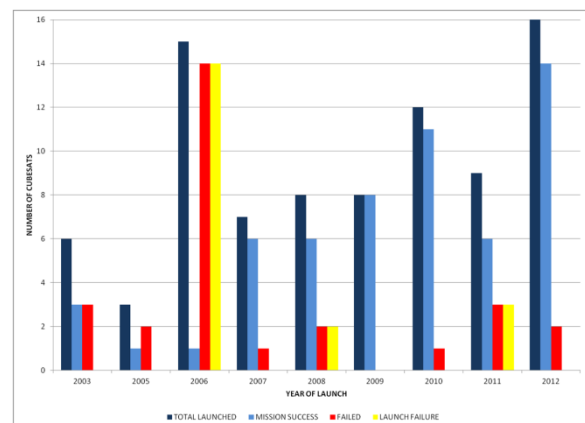

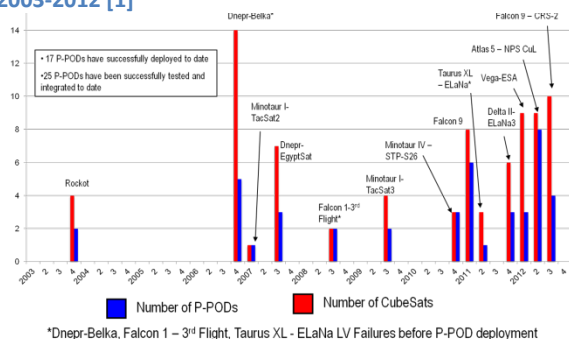Figure 2: CubeSat Launches, Successes & Failures 2003-2012 [1]

Figure 3: CubeSat Dispense Heritage and Timeline 2003-2012 [2]

the common 10 cm cube or 1U form factor for both cost and performance [1]. As shown, 1U configurations outnumber 30 x 10 cm (3U) form factor by nearly 4 to 1, with other variants such as the 2U design with negligible usage. The adoption and performance potential of the 1U design has enabled the proliferation of CubeSats to grow to encompass almost 10% of the LEO population in the past 6 years. With continuing advances, this rate continues to trend upward, and even neglecting the inclusion of proposed mass launches of CubeSats (> 50) from a single launch, results in CubeSats constituting at least 25% of the active LEO population of satellites by 2017.
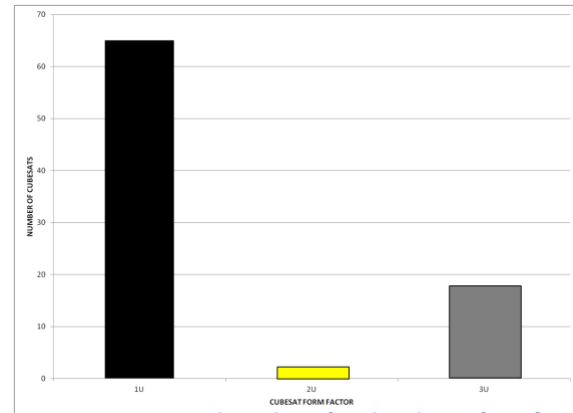

Figure 4: Total number of each CubeSat form factor flown 2003-2012 [1]

3.0 MISSION PHASES & TRACKING CHALLENGES

Three overall phases define any CubeSat mission: Deployment, Activation and Operations. As a rideshare, CubeSats have limited control over their deployment or its conditions. These conditions include separation angular rates, orientation and illumination. Any of these conditions taken individually or applied to a single CubeSat are a challenge, but are made more difficult by the fact that CubeSats are nominally deployed in clusters. The generation of these clusters is achieved by timers expiring and ejecting each CubeSat via mechanical springs. The order and separation of each CubeSat in the cluster is defined by timer delays and varying spring constants. These mechanical processes add to the uncertainty of the overall uncertainty in the timing of the deployment phase. The transition from Deployment to Activation varies from CubeSat to CubeSat, but it is highly unlikely that either phase occurs within view of any space tracking sensor. Regardless of the success of the deployment phase, first overflight of a space tracking sensor could be several revs post activation. In the interim the CubeSat mission operations team is in a hold state waiting to transition to the final phase of Operations until the orbit is determined and the CubeSat has been positively

Figure 5: CubeSat – Space Tracking System Dependency Diagram

identified. This dependency historically has required days to weeks to allow the mission to commence and begin collecting mission data in the Operational mode. This overall flow and its explicit dependencies with the space tracking system are depicted in Figure 5.
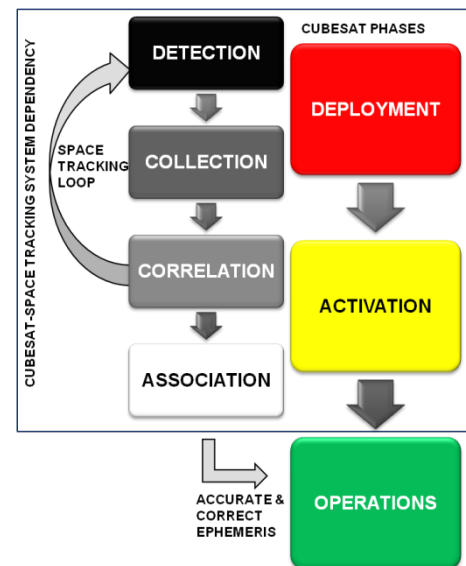
While the CubeSat is transitioning from Deployment through Activation and awaiting the data necessary to begin Operations, the space tracking system is iterating through a corresponding set of states with respect to knowledge of a given CubeSat. From the first successful overflight, detections are collected and trajectories are generated for the object. Subsequent collections are aggregated and correlated with previous observations sets to fit a consistent orbit. This consistency between current and archived data allows the object to be correlated, but not yet be identified or associated. The ability to positively associate a set of observations with a given object is a difficult process when in close proximity to other CubeSats in the cluster. The rate of miscorrelation between cluster elements is extremely high, and as mentioned above, required

days or weeks to coordinate and resolve. This timeline is driven by the variable drag effects acting upon each CubeSat and causing the cluster to breakup and increase the overall distance between elements. This differential drag induced motion provides knowledge of the tracked objects ballistic coefficient, which in turn aids in not only correctly associating the CubeSat, but also improves modeling of its ephemeris.
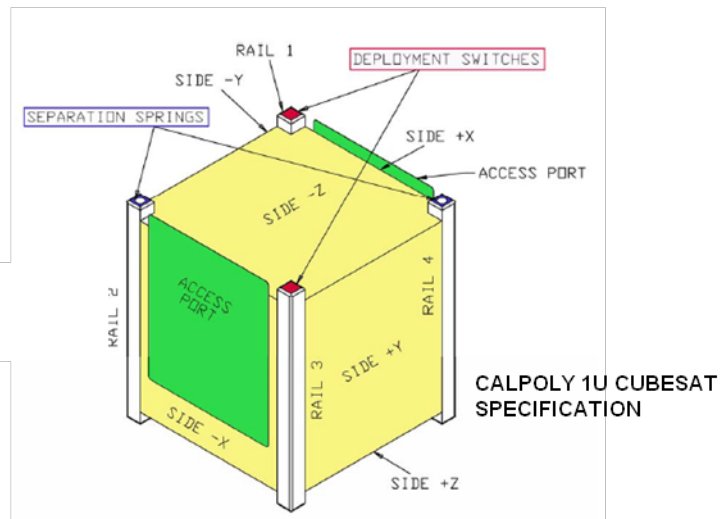

Figure 6: CalPoly 1U Specification [2]

This transition dependency from Activation to Operations via correctly associating the tracked object is challenged by the current control capabilities of 1U CubeSats, complex drag effects and the background debris environment. A 1U CubeSat is inherently mass, volume and power limited as shown in Figure 6 [2]. This power limitation, with eclipse periods nearly every orbit for non-dawn-dusk sun-synch orbits, precludes constant GPS processing, the operation of VHF/UHF passively timed beacons and most importantly precision attitude control. Depending upon the mass to volume ratio of the CubeSat its ballistic coefficient and corresponding drag deceleration could vary tremendously as a function of the cross sectional area presented to the ram direction. This attitude dependence is on par with the uncertainty

Figure 7: NASA LEO Orbital Debris Graphic [3]

in the atmospheric density at the CubeSat's altitude. Whether tumbling or controlled to a few degrees, the ability to model and account for this non-linear perturbation is a constant challenge for the space tracking system. Similarly, these same tracking sensors are further challenged by
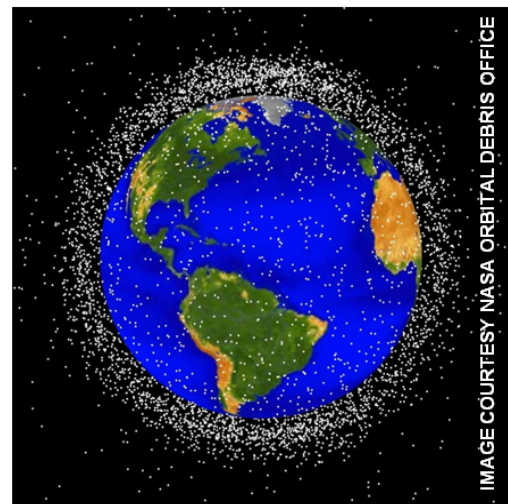
the fact that the same cross-section or even side will be presented to the sensor on a given overflight as seen previously. Again this variability makes the transition from correlated to associated all the more difficult.

The final environmental challenge is the amount of debris in LEO between 1 to 10 cm. NASA's Orbital Debris Office estimates that more than 20,000 pieces of debris are resident in the LEO regime as shown in Figure 7 [3]. With a CubeSat's size on the same order as a piece of debris, space tracking sensors must apply additional resources to resolve the tracked object and provide a positive identification to the CubeSat team to transition to Operations.
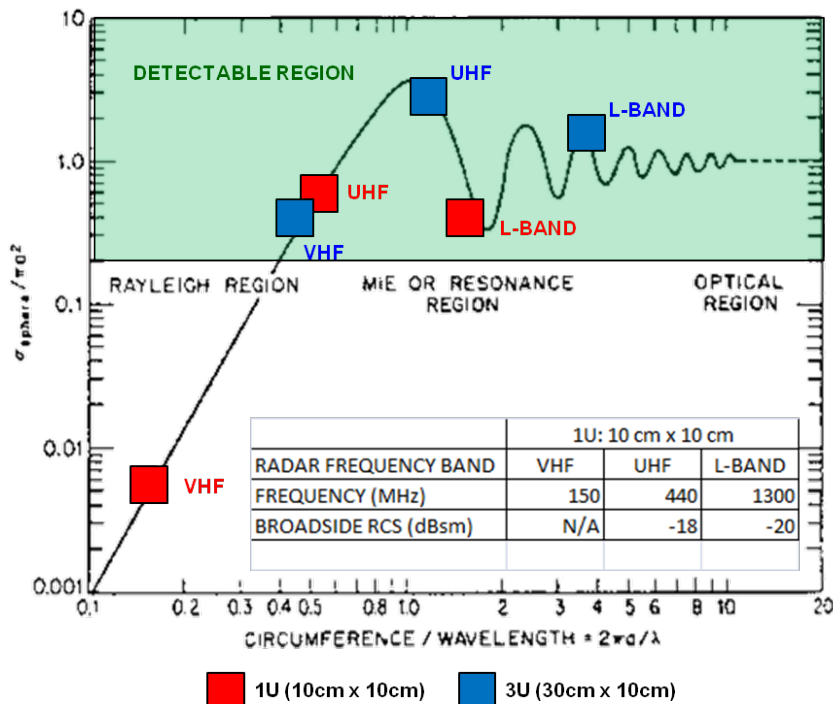
Figure 8: CubeSats present very low SNR targets [4]

At LEO altitudes, the CubeSat quickly transits through the terminator making for a difficult target for optical systems to detect. With poor lighting geometry and limited opportunities (i.e. no available optical sensor near terminator), most CubeSats are tracked by RF sensors in much the same way that debris measurements are made. Even at a few hundred kilometers in altitude these 1U CubeSats are a significant challenge for the RF space tracking sensor to even detect, let alone collect, correlate or associate. Using first order radar equations shown in Figure 8 a 10 cm x 10 cm cube represents at least a -20dBsm target for UHF and L-band systems [4]. Inclusion of environmental, mechanical, electrical and processing errors and biases decreases the sensitivity of RF sensor making tracking exceptionally difficult. Attempting to rectify these shortfalls by applying more power to the target does not necessarily solve the problem since geometry is as large a concern as sensor sensitivity and processing. Key to this geometry problem,
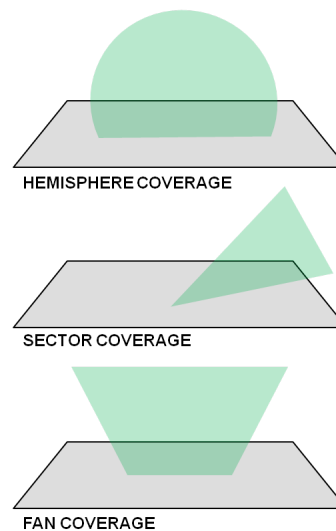

Figure 9: RF Sensor Geometry

is the angle with which the sensor is able to view the target. RF sensors nominally are capable of either hemispherical (e.g. dish), sector (e.g. phased array), or fan (e.g. fence) coverage. The hemispherical sensors require scheduling to accommodate the large number potential detectable targets across the sky. Sector sensors have the ability to miss overflights through limited field of regard angles, while fan coverage is challenged by the 2 seconds it takes for the CubeSat to transit across the fence's. Each of these RF sensor configurations are represented in Figure 9.
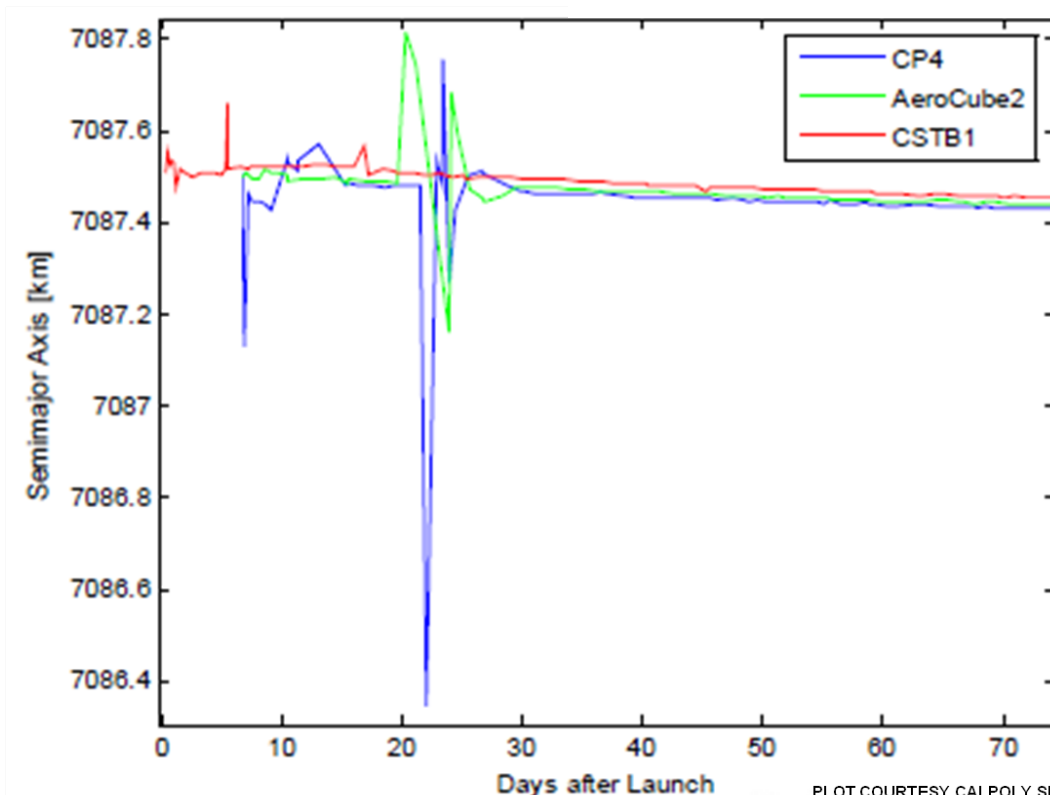
4.0 FLIGHT DATA EXAMPLE CASES

To illustrate the challenge and dependencies described in Section 3, the data from two recently flown successful CubeSat missions is presented. The first mission is the 7 CubeSats deployed from the 17 April 2007 Dnepr launch and the second mission is the two QbX CubeSats deployed from the Falcon 9 demo launch on 4 June 2010. In each case the CubeSats were part of an overall cluster deployed from multiple P-POD launch dispensers.
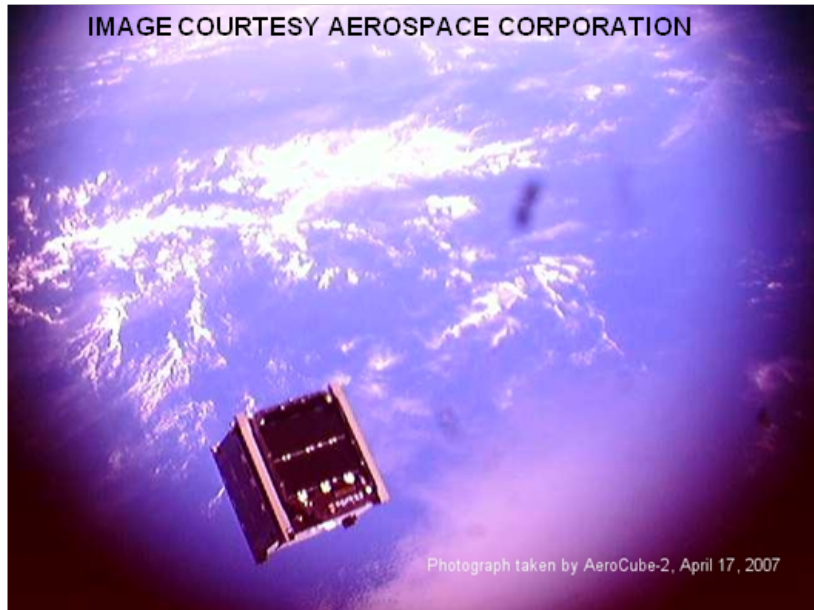
The Dnepr launch consisted of 3 P-POD

P-PODs A, B, & C

IMAGE COURTESY CALPOLY SLO CUBESAT TEAM

Figure 10: Dnepr CalPoly P-PODs [2]

PLOT COURTESY CALPOLY SLO CUBESAT TEAM

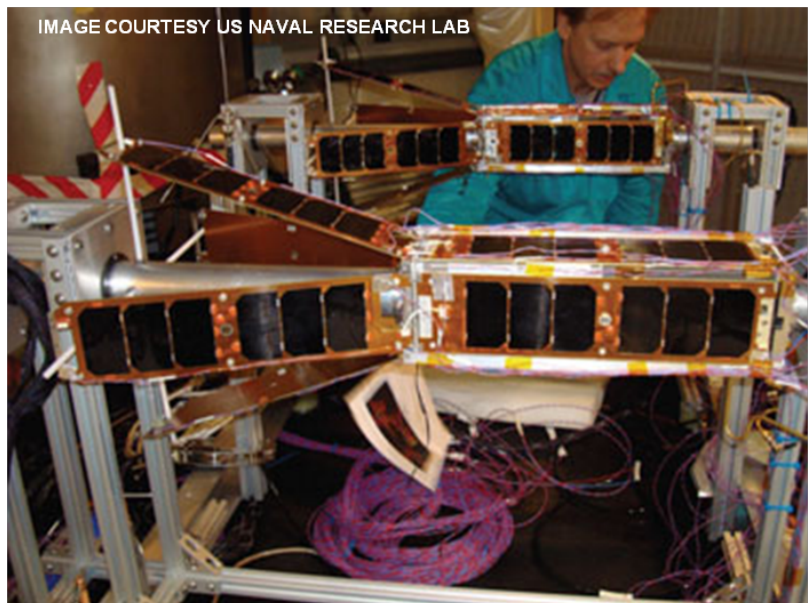Figure 11: Miscorrelations among 2007 CalPoly CubeSats [5]

dispenser named A, B and C. Of the seven CubeSats, three of the CubeSats included beacons to aid in correlating and associating each object in the cluster as shown in Figure 11. Several hours after launch, the Dnepr provided state vectors for each P-POD deployment mirroring the expected nominal case. Despite this support from the launch vehicle provider, it required over 2 days to detect all 7 CubeSats and after a month all 7 CubeSats were correctly associated [5]. Adding to the hold to transition to the Operational Phase was the initial 12 hour delay to receive

Figure 12: Close proximity of Dnepr CubeSat cluster [7]

initial TLEs to corroborate the Dnepr deployment vectors. The magnitude and number of miscorrelations is clearly depicted in Figure 11 [5]. This plot shows the provided semi-major axis for each CubeSat over the initial Activation to Operations transition. The large disconnects and jumps indicate that a object was miscorrelated with another object in the cluster or debris.

Again after day 20, the cluster has had sufficient time to allow differential drag to spread apart the cluster and generate more consistent ephemerides on each object. An additional aspect of this difficult Activation phase was the result of an off nominal Deployment phase. Where the Dnepr program office had supplied accurate state vectors for the location of each P-POD deployment, the assumed constant deployment speed for each dispenser varied greatly from what was expected. A variation in spring constant and friction resulted in only one of

Figure 13: US NRL 3U QbX CubeSats [8]

the 3 P-PODs to eject the CubeSats with nearly 5 cm/s. The other P-PODs only imparted between 0.3 and 1.5 cm/s. This shortfall and resulting close clustering is clearly seen in the image collected of CP4 by AEROCUBE-2 in Figure 12.

The second example highlights the inherent delay and lag in solutions provided by space tracking systems. The US Naval Research Laboratory (NRL) launched the two QbX CubeSats as part of an overall cluster of 8 from the 6 P-PODs resident on the Falcon 9. The two 3U CubeSats are shown in Figure 13 preparing for TVAC. For this deployment the QbX-1 was designated the first
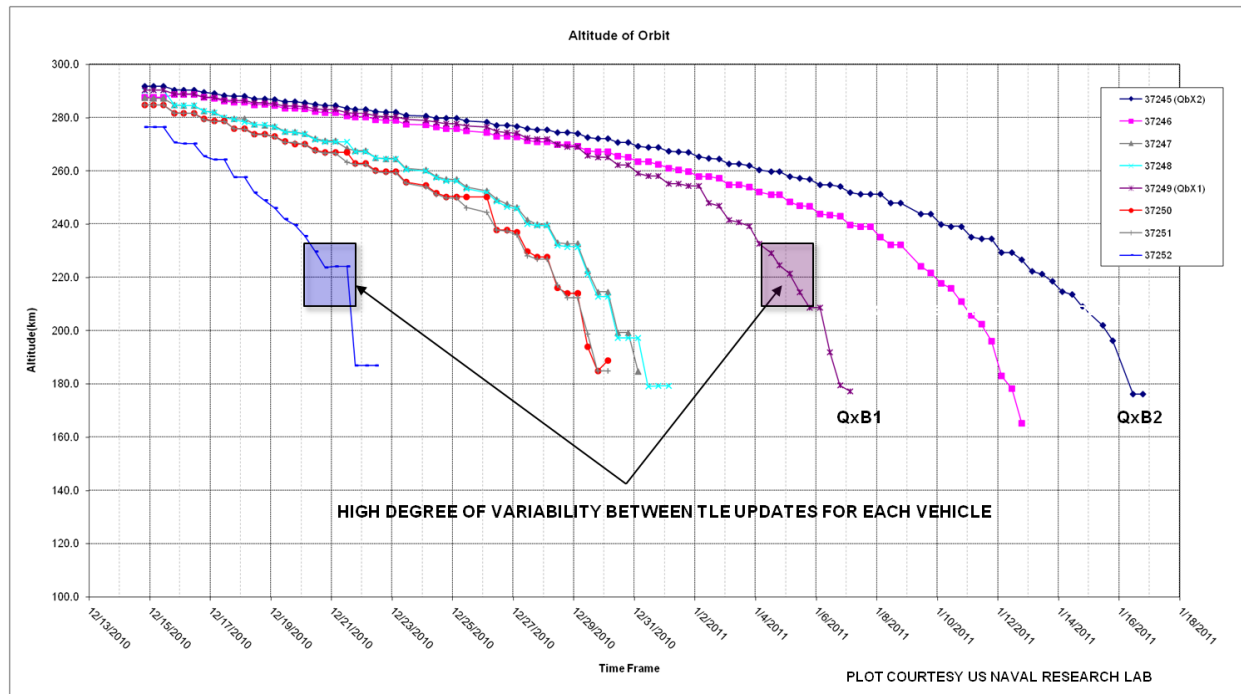

Figure 14: Falcon 9 CubeSat Cluster Evolution [6]

CubeSat to be released while QbX-2 was the last to be released and trailed the rest of the cluster [6].

Investigation of the update rate of the TLEs provided the QbX team with the at times coarse updates as illustrated in Figure 14. Over the month captured by the plot, the break up, decay and resulting deorbit are clearly illustrated and highlight the processing challenges posed by even 3U CubeSats to space tracking systems.

5.0 SUMMARY

This paper detailed the dependencies and challenges CubeSats present space tracking systems. These couple efforts will continue to increase in complexity as the number and overall mission utility of a 1U CubeSat continues to increase nearly exponentially. At present nearly 10% of all active LEO objects are CubeSats, whereas by 2017 it is projected that nearly 25% of the active LEO catalog will be CubeSats or smaller as shown in Figure 15 [1].

The ability to quantify the growth and potential impacts of CubeSats on the overall space tracking system provides a significant method for fostering international cooperation and research into ways to address the challenge posed by CubeSats.
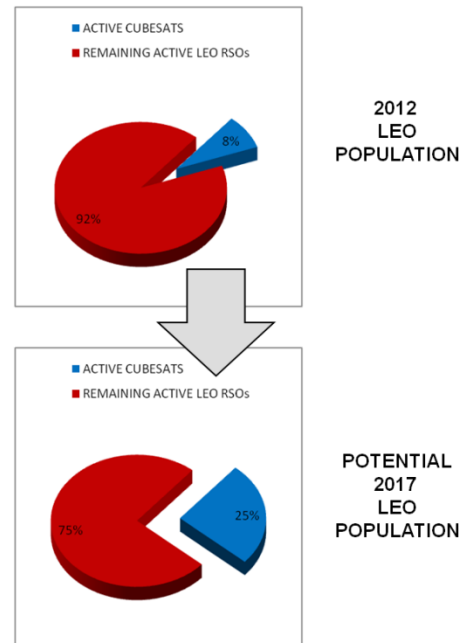
Figure 15: Projected CubeSat Growth 2012-2017 [1]

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