CubeSats to NanoSats; Bridging the Gap between Educational Tools and Science Workhorses

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Abstract— **Since their initial development and launch in the early 2000's, the CubeSat platform has captured the imagination and energy of our next generation of spacecraft technologists around the world. Once thought of by the established space community as "toys" and educational novelties, the CubeSat has revolutionized the space-community and broken the acceptance barrier with proven development and on-orbit performance. Leveraging CalPoly's published specification, CubeSats have demonstrated the advantages of a common form factor that can be launched and deployed using a common deployment system by smashing the cost-to-orbit price-point while offering significant mission manifest flexibility.**

The challenge now lies in transitioning the strengths and success of the CubeSat to mainstream science investigations. While the CubeSat's successes combined with today's budget constraints have served to open the established space community to discussions of innovative ideas to reduce costs; it faces both perceived and real constraints related to mission applications, reliability, payload performance, communications, and operations. The CubeSat model must be evolved to penetrate the stigmas and applied appropriately to become an accepted tool in the world of mainstream science investigations. This paper identifies issues and presents potential solutions and lessons-learned regarding these issues based on several recent mission concept developments for potential real-world applications.

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1. INTRODUCTION

The CubeSat platform has captured the imagination and energy of our next generation of spacecraft technologists around the world. Once thought of by the established space community as "toys" and educational novelties, the CubeSat has revolutionized the space-community and broken the acceptance barrier with proven development and on-orbit performance. The challenge now lies in transitioning the strengths and success of the CubeSat to mainstream science investigations.

This paper identifies issues, both perceived and real, that exist in bringing the nanosat/CubeSat paradigm to the established space community. The authors discuss real world issues and solutions developed as concepts for recent mission applications.

2. CUBESATS – A HISTORICAL PERSPECTIVE

CubeSats, like those shown in Figure 1a, adhere to the CubeSat Specification developed by California Polytechnic State University (CalPoly) and Stanford University in 2001. This specification sets limits on the vehicle for mass (1kg) and volume (10 cm x 10 cm x 10 cm) in blocks or Units (U) with the "3U" CubeSat configuration being the most common. CubeSats are a subset of nanosatellites, shown in Figure 1b, which generally refer to any small satellite less than 50 kg. Historically, CubeSat development has occurred in three sectors: universities, university-centered small businesses, and commercial companies. University nanosatellites are often deemed a success so long as they survive launch and briefly communicate with the ground, regardless of payload mission success. The training and development of the students is the primary concern, providing invaluable experience for the students but also leading to a relatively high failure rate (historically ~50%) due to poorly constructed components.

Most CubeSats have historically carried one scientific instrument as their primary mission payload. Most often these payloads are simple devices or low performance sensors limited primarily by size, power, and/or communication constraints. The payloads are normally built from commercial parts with little or no reliability engineering applied.

The use of nanosatellites within their present markets is enabled by utilizing the excess launch vehicle throw mass capacity for major missions launched by DoD and NASA. This concept, known as "ridesharing," often allows the primary mission to recoup some of the launch vehicle costs while enabling organizations developing small satellites to achieve orbit. Recently, through NASA's Educational Launch of Nanosatellites (ELaNa) Program, DoD's Space Test Program (STP), and commercial initiatives, there has

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Figure 1. (a-left) CubeSat during integration (b-center) Nanosatellite during integration, (c-right) CubeSat P-POD deployment mechanism [1]

emerged an abundance of these rideshare opportunities. Use of a common form factor, common launching mechanisms, and ride share opportunities have enabled previously unimagined price points of <$100k/kg [1].

3. MAINSTREAM SCIENCE AND AEROSPACE COMMUNITY ACCEPTANCE

Acceptance of nanosatellite-based missions within the science mainstream requires mission performance at or above existing mission capabilities bolstered by potential cost savings and increased reliability. The success of CubeSats at price points and schedules far below what have become standard development norms has served to garner attention within the established space community. This is evidenced by recent requests for information and nanosatellite proposals from both NASA and other government agencies. The recent NASA Earth science request for proposals (Earth Venture -2) included as one of its focal points, a call for innovative ideas allowing the use of moderately higher-risk technologies or approaches; the Cyclone Global Navigation Satellite System (CYGNSS) mission brief provided later in this paper is an example of how nanosatellite technology can be applied to replace existing accepted solutions at significantly reduced cost while providing an increase in performance. While nanosatellite applications are beginning to be recognized by the community, there remains significant inertia against the use of nanosatellites for science missions. Reasons for this resistance include both real and perceived issues.

Perceptions – Opinions within the mainstream science and aerospace community typically hinge on the CubeSat's heritage that has gotten it so far, specifically that of the nanosatellite/CubeSat as educational "curiosity". These vehicles were usually designed outside the established development community and not subjected to peer review by the "establishment". Of course, this model enabled the CubeSat cost and schedule breakthroughs, but the lack of vetting did little to bolster the reputation of it as a reliable tool. Another false perception is that nanosatellites are only capable of limited science. How can something so small produce precise and reliable science data? While it is true that certain applications involve physics and/or technology that presently are not compatible with nanosatellite platforms (telescopes with long focal lengths and/or apertures, applications requiring significant power, highly sensitive antenna arrays, etc), there exist many other traditional areas that can be opened to the low-cost and short schedule potential of a nanosatellite-based mission.

Reality – A real reason for lack of nanosatellite applications is the lack of nanosatellite development experience. Most established aerospace corporations don't inherently include the nanosatellite as a tool in their mission design trade space because they don't have heritage with the nanosatellite-class of vehicle. Reasons for the omission of nanosatellites as a mission option are varied and tied to specific corporate situations. They include lack of insight into mission design flexibility offered by application of nanosatellites, infrastructure tuned to larger, more standard spacecraft, and cost models tied to the larger spacecraft-classes. If a company doesn't have heritage with applying nanosatellites as a solution, it requires significant capital investment at all phases of development to shift paradigms; mission design models and simulations must be developed, subsystem design tools have to be updated, mechanical ground support fixtures must be developed, test procedures must be created, etc. Along with the paradigm shift comes increases in risk and reduction in heritage status.

Momentum for nanosatellite missions has been building recently, totaling upwards of 150 as shown in Figure 2, led primarily by university and non-US space agencies. To enable realization of present nanosat/CubeSat price points it is necessary to offset the need for infrastructure investment. In the US, government agencies have sponsored the majority of the development through pathfinding initiatives such as the NSF CubeSat Competition, the DoD University Nanosatellite Program, NRO's Colony 1 and 2 programs, and most recently the DoD's Space Environmental Nanosatellite Experiment (SENSE) program. According to representatives at the SMC/XR that spoke at the CubeSat Workshop held in San Luis Obispo, CA in April 2011, while the scientific results of this mission are interesting, the Air Force's primary motivation for sponsoring the SENSE mission is to lay ground work for future nanosatellite missions; to cultivate new metrics for nanosatellite mission

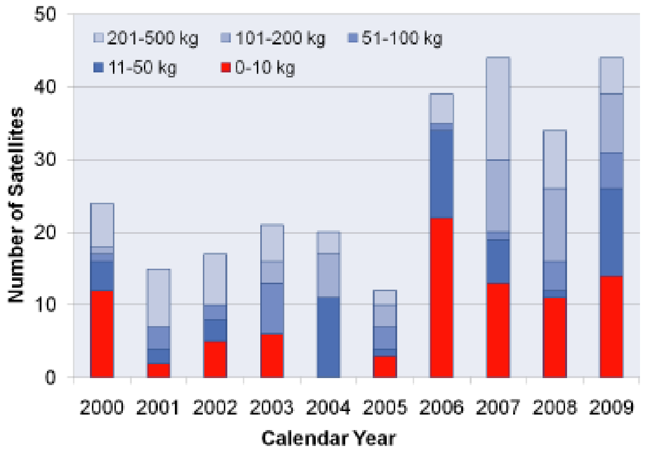

Figure 2 . Small satellite missions launched per calendar year [18]

planning, and evaluate the development with the anticipation of launching future missions and implementing the lessons learned.

Technical Issues to be Addressed

Required Technology Advances – Standard spacecraft avionics suites consist of power distribution, spacecraft computer, health and monitoring functions, attitude determination and control component interfaces, and spacelink communication. Existing avionics to perform these functions typically occupy a volume of 31 x 23 x 28 cm with masses of 17 kg – more than three times the size of a 3U CubeSat – at a recurring cost of $2-5M. In order to realize a high-reliability, radiation tolerant nanosatellite avionics suite, research studies and development tasks must be undertaken. All avionics and components must fit within the size, weight, and power constraints of the nanosatellite specifications. This challenge will be surmounted by researching novel packaging methodologies and nanosatellite tailored avionics functionality. The avionics must be affordable at a nanosat/CubeSat price point. Use of radiation tested commercial grade parts and affordable packaging solutions is necessary to address this challenge. Finally, the avionics must be expandable to meet requirements of a variety of nanosatellite platforms and incorporate scalability in processing capability and functionality.

Despite this emerging market, there still exist very few options in spacecraft components for nanosatellites. Many missions require internal development to produce technologies required for all nanosatellites but beyond the developer's realm of expertise. The resultant technologies are often limited in their functionality, diversity, and reliability. They are not designed by people with experience building space hardware.

Reliability – Reliability is achieved through design; both at the component and at the mission levels. Typical mission design lifetime for CubeSats using standard commercial practices are for much less than 1 yr. Future application of nanosat/CubeSats within the science mainstream will require design lifetimes of 2-3 yrs. This type of reliability can be met through a strategy of improved parts engineering, selective on-board redundancy (typically for moving parts), and mission fault tolerance afforded by the nanosatellite constellation itself.

Present parts engineering for the nanosat/CubeSat markets is nearly non-existent. Acceptance into the mainstream aerospace community requires that the present commercial model of low-cost, no reliability designs morph to designs with sufficient analyses and part-level selection necessary to meet mission requirements. Mature semiconductor manufacturing processes typically produce highly reliable electrical piece parts with a relatively low likelihood of failure. A properly tailored combination of traditional parts assurance techniques and assembly level screening with qualification testing can be used to achieve a reliable design. This type of a parts program uses a modified EEE-INST-002 Level 3 approach enhanced by a significant amount of unit level stress testing. The parts program would use Level 3 parts when resources allow, and when they do not, the parts are procured to the highest quality standards available with a preference for parts from QML-certified manufacturers. Stress screening and life testing of the flight design is conducted on a single assembly to assure that the design meets the mission requirements. Each flight unit also undergoes a screening burn-in prior to the normal test flow to expose infant mortality issues.

Use of nanosatellite constellations allows mission fault tolerance to be improved by including entirely redundant flight assets on-orbit such that the loss of a given number of observatories does not impact mission success. This is significant strength of the nanosat/CubeSat constellation over single, monolithic spacecraft applications as it potentially serves to improve the performance of the constellation during the early stages of the mission. The design process requires specific modeling and analyses not performed during standard mission design efforts. This effort involves the statistical evaluation of spatial and temporal considerations to determine the minimum number of vehicles required to meet mission requirements. The issue then becomes a program trade between the number of on-orbit assets the program can afford versus what fault tolerance the mission is able to accept.

Communication and Operational Strategies – Communication with a constellation of spacecraft using existing standard spacelink communication and operation strategies quickly overwhelms available assets. Separate initiatives are underway within the Consultative Committee for Space Data Systems, NASA, DoD and other agencies (governmental and commercial) to develop cost-effective operational and communication strategies more in line with the needs of constellations. The future success of nanosat/CubeSat application is heavily reliant on the proper development of this infrastructure.

Orbital Debris Mitigation

No discussion about space-based missions is complete without a short reminder about orbital debris mitigation. Acceptance of nanosatellite-based missions, whether they employ single CubeSats or large constellations must be designed to remove themselves well within accepted standards for debris mitigation. There exist several techniques to accomplish this function at very minimal costs; including end-of-life propulsion maneuvers, deployable drag devices, and proper design of mission orbits.

4. A NEW MISSION PARADIGM

This paper presents three detailed summaries of potential missions enabled by the application of a nanosatellite constellation. They are small, complete missions representative of a new paradigm in space science investigations, where a mission architecture of multiple, low-cost observatories replaces traditional, high cost, monolithic spacecraft. They address key holes in the capabilities of existing large systems at a fraction of the cost. Additional possible applications include border monitoring, disaster relief monitoring, situational awareness, ocean current studies, and tsunami detection; the list is limited by only the imagination.

Application Example in Space Weather

Mission summary – The Solar wind Anatomy and Dynamics Imaging Explorer (SADIE) is a low-cost Small Complete Mission of Opportunity (SCM) to yield breakthrough understanding of the physics and dynamics of the solar wind and coronal mass ejections (CMEs) via quantitative, high resolution imaging of the inner heliosphere. A CME is a very large solar release of mass, momentum and energy that have the potential to disrupt communications, satellite operations, power grids, etc on Earth. A key issue with CMEs is that it is extremely difficult to observe them as they travel from the sun to the Earth, meaning that from the time they leave the sun until the hit the Earth's space environment, we can only estimate the time of arrival and the size of the CME. The SADIE mission attempts to change this at low cost using resilient mission design consisting of a constellation of free-flying nanosatellite observatories. SADIE is enabled by an aggressive simplification of flight assets, in favor of only recently available sophisticated ground analysis techniques and extensive catalog subsystems at very high TRL, available from multiple vendors.

Science – Because existing measurements do not capture much of CME structure, CME evolution is poorly understood, leading to uncertainty in connecting interplanetary CMEs to their solar origins, and difficulty in predicting arrival time or geo-effectiveness of Earth-directed CMEs [2]. SADIE deblurred data will cover the same elongation range as STEREO mission Heliosperic Imager-1 (HI2) with as much relative detail as existing coronagraphs, enabling tracking of CME substructure evolution in the heliosphere. With blur-free imagery and improved background subtraction via polarized imaging, SADIE reveals now-inaccessible features required to understand CMEs:

- Pile-up of material, which drives drag, shock formation, and CME-wind interaction;
- Steepening and shock formation at the leading edge of the CME piled-up sheath, which will be visible as sharpening of the leading edge measurable to ~200-400 Mm at 0.5-1 AU;
- Turbulent, chaotic structures in the body of CMEs, currently visible in coronagraph images but not in most heliospheric images;
- Cavities (0.2-20 Gm), both remnants of three part CME structure and voids formed in-situ;
- Filaments, which are observed less often in-situ than expected based on coronal observations;
- Secondary structures formed by the eruption and passage of CMEs.

SADIE provides detailed, quantitative boundary conditions for existing models, i.e. CME structure, trajectory and density vs. time, and a means by which features in the SW (e.g. current sheets, streamers, CIRs, turbulence) can be accurately identified. Empirical adjustments to the models and direct observation of signatures (e.g., flux rope profiles, corrugated fronts, and plasmoids) probe other-wise inaccessible physics controlling CMEs.

Background removal is the greatest technical challenge of heliospheric imaging, as the signal is ~2-3 orders of magnitude fainter than the celestial background formed by stars and the zodiacal light. SADIE is the first heliospheric imager with a polarizer, which enhances background rejection in data analysis and enables direct extraction of 3-D data from the polarization profile of bright features. SADIE's data volume is ~100x larger than previous missions, allowing powerful approaches to ground data reduction, including deblurring of long exposures, that are not possible with conventional bandwidth-limited missions. Further, SADIE's unique polarized imaging of Thomson-scattered light from heliospheric electrons rejects background light sources such as the high altitude aurora and enables direct removal of the unpolarized celestial background, which required model-dependent analysis with all prior heliospheric imagers.

Mission Concept – SADIE's mission design exploits strong mission resilience to reduce cost and risk while enhancing science return in a Class D mission assurance environment. To achieve the science measurement objectives, SADIE observes the full inner heliosphere continuously from ε=18°-70° at high cadence and data rate, driving a distributed imaging solution in low Earth orbit with the SADIE observing geometry. The SADIE science objectives directly drive observing requirements that in turn flow to

Mission and Instrument level requirements and ultimately define the constellation mission. Characteristics that make SADIE ideally suited to a constellation of nanosatellites include the resilience of multiple observing platforms, the diversity of sensitivity and time resolution, the flexibility of compatible orbits, and the cost effectiveness of rideshare opportunities. The size of the constellation is driven by the mission requirements for field of view and number of observed events. A minimum of three observatories operating for 6 months is required to meet mission requirements. SADIE guarantees three observatories at end of life by launching a total of five, providing high mission resiliency at minimal incremental cost. Allowing drift of the individual observatories yields observations with different combinations of sensitivity and time resolution. Early in the mission when the observatories are clustered together, individual fields of view overlap, providing high sensitivity over a limited instantaneous region with coarse (100 min) time resolution. As the observatories drift apart, the instantaneous constellation field of view expands, providing tighter time resolution and lower instantaneous sensitivity. SADIE can be operated in a range of orbits routinely accessible by commercial launch services. The constellation must be inserted into a near twilight orbit to support the observing requirements and thermal design. Data from the observatories are merged on the ground to form a single stream of images of the inner solar system with the resolution, sensitivity, and cadence necessary to address all SADIE science objectives.

Flight Segment Design – SADIE comprises a constellation of five three-axis stabilized, Sun-pointed nanosatellite observatories (Reference Figure 3), deployed as secondary payloads into a 625-750 km Sun-synchronous twilight orbit. LEO allows for very high data rates, enabling the downlink of high cadence images. This, in turn, enables many improvements compared to prior missions; including 0.15° (9') resolution imagery of bright CME structures (3' pixels). This is an order of magnitude improvement over previous imagers. Use of a constellation strategy provides high observing cadence and sensitivity, and yields extreme mission resilience to failures through full observatory-level redundancy.

SADIE Instrument – Each of the SADIE observatories carries a single deeply baffled, dual-beam polarized wide-field Imager to measure Thomson scattered light from plasma structures in the heliosphere. In concert, the observatories provide continuous coverage of the entire inner heliosphere from 18°-70° solar elongation (ε: angle from the Sun).

Nanosatellite Spacecraft – Nearly all of SADIE's flight subsystems are existing vendor catalog components.

Structure and Thermal: The spacecraft is built around a small, simple Al structure that contains mount points for subsystems and the SADIE instrument. The size of the SADIE nanosatellite is slightly larger than a 3U CubeSat due to the instrument baffle.

Electrical Power: Solar panels, batteries, and power conditioning to +28V bus voltage provides subsystem power sufficient to meet all end of life requirements with margin.

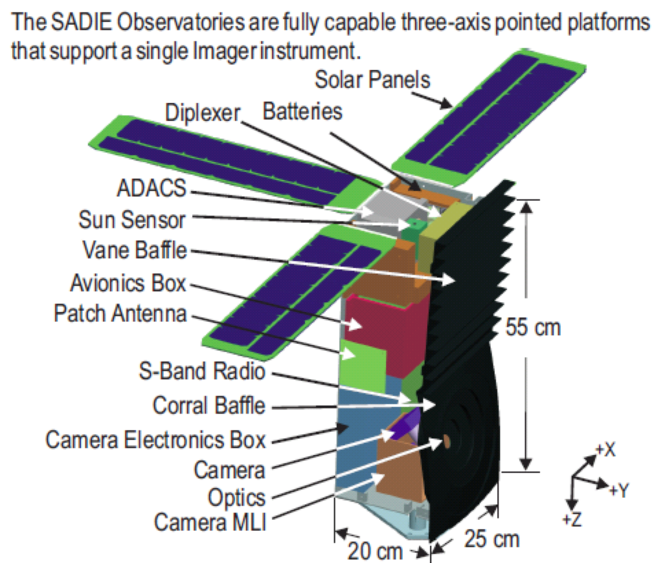

Figure 3 The SADIE configuration closely mimics the CubeSat definition though with enlarged dimensions to accommodate the SADIE instrument. Extensive use of commercial components is exploited to reduce risk and cost

Command and Data: The command data subsystem is built around a DSP-based single board computer. Science data acquisition requires transmission of 3.3 Gbits/day. This is implemented using an S-band transceiver. Data downlink is accomplished using five ground station passes of six minutes each, at a downlink rate of 2.5 Mbps. Low data rate commanding and telemetry capability is also provided by the S-band transceiver.

Attitude Determination and Control: SADIE utilizes a self contained, turnkey, miniaturized, hermetically sealed attitude determination and control subsystem with reaction wheels, magnetic torque coils, and a microcontroller enclosed. This is augmented with a fine sun sensor (FSS) and digital star tracker (DST) that together yield 30 arcsec precision in a fine pointing mode.

Application Example in Ionospheric/Thermospheric Science

Mission Summary – The Earth's ionosphere and thermosphere are driven in a variety of regions on multiple scales, and changes in the upper atmosphere can adversely affect our society's increasingly critical space-based infrastructure. For example, satellite drag knowledge is crucial in predicting when possible collisions may occur between costly assets in low-Earth orbit. Successful forecasting of these space weather events will not be feasible until there is an improved understanding of how this complex system reacts to energy inputs. Armada will provide regional and global assessment of thermospheric feature scales using a constellation of CubeSat observatories. Each Armada observatory will be equipped with a Wind Ion Neutral Composition Suite (WINCS), which contains four electrostatic analyzers (two for ions and two for neutrals) and two mass spectrometers (one for ions and one for neutrals). This combination of instrumentation will measure the in-situ density, temperature and composition of the thermosphere while also measuring the neutral winds and ion flows. The CADRE mission, funded by the National Science Foundation, is a precursor to the Armada constellation.

Science – The thermosphere and ionosphere are two tightly coupled, overlapping regions of the atmosphere. Below the thermosphere, the atmosphere is relatively well mixed and is dominated by neutral dynamics such as tidal structures and gravity waves. Within the thermosphere, individual species start to separate from each other, the ionosphere forms, and the dynamics become dominated by the interaction with charged particles. The forces on the ionized plasma are significantly different than the neutral fluid below. For example, the magnetospheric electric fields cause the ions to move across magnetic field lines at high latitudes, while these fields do not directly influence the neutrals. The ions, which have a density roughly 1/1000th the neutral species, exert both a frictional drag and a frictional heating on the neutrals. Therefore, while the neutrals are not directly influenced by the magnetospheric electric fields, they are indirectly forced through the ion drag.

The high-latitude ion flows in the F-region ionosphere, which are mostly described by the magnetospheric electric field, are quite variable and are controlled by the interplanetary magnetic field (IMF) and solar wind conditions. Many forces, such as ion drag, viscosity, Coriolis and gradient in pressure, on the other hand, influence the neutral winds. The balance between these forces is strongly dependent on location, the density of the ionosphere, the temperature difference between the night-side and dayside thermosphere and the strength of the ion flow [3]. Further, because the neutrals have so much more mass than the ions, the neutral winds tend to be quite sluggish in their changes, while the ions flows tend to change quite rapidly [3]. This can then influence the frictional heating that occurs because of the difference in flow velocities between the ions and neutrals [4] [5]. This heating is extremely important because it strongly controls the mass density of the thermosphere at a constant altitude, which, in turn, controls the drag on low-Earth orbiting satellites [6] [7]. Further, the neutral winds, at mid- and low latitudes, can push the ionosphere up and down magnetic field lines, which strongly controls the plasma density, affecting over-the-horizon communication systems and GPS accuracy.

There are a few ways of measuring the coupling between the ions and the neutrals. One of the most successful satellites to explore the coupling was Dynamics Explorer-2 (DE-2), which had many instruments on board that could measure both the ion and neutral states, such as the density, temperature and winds. DE-2 was a near-polar orbiting satellite that lasted from late 1981 through early 1983. Since then, there have been no satellites that could explore the coupling that occurs between the ions and neutrals in the high-latitude region in a similarly complete way.

Mission Concept – The only way to truly address the Armada science is through statistical analysis of many different events. This is because a single low-Earth orbit observatory has an orbital period around 90min, which is much larger than the time-scales in which the dynamics of the ionosphere and thermosphere take place. Further, the thermospheric reaction to energy input is strongly dependent upon the background conditions, which vary dramatically with local time. The Armada constellation mission concept is to utilize a large number of CADRE spacecraft in different orbital planes to simultaneously measure the thermospheric and ionospheric density, temperature, winds and composition across the globe. The Armada constellation has been designed to provide global spatial coverage with a temporal resolution of 12 min.

Flight Segment Design – The Armada flight segment consists of two payload elements and the spacecraft.

Armada observatory Payload – Armada will have two payload elements. The primary payload is WINCS, developed by NASA Goddard and the Naval Research Laboratory (NRL). The four WINCS instruments are: the Wind and Temperature Spectrometer (WTS), the Ion Drift and temperature Spectrometer (IDS), the Neutral Mass Spectrometer (NMS) and the Ion Mass Spectrometer (IMS). The secondary payload will be a low-cost, dual frequency GPS receiver.

Small-Deflection Energy Analyzer*:* At the heart of the WTS/IDS instruments is the small-deflection energy analyzer (SDEA), shown in Figure 4. The SDEA instrument has two identical, but mirrored sensors.

The top of the left chamber in Figure 4 (left) can be used to deflect the ambient ions and to ionize neutrals. This means that one half of the SDEA can be utilized for ions (e.g., bottom half) while the other half (e.g., top) can be utilized for neutral particles.

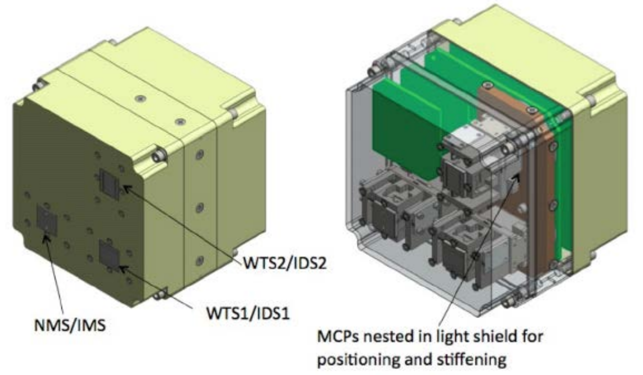

Figure 4 Layout of the 4 WINCS spectrometers. Overall dimensions are 7.5x7.5x7.1cm3. WTS and IDS are paired in two spectrometer modules with mutually perpendicular FOV.

Measuring Winds and Ion-drifts: Neutral wind and ion-drift measurements are obtained from the angular and energy distributions of the particle flux [8]. Two separate analyzers measure the angular-energy distributions in two perpendicular planes, their collinear axes pointing within a few degrees of the ram direction (e.g., WTS1 and WTS2 in Figure 4).

Neutral and Ion Composition Measurements: The Ion Mass Spectrometer/Neutral Mass Spectrometer (IMS/NMS) uses two Gated Electrostatic Mass Spectrometer (GEMS) time-of-flight mass spectrometers developed at Goddard [9].

GPS Receiver: The receiver will measure phase delays between the L1 and L2 transmissions from the GPS constellation. At transmission, L1 and L2 are in phase. The media through which the signals pass introduces phase delays between the two signals. Assessment of the delay will be used to measure total electron content (TEC) of the ionosphere and density measurements of the troposphere.

Nanosatellite Spacecraft – The WINCS instrument requires an capable satellite bus to perform optimal scientific measurements. The main drivers of the satellite design are the attitude determination and control requirements and the large amounts of science data to download. Figure 5 provides an illustration of the Armada observatory physical configuration.

Structure and Thermal: The Armada nanosatellite spacecraft is configured as a 3U CubeSat with the +Z axis pointed parallel with the velocity vector so that WINCS will have direct impact with the oncoming environment.

Thermal management will be an integral design challenge for CADRE due to continuous payload operation and attitude control. These devices consume 50-75% of the on-orbit power generation. Since traditional body mounted solar panels present challenges for radiation of excess heat, deployable panels will be used to allow for radiators on nadir pointing faces of the satellites. Heat will be piped to these surfaces to maintain proper thermal environments.

Electrical Power: The electrical power subsystem is based on a peak power tracker design from RAX-1. The system will peak power track individual panels. Lithium Ion battery cells will be used for energy storage. Four deployed solar panels provide power for battery recharge and operations during illuminated orbit periods.

Command and Data: A variety of flight computers will operate the Armada observatory. The primary flight computer will be a derivate of the RAX-1 and MCubed Linux-based processors. It will provide high-speed data processing and general purpose housekeeping operations. It will execute stored commands and process ground commands. A secondary embedded processor will act as a watchdog system monitoring bus activity and primary computer operation. It will be tightly integrated with the UHF radio, which also has watchdog capabilities. The secondary processor and UHF radio can process direct ground commands for reset and power cycling of the satellite.

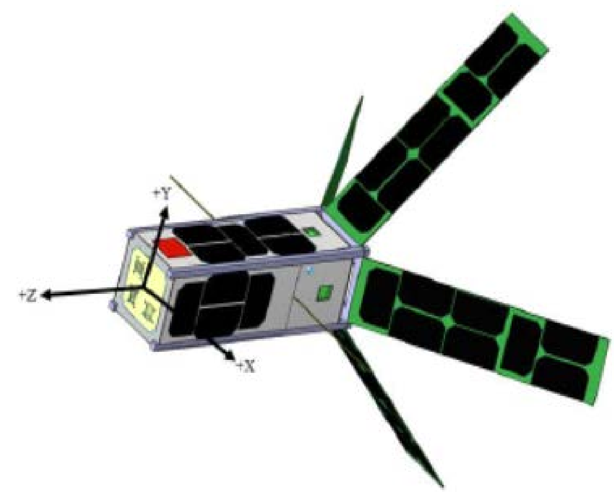

Figure 5 The physical configuration of the Armada observatory; WINCS is on the +Z face (ram vector). Deployable solar arrays provide electrical power and passive aerodynamic stabilization

Communications uses a low speed UHF transceiver for command and control with a second higher speed radio for downlink over S-Band frequencies. The payloads are capable of generating over 280 MB of raw data per day. The S-band radio is a single card communication solution developed by SwRI to provide a low-cost, radiation-tolerant, communication system. The core of the radio is a Software Defined Radio architecture configured to provide1.25 Mbps S-band data transmission.

Attitude Determination and Control: Armada's attitude determination and control uses a 3-axis stabilized approach Dual axis sun sensors and a triaxial magnetometer provide sufficient measurements for determination during sunlit portions of the orbit while a low-drift gyro is used during eclipse. Attitude estimation is calculated on board with an extended Kalman filter derived from RAX-1 heritage. Attitude control is accomplished with a standard configuration of three momentum wheels for control and three axis magnetic torque rods for wheel desaturation.

Application Example in Earth Weather

Mission Summary – The Cyclone Global Navigation Satellite System (CYGNSS) will measure the ocean surface wind field with unprecedented temporal resolution and spatial coverage, under all precipitating conditions, and over the full dynamic range of wind speeds experienced in a tropical cyclone (TC). It does so by combining the all-weather performance of GNSS-based bistatic scatterometry with the sampling properties of a nanosatellite constellation. Near-surface winds over the ocean are major contributors to and indicators of momentum and energy fluxes at the air/sea interface. CYGNSS' goal to understand the coupling between the surface winds and the moist atmosphere within a TC is key to properly modeling and forecasting its genesis and intensification.

Science – TC track forecasts have improved in accuracy by ~50% since 1990, largely as a result of improved mesoscale and synoptic modeling and data assimilation [10]. In that same period, there has been essentially no improvement in the accuracy of intensity forecasts. This fact is widely recognized not only by national research institutions [11] [12] but by the general public as recently demonstrated by Hurricane Irene.

The fact that forecast improvements in TC intensity have lagged so far behind those of TC track suggests that the deficiency lies somewhere other than proper observations and modeling of the mesoscale and synoptic environment. CYGNSS has been designed to resolve the principle deficiency with present TC intensity forecasts, which lies in inadequate observations and modeling of the storm's inner core. The inadequacy in observations results from two causes: 1) much of the inner core ocean surface is obscured from conventional remote sensing instruments by intense precipitation in the eye wall and inner rain bands, and 2) the rapidly evolving (genesis and intensification) stages of the TC life cycle are poorly sampled in time by conventional polar orbiting, wide-swath imagers.

Instrument Basis of Operation – When electromagnetic radiation scatters off the ocean surface, the scattering process changes the characteristics of the propagating signal in a way that is dependent on the reflecting surface. These changes contain information on the sea surface waves and indirectly on the near-surface meteorological conditions. Most radar-based ocean remote sensing is founded on this general principle, but generally use actively transmitted radar pulses and then detect the received power of the backscattered radiation. An alternative signal source using Earth reflected GNSS signals as a means of sensing the ocean surface was proposed in 1988 [13]. Researchers subsequently used data from the GNSS-R experiment on the UK-DMC satellite to demonstrated that signal retrievals of sufficient signal-to-noise ratio (SNR) could be used to perform successful ocean wave and wind estimation [14] [15] [16]. These results show that it is possible to detect reflected GNSS signals from space across a range of surface wind and wave conditions using a modest instrument configuration thus enabling an alternative to active sensing ocean remote sensing using bi-statically reflected signals transmitted from global navigation satellites (Reference Figure 6).

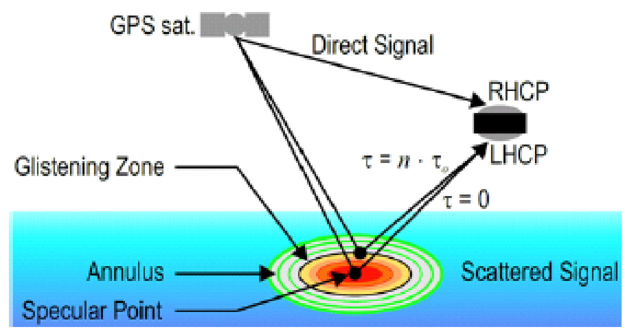

Figure 6 Geometry for GNSS signal surface reflection showing specular point and three ellipses of constant delay

Use of the GNSS signal source is especially beneficial for TC science investigation due to its precipitation attenuation characteristics (Reference Figure 7). The one-way slant path atmospheric attenuation experienced by a GNSS (green), ASCAT (yellow) and QuikScat (red) signal propagating through a typical tropical storm (5 km freezing level) as a function of surface rain rate. Rain has a negligibly small effect on the GNSS signal, even at the highest rain rates. ASCAT is attenuated enough at the highest rain rates to severely impact its ability to retrieve surface winds. QuikScat signals are effectively blocked by heavy rain and cannot sense the surface at all.

Mission Concept – CYGNSS combines the rain penetrating capabilities of GNSS-based bistatic ocean scatterometry with the high frequency sampling of a nanosatellite

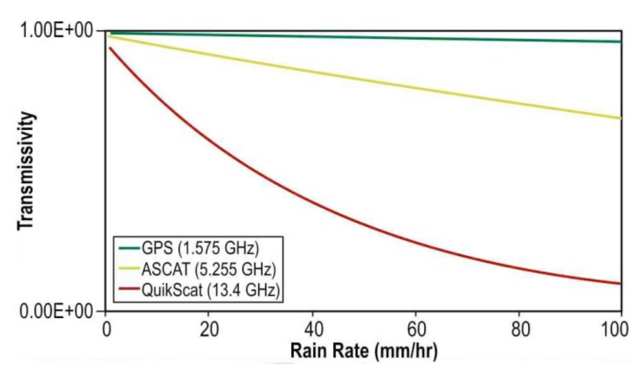

Figure 7 Signal attenuation through precipitation

constellation. The poor spatial coverage and temporal resolution limitations of a single observatory are overcome by a nanosatellite constellation where each observatory simultaneously tracks scattered signals from up to four independent transmitters in the operational GNSS network. The CYGNSS nanosatellite constellation provides unprecedented temporal sampling of ocean surface winds in the tropics in general, and of the primary latitude "corridors" historically followed by storm tracks in particular. The probability distribution of revisit times is shown in Figure 9 for all of the tropics (solid lines) and for samples of the historical storm tracks (dashed lines). With a mean revisit time of 4 hr and 90% of all storms revisited in ~9 hr or less, short time scale dynamics such as rapid intensification are observable with radically better fidelity than conventional monolithic scatterometers observatories.

Flight Segment Design – The CYGNSS flight segment consists of 8 nanosatellite-class observatories installed on a

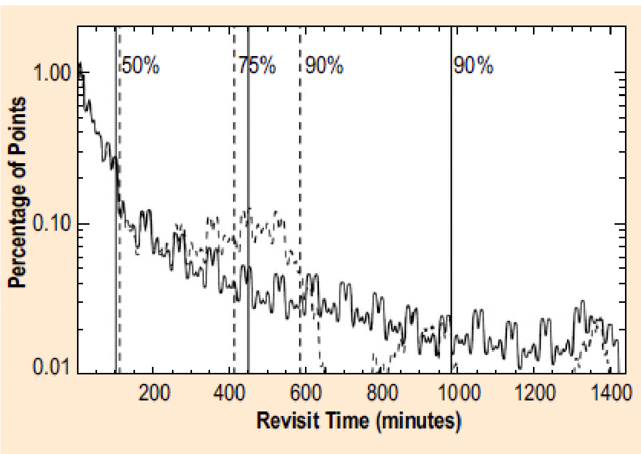

Figure 8 Probability distribution of CYGNSS for all of the tropics (solid line) and historical storm tracks (dashed lines)

deployment module for launch. While the constellation is central to meeting science requirements, the individual observatories act independent of one another, with no need to synchronize with the other observatories. They are identical in design but provide their own individual contribution to the CYGNSS science data set. The observatory consists of the GNSS receiver/processor instrument integrated with the nanosat. Global coverage is provided by the 8 observatories loosely dispersed about a circular 35° inclination, low Earth orbit. The mission profile does not require any orbit maintenance as random spacing of the observatories is preferred.

GNSS Instrument – The CYGNSS instrument uses Surrey's build-to-print GNSS Receiver-Remote Sensing Instrument (SGR-ReSI; reference Figure 8), an upgraded version of the UK-DMC-1 instrument that flew in 2003. In total, the instrument consists of the receiver electronics unit, two nadir-pointing antennas for collecting reflected GNSS signals, and a zenith-facing antenna providing space-geolocation capability. In addition to performing standard GPS navigation and timing functions, the SGR-ReSI's enhanced digital signal processing (DSP) capabilities enable the science applications required by CYGNSS. Onboard processing generates maps of GNSS signals scattered from the ocean surface.

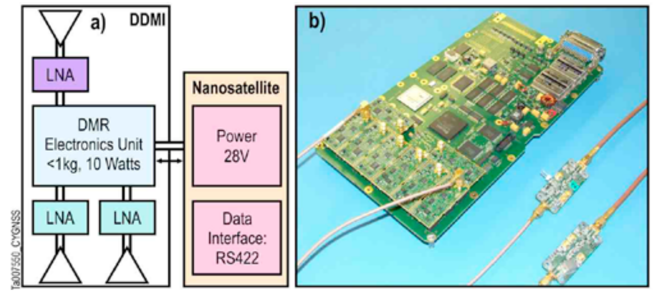

Figure 9 (left) the GNSS instrument functional block diagram, (right) the GNSS receiver and LNAs

Nanosatellite Spacecraft (Reference Figure 10) – CYGNSS uses a single string H/W architecture with functional and selective redundancy included for critical areas. The main drivers of the satellite design are the accommodating the GPS antennas, the attitude determination and control requirements and the large of amounts of science data to download.

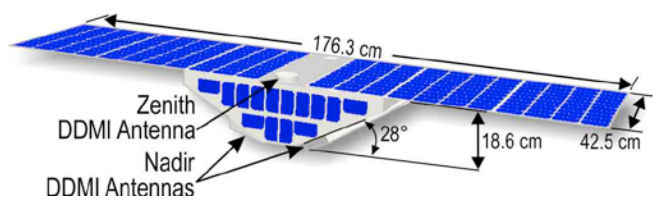

Figure 10 The CYGNSS observatory in flight configuration

Structure and Thermal: The nanosat's shape is specifically configured to allow clear nadir and zenith FOV for the nadir and zenith GNSS antennas, while its structure integrates the nanosatellite and instrument electronic boards directly by creating avionics and GNSS Receiver "bays". The avionics and GNSS receiver bays form the core of the nanosat; all other components are mounted to this backbone with structural extensions included to accommodate the Al honeycomb-based S/As and nadir GNSS antenna assemblies. The arrangement of internal equipment is used to aid thermal control and eliminate the need for supplemental heaters except for survival operations.

Electrical Power: The EPS is based on a 28±4 Vdc primary power bus with electrical power generated by a 8-panel rigid S/A with 4 of the 8 panels are "z-folded" for launch. Electrical power storage for eclipse operations is provided by 2 1.5 A-hr Li-ion batteries connected directly to the primary power bus. Battery charge regulation for the CYGNSS EPS is a peak power tracking (PPT) type regulator. The TRL 6 PPT, developed using SwRI internal funds, matches S/A conductance to the observatory load through pulse-width modulation using an optimization control circuit that integrates S/A W-sec over a preset period of time.

Command and Data: The CYGNSS spacecraft avionics core is SwRI's Centaur board. The Centaur consists of SwRI's space-qualified heritage Atmel SPARC8 processor integrated with heritage CCSDS compliant command and telemetry interface, 4 GB Flash data storage, instrument data interface, and attitude determination and control interface designs. The simple operational nature of the GNSS instrument and science profile allows the command data subsystem to operate autonomously during all normal science and communication operations. The Centaur also provides FSW-independent execution of a Level-0 command set used for ground-based fault management. All other commands are passed to the flight software for processing.

S-band communication links are provided to uplink command sets and downlink science and H/K data. The S-band transceiver uses SwRI's low-cost, radiation-tolerant, single card communication solution. The core of the transceiver is a Software Defined Radio architecture configured to provide S-band (2 GHz) communications. The transceiver provides O-QPSK encoded transmit data at 1.25 Mbps with a FSK uplink receiver supporting data rates to 64 kbps.

Attitude Determination and Control: The CYGNSS ADCS is a standard nadir-pointing, 3-axis, pitch momentum- bias design using pitch/roll horizon sensors and a 3-axis magnetometer for attitude determination with a pitch momentum wheel and 3-axis torque rods to provide attitude control (torque rods also provide momentum wheel desaturation). The only attitude "maneuver" required by CYGNSS is to recover from DM separation tipoff rates and establish a nadir-pointing configuration, allowing an extremely simple mode flow of nadir pointing for all operational states.

5. CONCLUSION

CubeSats have demonstrated their usefulness in academia and revolutionalized the space-community by setting price performance levels not before imagined. There exists growing momentum to incorporate the nanosatellite as a tool for solutions within mainstream space community but significant inertia still exists to be overcome. Technology development in the areas of mission design, spacecraft components, instrument components, and spacecraft development must be focused to ensure the continued acceptance of the nanosatellite paradigm. Success begets success; as more nanosatellites break through the barrier, the toolset will become more accepted and embraced. In order to transition the momentum gained within the CubeSat movement to mainstream science applications, it will be necessary to merge the CubeSat's "University" culture with proven space-qualified engineering techniques without losing the cost-effective, innovative advantages seen in today's CubeSat while finding ways to apply the benefits offered by nanosatellite constellations.

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BIOGRAPHIES

Randy Rose *received a B.S. in Electrical Engineering from the South Dakota School of Mines & Technology (1980). Mr. Rose is a staff engineer for SwRI Space Systems Division where he serves as a lead for spacecraft systems development. He has over 30 years experience in all aspects of spacecraft development including project management, systems engineering, computer architecture, hardware and software design, I&T, and operations. His experience includes hands-on hardware development experience with all spacecraft subsystems.*

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