The launch of Explorer-1 in February 1958 heralded the dawn of the space age in the US. It was an appropriate response to the Soviet Union’s Sputnik mission, launched the previous year, in that it was a true mission of science exploration, part of the US contribution to the International Geophysical year, leading to the discovery of the Van Allen radiation belts that gird the Earth. Thirteen years later, Apollo astronauts had walked on the Moon several times, the US had a system of satellites in place to monitor weather, probes had flown by Mars and Venus providing the first close-up views of our sister planets, a probe was measuring the solar wind for the first time, and the first Landsat spacecraft was on its way to the launch pad. This incredible burst of creativity and innovation was sparked by the launch of a satellite with 14 kg mass, built in just 84 days by the Jet Propulsion Laboratory (JPL).

This paper will put forward the argument that cubesats are at or have passed their ‘Explorer-1 moment’. Missions like the University of Michigan’s Radio Aurora Explorer, MIT/Draper labs’ Exoplanetsat, JPL’s CHARM mission, are all recognizably science-driven missions, designed to return valuable science data for heliophysics, astrophysics and Earth Science. Rob Staehle at JPL has proposed interplanetary cubesats, and others have suggested cubesats at Mars could yield unique science data.

It’s now possible to imagine a future – about 13 years hence, in which constellations of cubesats are integral to observations of the Earth system and climate change, dozens of cubesats are out beyond Earth orbit, helping to access the hidden corners of our solar system, monitor the Sun, and
explore the Universe. This talk will describe some of the efforts under way at the JPL to help enable this future.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a grant from the National Aeronautics and Space Administration.

9:45 AM
EDSN Update
Bruce Yost – NASA Ames Research Center

The Edison Demonstration of Smallsat Networks (EDSN) mission is one of the first to be executed by the Small Spacecraft Technology Program in NASA’s Space Technology Mission Directorate. EDSN’s mission objectives are to demonstrate multi-point, repeatable science measurements, and to create a basic satellite communications network using a swarm of cubesats. Additionally, EDSN will build on the recently flown Phonesat hardware as the EDSN spacecraft will use smartphone processors and other sensors and devices that are have been demonstrated or are under development within that project.

10:00 AM
Big Numbers for Small Missions: NASA’s Future with CubeSats
David Korsmeyer, Jason Crusan – NASA Ames Research Center

A new paradigm for NASA spacecraft has begun to take hold, leveraging the intersection of advanced commercial technologies, secondary launch opportunities, and very-small packaging - along with a new high-risk posture. NASA has had tremendous historical success with its typical robotic missions to LEO and beyond into the Solar System. However, the traditional low-risk mission approach to maximize science return can lead to significantly increased costs and drive even more complexity into the systems and missions. In this paper, we assess an alternate approach for NASA to greatly lower costs, by accepting higher mission risks, and using established engineering capabilities to achieve worthwhile science return and technology advancement - the Cubesat. The Cubesat format was developed by Universities as a educational framework to teach spacecraft engineering through the simplification of the satellite's infrastructure and design. This enabled teams to produce a workable satellite at a rapid pace and low cost, with a pre-defined launcher-payload interface that takes away the engineering for mating the satellite with a launcher. In 2006, NASA launched it¹s first scientifically viable Cubesat - Genesat. This began the era of low-cost (by NASA standards) science spacecraft that accepted high mission risk in exchange for rapid development, and an inexpensive launch. As the capabilities of Cubesat missions have expanded, the secondary launch market for them has kept pace as primary missions on U.S. launch vehicles have partnered with NASA’s CubeSat Launch Initiative and its series of Education Launch for Nanosatellites (ELaNA) missions to enable a clearinghouse for Cubesats that demonstrates market demand for reoccurring launches. Now NASA is beginning to target large numbers of mission
concepts that utilize the 3U and evolving 6U Cubesat form-factor for high-value science and exploration missions while retaining the high-risk and low-cost management models.

10:15 AM
Getting CubeSat Missions to Orbit Over the Next Decade
Garrett Skrobot – NASA Kennedy Space Center

Over the past few years there has been a renascence in the CubeSat community. This insurgence has led to the need to explore new and innovative ways to place these unique spacecraft on orbit. The NASA CubeSat Launch Initiative has selected over 90 CubeSat proposals as potential candidates for launches. To date, 12 of these missions have launched and 23 are manifested for flights in 2013; however this still leaves over 50 missions seeking a launch opportunity. So how do we accommodate these missions in the near future? We need to look at new and creative carries systems that can accommodate multiple structures. The NRO, in concert with ULA, developed the Aft Bulkhead Carrier (ABC) system. The ABC system allows for up to 8 P-PODs to be launched on one mission and was recently flight-proven on the Atlas V. This now provides CubeSats access to space on the Atlas V launch vehicle.

SpaceX has successfully completed three Falcon 9 flights in support of the International Space Station (ISS) resupply mission. With additional flights scheduled for the future, NASA has now manifested P-PODs on some of these upcoming missions. The P-POD will be located in the second stage trunk section and after the Dragon is separated and on its way to ISS, the P-PODs will release their CubeSats. This configuration is good for F9 ISS missions but what do we do for Falcon 9 missions that have a spacecraft with a fairing? The NASA Launch Services Program is working with SpaceX to develop a system on the aft end of the second stage that will allow up to six 3U carriers and four 6U carrier systems. This will provide additional flexibility in securing launches for ELaNa CubeSats.

When a CubeSat is assigned to the mission it is classified as a secondary payload and as such must meet a numerous stringent requirements to ensure the CubeSat or carrier system does not increase the risk to the primary mission or launch vehicle. This posture is acceptable for some CubeSats however it hinders the development of others in the creative search of new technologies. So how do we move forward?

In addition to the work that is currently being performed to provide access to more launch vehicles, NASA is involved in the Small Business Innovation Research (SBIR) Nano/Micro Satellite Launch Vehicle Technology Sub Topic. The focus for this topic is a Nano/Micro Satellite Launch Vehicle (NMSLV) that will provide a new capability for small payload access to space. The primary objective is to develop a capability to place Nano and micro satellites weighing up to approximately 20 kilograms into a reference orbit, defined as circular, 400 to 450 kilometer altitude, from various inclinations ranging from 0 to 98 °. The NMSLV is a commercial solution for a possible Nano and micro spacecraft launch vehicle to support the growing need for CubeSat launches.
Can a Constellation of CubeSats Create a Capability? Satisfying Australia’s Future Need for Multi-Spectral Imagery
Leon Stepan, Iain Cartwright, David Lingard – Defence Science Technology Organisation

The emergence of the cubesat architecture and continued advancements in technology has enabled unprecedented capabilities using nanosatellites. There is a growing trend from simple technology demonstrators and educational platforms toward missions of greater significance and utility.

In 2011 Geosciences Australia released a document titled “Continuity of Earth Observation Data for Australia - Operational Requirements to 2015 for Lands, Coasts and Oceans.” This paper was produced in consultation with domestic stakeholders to identify future satellite imagery requirements of the Australian economic region in the 2015 timeframe.

A need was identified for medium resolution multi-spectral coverage of the entire Australian landmass every day. This medium spatial resolution and high temporal resolution challenge lends itself to a constellation of small satellites.

This paper estimates the gap in required imagery that will remain in 2015 when new public good satellites are operational. It then describes a modification of the 6U 8kg cubesat system proposed by Tsitas and Kingston [2] that could supplement the public good systems.

Using commercial software Collection Planning & Analysis Workstation (CPAW), a model of the proposed space and ground segment is presented. This analysis methodology allows for a rigorous appraisal of the satellite consumables such as power and data storage. The consumables are tracked and collection plans are optimised using sophisticated algorithms. These high fidelity models enable an accurate estimate of what imagery can be collected beyond simple access simulations.

Success of this concept would rely heavily on international collaboration. One of the major factors identified is ground station location and availability as a key determinant of overall system performance. A sophisticated space segment must be appropriately supported by a distributed ground segment to ensure all imagery collected is downlinked and processed.

A key conclusion of this analysis is that a relatively small investment in cubesats might meet a significant portion of Australia’s future space imagery requirements. In doing so the investment would also provide assured access to imagery from space, transform Australia into an “active”™ rather than a “passive” user of Earth observations from space and increase Australia’s international leverage.

Finally a discussion of some of the challenges in moving forward with the operational concept will be presented.
11:15 AM
**Updating the CubeSat Design Specification**
Justin Carnahan - Cal Poly, SLO – CubeSat

No abstract available.

11:30 AM
**Understanding System Safety: Hazards, Controls, Inhibits, and Independence**
Gerry Shaw – SRI International

Meeting System Safety requirements is really an exercise in assessing potential hazards and implementing the appropriate controls. The intent of this presentation is to explain the basis for the requirements, suggest an approach to help identify hazards and provide some good and bad examples of inhibits and controls.

11:45 AM
**Status of Technology Demonstration for a Drag-Free CubeSat**
Andreas Zoellner – Stanford University; Abdul Alfauwaz, Ahmad Aljadaan, Salman Althubiti – King Abdulaziz City for Science and Technology; Karthik Balakrishnan, Sasha Buchman, Robert Byer, Grant Cutler – Stanford University

A drag-free satellite is freed of all forces but gravity. A free floating test mass inside the satellite acts as gravitational reference and a control system maintains the satellite’s position relative to the test mass. The position of the test mass is measured with a differential optical shadow sensor. The entire system furthermore includes a caging mechanism to lock the test mass during launch and a UV LED based charge management system to reduce the effects of electrostatic forces between the test mass and its housing. Drag-free satellites have been flown in the past, however, the nature of the gravitational reference sensor and the disturbance compensation system of the proposed Drag-free CubeSat differ in many aspects and therefore need to be space qualified in order to reduce the overall risk for the drag-free mission. Here we show the recent progress made in this process. The differential optical shadow sensor has been redesigned to fit in the envelope of a CubeSat payload and has undergone first qualification and performance tests. The caging mechanism is scheduled to fly on a zero-g parabolic flight where the uncaging and re-caging capabilities are demonstrated. The UV LED charge management system is scheduled to launch on a microsatellite in September. Together, these technology demonstrations raise the TRL of the main subsystems of the gravitational reference sensor and the disturbance compensation system and enable a successful Drag-free CubeSat mission.
**12:00 PM**

**Deployable Articulating Array for Nanosatellites**

Philip Keller, Robert Taylor, Sam Nelson, Larry Adams – Composite Technology Development, Inc.

Under Army SBIR funding CTD has developed a deployable, articulating solar array for nanosatellites. The CubeSat Articulating Solar Array (CASA) provides the community with a solar array module compatible with the standardized CubeSat chassis, and compliant with the P-POD launch canister specification. This development included a bolt-on CASA module, which encompassed a launch restraint system, the deployable solar array, the articulating mechanism and associated control electronics. During the recently completed Phase II effort the CASA system was developed to TRL 5. This Phase II development focused on a 50W point design, for a 3U CubeSat.

The innovation of the CASA deployable array system is twofold. First, CASA provides a very large, modular (i.e. scalable), solar panel area. This planar array stows within the standard P-POD volume that surrounds the nanosatellite spacecraft. On-orbit the CASA panels deploy into a co-planar operational configuration. Second, CASA utilizes shape-morphing composite slit-tube boom technology. This morphing composite structure serves multiple functions, thus eliminating parasitic mass and complexity of traditional mechanical systems. The boom provides all the necessary deployment actuation energy for the CASA solar array. Once deployed this same boom is the primary solar array structure that locates the array panels well away from the spacecraft (to prevent shading on the panels from the nanosatellite or nanosatellite payloads), and enable active pointing towards the sun. While multi-functionality results in an elegant final solution, the conflicting requirements presented significant design challenges.

The proposed paper will describe the development, flight qualification, and near-term applications of the CASA technology, with a heavy focus on testing of the CASA Engineering Development Unit (EDU). The often times conflicting design requirements of CASA’s multi-functional, shape morphing composite array structure will be discussed in detail. In addition, analysis showing the trade studies and design methodology behind CASA’s selection of a single degree of freedom articulation mechanism vs. a two-axis gimbal will be presented.

**12:15 PM**

**Power Efficient Pulsed Plasma Thruster with Precise Control of High Voltage Generation**

Marcos Compadre, Craig Clark, Peter Marinov – Clyde Space Ltd.; Simone Ciaralli – University of Southampton; Michele Coletti – Mars Space Ltd; Stephen Gabriel – University of Southampton

The lifetime of LEO (Low Earth Orbit) Nanosatellites and CubeSats is currently limited by their susceptibility to natural de-orbiting. An appropriately scaled pulsed plasma thruster offers the most adaptable technological solution to this problem by compensating for atmospheric drag. This technology can be used to aid the spacecraft de-orbiting to comply with the 25 years de-orbiting guidelines.
A PPT consists of a pair of electrodes separated by a propellant bar that can be fed either from the side or from the breech of the electrodes. The electrodes are connected to a main capacitor bank charged to a voltage of the order of 1-2kV and storing energy of some joules. To operate the thruster a high voltage pulse (5-10kV) is sent to a spark plug. This triggers a discharge between the two main electrodes that ablates some of the propellant, ionizes it, and expels it to high velocity generating thrust.

The design of the electronics and the thruster head of the nanosat and CubeSat PPT have evolved over time based on tests and experiments during several test campaigns. Inherent constraints such as small size and limited power budget of this type of satellites have been overcome by the use of the proposed topology.

Previous designs use voltage multipliers for high voltage generation in the ignition circuit. These circuits provide a very simple way of generating the high voltage needed for such circuit. However the repeatability of the high voltage pulse event it is not precisely controlled.

The following paper presents a new topology used for the electronics of the PPT that brings the following advantages with respect to other topologies used: lower power consumption achieved by the use of a pre-charged stage before all the energy is released into the high voltage stage, better control of the power consumption; a more accurate control of the firing process; and a smaller size. These characteristics allow the use of the same circuit to provide the high energy to be stored between the anode and the cathode of the chamber and for the ignition circuit, thus simplifying the design and test of the overall system.

The results presented in this paper show that the design proposed provides lower power consumption and a more precise control of the ignition process compared to previous designs. The proposed design is also scalable to be used in thrusters for bigger satellites offering the previously cited advantages.

1:30 PM
Development of a CubeSat Water-Electrolysis Propulsion System
Lenny Paritsky, Jonathan Wrobel, Todd Moser, Jeffrey Slostad, Nestor Voronka, Robert Hoyt – Tethers Unlimited, Inc.

Over a decade ago the development of the CubeSat standard and the P-POD deployer ushered in a new era of low cost technology demonstration and science missions. Up to now, however, CubeSats have been limited to missions requiring low power levels and little or no propulsion, largely due to high costs and restrictions on stored energy designed to protect primary payloads during launch. The development of high power generation systems and small-scale propulsion solutions that comply with the P-POD launch restrictions will greatly increase the scope and utility of missions serviceable by this low cost satellite platform.
The Water-Electrolysis Thruster (WET), a novel “green” CubeSat propulsion system, will allow missions to launch with a safe, storable and non-toxic propellant – deionized water. Once on-orbit, water is electrolyzed to supply gaseous oxygen and hydrogen to a versatile bi-propellant thruster. When integrated with an innovative deployable solar array as part of the PowerCube™ module, the WET propulsion system will let the CubeSat platform reach its full potential and accomplish high performance missions involving precision pointing, orbit raising, plane changes, and rapid response. When supplied sufficient water, either before launch or from ISRU upon arrival, the WET propulsion system will even enable CubeSats to travel beyond LEO and ultimately conduct science and exploration missions to GEO, Lagrange points, the Moon and NEOs.

This paper will focus on progress made by Tethers Unlimited, Inc. towards the development of the Water-Electrolysis Thruster. The authors will discuss efforts to design and build a compact CubeSat scale water-electrolysis fuel cell capable of functioning in a zero gravity environment, as well as a pulsed microthruster that utilizes gaseous oxygen and hydrogen propellants. Preliminary test results will be presented, demonstrating gas production rates up to 6 cm³/min/W and fuel cell efficiencies up to 88%. The design of a modular microthruster will be discussed, and a preliminary analysis of hot fire testing will be presented. Several high performance missions enabled by the WET propulsion system and the standalone PowerCube™ module will be highlighted.

1:45 PM
Characterization and Radiation Testing of Low Mass High Voltage Converters for MicroThrust
Benoit Chamot, Hervé Meyer, Lucas Perrin, Muriel Richard – Swiss Space Center EPFL; Wojtek Hajdas – Paul Sherrer Institut; Richard Visee – SystematIC

Since 2008, the MicroThrust (MT) consortium consisting of EPFL, Nanospace, QMUL, SystematIC, and TNO has been working on the development of a MEMS based propulsion system. Since 2010, the work has been performed as part of the European Union’s FP7 programme with the goal to design, build and test an engineering model of such a system.

One of MT’s critical subsystems is the power conditioning and distribution unit, as very stringent mass and voltage requirements have been defined. During the preliminary design of MT, several High Voltage Power Converters (HVPC) have been identified, each with very low masses and volume. These HVPC are commercial off-the-shelf (COTS), and before being used in space they need to go through a series of environmental tests.

This paper presents the procedure and results of radiation tests of two types of high voltage, COTS DC/DC converters. Both are able to provide up to 4 [kV] for an input up to 5 [V] and were tested at the Paul Sherrer Institut, in Villigen, Switzerland. Low and high dose-rates were applied, thanks to high-energy (200 [MeV]) protons. Both converters were able to sustain a total ionizing dose (TID) of 100 [krad].
Despite a generally good behavior, small voltage drops and glitches, due to single event effects (SEE), were observed. All the results will be presented in details.

2:00 PM
**Electrospray Mission Modeling for CubeSats**
Angie Hatch, Jonathan Black – Air Force Institute of Technology

Using propulsion on a CubeSat opens up promising new mission possibilities. Several electrospray thrusters are in development for use on CubeSats, including variants that require high power but in return yield significantly higher delta V. High power and high delta V electrospray thrusters are especially promising for CubeSats and are analyzed in this research. In order to analyze the capabilities provided by such thrusters, a Mission Modeling Tool (MMT) is developed to analyze information from several software programs in one cohesive manner. Reports from Satellite Toolkit (STK) are combined with MATLAB programming in order to provide analysis of the state of health of several satellite subsystems over a set period of time. A GUI interface is added to allow the user to easily input initial satellite parameters. The end results are exported in graphical form, allowing the user to look at the parameters of the subsystems and compare the telemetry at a specific point in time. This is especially useful to analyzing thrusters because it allows a side-by-side analysis of power available versus delta V achieved.

Once MMT is developed, several scenarios are analyzed for a CubeSat outfitted with a 56-W solar array, carrying a payload of eight electrospray thrusters, and established in a Sun Synchronous (SSO) orbit. The primary thruster configuration of five thrusters on one end of the spacecraft with three thrusters on the other end is studied, along with the backup configuration of four thrusters on either end of the spacecraft. First, satellite orientations and the effects of Local Time of Ascending Node (LTAN) on the power provided in a 600 km SSO is studied. Such studies provide insight into the types of orbits that are acceptable for the amount of power required by the MEP thruster mission. It is shown that a CubeSat that is aligned with the velocity vector but that is allowed to roll about the velocity vector to achieve the maximum sun angle allows a satisfactory thrusting profile and orbital average power (OAP) for the scenario.

Additionally, power profiles are developed stepping through the LTAN one hour at a time, showing the differences in OAP generated based on the LTAN of the established orbit. Next, generic power scenarios are analyzed for pointing and delta V experiments in order to determine the number of electrospray thrusters and modes that should be used for each respectively. Assuming that the pointing experiments take approximately 30 days and that the delta V experiments take approximately up to a year, it is shown that pointing experiments should use two thrusters in active mode with two in standby mode, while the delta V experiment should use a combination of three thrusters in active mode followed by four thrusters in active mode. In this manner, 1 km/s of delta V can be reached in as little as 177.7 days.
2:15 PM
MISC 3: The Next Generation of 3U CubeSats
Andrew Kalman, Adam Reif, Jerami Martin – PUMPKIN, Inc.

The NRO’s Colony I and II programs have established the 3U CubeSat as a capable and low-cost platform for technology demonstration and other missions. Experience gained from successful Colony-class missions has raised expectations for the capabilities expected in a 3U CubeSat. In this presentation, we will address how we have recently integrated new technologies, including star trackers, high-power solar arrays and EPS, advanced battery protection, higher-speed radios, GPS, propulsion, more powerful computing platforms, new manufacturing techniques and materials, and advanced payloads interfaces into what remains a volume- and mass-limited form factor. We will address the impact on mission-specific configuration requirements on packaging and costs, and discuss real-world examples of customer-driven requirements and their impact on semi-custom designs.

2:30 PM
Design and Implementation of a Nanosatellite Thermal Control System, A Case Study
Alex Potapov – Space Concordia; Scott Gleason – Concordia University; Nick Sweet – Space Concordia

This paper describes the design and implementation of a nano-satellite thermal control system. The system is implemented and tested on ConSat-1, a 3U CubeSat developed by Concordia University’s Space Concordia for the Canadian Satellite Design Challenge. ConSat-1 is a candidate for launch in late 2013.

Topics discussed include: general design theory, analysis, orbital environment factors, operations, as well as thermal vacuum/functional test procedures and results. The purpose of this document is to provide design guidelines to assist in the development of future CubeSats, especially for university groups.

2:45 PM
Onboard Software Development 400 Miles From the Cleanroom: Component-based Reusable Software for UKube-1
Peter Mendham, Mark McCrum – Bright Ascension Ltd.

While the development of any CubeSat is challenging, UKube-1 presented some particular challenges from the outset of our involvement as Onboard Software subcontractors. Chief among these were a tight schedule, subsystems and payloads that were still in development and the need to deliver early capability to support hardware testing. Despite the late stage at which we joined the project, the operational concept for the mission was not clear and many requirements were uncertain or ill-defined. One thing we did know for sure was that many requirements would not be
tied down until very late in the development. This paper describes our experiences and lessons learned from the development of software for UKube.

In this dynamic environment a traditional waterfall-based process would be unworkable, instead we employed a more iterative, agile approach. This involved putting functional software in the hands of the customer at the earliest opportunity then providing incremental capability with each iteration. At each step we were able to plan the next iteration in response to customer feedback and the evolving priorities of the wider development and testing schedule for the spacecraft.

We also attempted to build flexibility into the design of the software itself. The architecture is based around many individual components, each of which is relatively simple. These execute on an abstraction layer, decoupling them from the underlying operating system. We were thus able to develop components on standard Linux PCs and leverage mature automatic testing frameworks to carry out extensive unit-testing prior to deploying them on the OBC. The overall function of the software comes largely from the ways in which these components are used (the deployment). Reconfiguring a deployment gave us an easy way to accommodate late changes to operational requirements without having to modify component code. When hardware subsystems changed, the uniform component framework meant that code changes were limited to the subsystem component and could be unit tested.

When software development is subcontracted for large spacecraft, a simulator is usually used in place of hardware. In most CubeSat projects this expense is not necessary as the software is developed in house with good hardware access. For UKube we had neither physical access to the hardware nor a simulator. Instead, we were able to set up a remote access facility which allowed us to program and operate the OBC from over 400 miles away. The I/O abstraction framework in the software allowed us to substitute a simulated spacelink, allowing us to send telecommands and receive telemetry over the internet rather than an RF link. This proved important, both for OBSW development before ground station facilities became available, and as the primary means of interacting with the spacecraft during hardware testing.

Although UKube-1 might be small, the demands placed on the OBSW are not. The spacecraft has multiple payloads and yet the mission must operate with limited ground contact and bandwidth. We therefore needed to include software features more often associated with larger spacecraft such as highly-capable automation, onboard scripting and file-based storage. A configurable health monitoring system gathers, processes, stores and downlinks telemetry from spacecraft subsystems. All system features can be accessed and re-configured from the ground. This provides maximum flexibility to the spacecraft operators to facilitate platform characterisation and troubleshooting, crucial for an experimental spacecraft such as UKube.

An important goal for the project was to allow reuse on future UKube spacecraft and other CubeSats. The component-based architecture also helps us to deliver new capabilities incrementally and greatly increases code reusability. New spacecraft will be easily supported in the future by re-deploying the components already developed and supplementing them with new components where necessary.
The advances in microelectronics have made small satellite technology an effective alternative to large and expensive satellites by decreasing space mission costs, without greatly reducing the performance. Small satellites can be launched in close formation flying patterns to perform coordinated measurements of remote space missions. This will allow a cluster of small satellites to be used to collect data from multiple points and time, thereby providing spatial and temporal resolutions that cannot be achieved with a single, conventional large satellite. There are three different formation flying patterns under study; Leader-Follower (A-Train), Cluster and Constellation.

Inter-satellite communication eliminates the use of expensive ground relay stations and ground tracking networks. When satellites fly in constellations, using inter-satellite communications, it’s not necessary to sink all the data from each of the small satellite to ground, thus eliminating the need of intermediate ground stations for sending data. The small satellite formation control problems, particularly, attitude and relative position can be solved using inter-satellite communication by exchanging the attitude and relative position information among the small satellites. It can also provide timing synchronization. Therefore, inter-satellite communication plays a vital role when small satellites fly in close formations.

This presentation aims to propose and validate inter-satellite communication protocols for distributed small satellite networks. We investigate the possibility of implementing a feasible Medium Access Control (MAC) and routing layer protocols for the three different formation flying patterns. A modified MAC and routing protocols particularly the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) with Request to Send/Clear to Send (RTS/CTS) protocol are analyzed. Our proposed system performance is evaluated using throughput, access delay and end-to-end delay by running extensive simulations. The throughput of the system is defined as the fraction of the total simulation time used for a valid transmission. For the Leader-Follower formation flying pattern the maximum throughput we can achieve using the proposed protocol is about 23% and for Cluster formation pattern, the maximum throughput is found to be 11%. Average access delay and end-to-end delay are less for Leader-Follower formation pattern compared to the Cluster formation flying pattern. We are currently working on the Constellation formation pattern. We have investigated the three types of formation for which we will describe the relative merits of each formation. The decision of which formation flying pattern has to be used depends on the mission architecture, e.g. number of satellites, orbits, power, etc.
3:45 PM
**Enabling Radio Crosslink Technology for High Performance Coordinated Constellations**
Nestor Voronka, Tyrel Newton, Peter Gagnon, Alan Chandler – Tethers Unlimited, Inc.

This paper describes the use of an advanced high-performance software defined radio architecture to provide small satellites, including CubeSats, with the ability to operate in coordinated constellations and fractionated systems. While the advantages of small satellite constellations are frequently discussed, the challenges of cooperative operations in a constellation are often overlooked.

We will discuss the additional requirements that are often levied against a small satellite constellation or fractionated system and how these requirements can be efficiently addressed using software defined radio intersatellite RF links. In particular, we will discuss the capabilities of the SWIFT SDR platform and how it can be used to provide small satellites with a high-speed data crosslink (>10 Mbps), timing and frequency synchronization (<10ns and <10ppb), and relative navigation information (<0.1m range accuracy).

These capabilities will then be discussed relative to traditional, uncoordinated solutions and how these capabilities enable classes of missions that would otherwise be difficult to implement. In particular, missions requiring cooperative, synchronized multi-point measurements and real-time station keeping will be discussed.

4:00 PM
**From Single to Formation Flying CubeSats: An Update from the Delft Programme**
Jian Guo, Jasper Bouwmeester, Eberhard Gill – Delft University of Technology

In the recent two decades, very small satellites, such as Cubesats, are attracting more and more attentions from academia, industries and space agencies due to their low cost, short development cycle and promising capability. Currently, most Cubesat missions are used for technology demonstrations or education, which only explore the capability of an individual satellite. However, the capability of Cubesats can be extremely enhanced by flying a cluster of satellites. For example, several missions such as QB50 and OLFA have been proposed for this purpose.

This paper provides an update of the Delfi programme of the Delft University of Technology (TU Delft). Delfi-C3, the first CubeSat in the Delfi programme, was launched on April 29, 2008 and is still operational after more than five years. Delfi-n3Xt, the second Delfi CubeSat, has been completed in January 2013 and is waiting for launch. The perspective of TU Delft on future small satellites motivated DelFFi, the third Delfi CubeSat mission, which is expected to be launched in 2015 within the QB50 framework and to demonstrate autonomous formation flying using two CubeSats named Delta and Phi.
This paper consists of three primary parts. The first part provides an overview of results and lessons learned from the development and the mission implementations of the Delfi-C3 and Delfi-n3Xt satellites, with emphasis on subsystem development, satellite design, Assembly, Integration and Test (AIT) and project management.

The second part of the paper presents the differences and improvements from Delfi-C3 and Delfi-n3Xt towards DelFFi. One of the important improvements is an advanced version of the Attitude Determination and Control Subsystem (ADCS) with sensors and actuators for 3-axis control. Delfi-C3 has no active attitude control, and on Delfi-n3Xt 3-axis attitude is only an experiment. While on the two DelFFi satellites, a more mature ADCS will be an integrated part of the platform. Another improvement is on the project management, where an innovative “spiral development” strategy is utilized. Different with the traditional phase-based project management process, in the DelFFi development several design cycles will be implemented and in each cycle improvements are applied to only part of the satellite. This strategy will provide every student with an opportunity of performing end-to-end systems engineering within their limited thesis work period, which is extremely preferred for training purpose.

The third part of the paper focuses on the payloads of DelFFi that enable the autonomous formation flying. Here the technology developments are threefold: communicating, which concerns on intersatellite communication and ranging using an innovative and very miniaturized device; processing, which utilizes multi-agent based artificial intelligence technology for cooperative control of the two CubeSats; and actuating, which performs formation control using a solid cool gas/micro-resistojet combined propulsion system with high volume efficiency and a specific impulse at 150s. Details of these technology developments are addressed.

4:15 PM
Simultaneous Multi-Point Space Weather Measurements using the Low Cost EDSN CubeSat Constellation
Adam Gunderson, David Klumpar, Andrew Crawford, Matthew Handley, Keith Mashburn, Ehson Mosleh, Larry Springer – Montana State University; James Cockrell – NASA Ames Research Center

The ability to simultaneously monitor spatial and temporal variations in penetrating radiation above the atmosphere is important for understanding both the near Earth radiation environment and as input for developing more accurate space weather models. Due to the high variability of the ionosphere and radiation belts, producing such a data product must be done using high density multi-point measurements. The most recent solar and space physics decadal survey states that these measurement densities have the potential to be provided by CubeSat constellations. The primary scientific purpose of the Edison Demonstration of Smallsat Networks (EDSN) mission is to demonstrate that capability by launching and deploying a fleet of eight CubeSats into a loose formation approximately 500 km above Earth. The Energetic Particle Integrating Space Environment Monitor (EPISEM) payload on EDSN will characterize the radiation environment in low-earth orbit (LEO) by measuring the location and intensity of energetic charged particles simultaneously over a
geographically dispersed area. This is made possible because the EPISEM samples are acquired from across the dispersed constellation of eight EDSN spacecraft. This paper describes the fabrication approach of this miniaturized radiation detection instrument and operational considerations unique to constellation missions of this class. Collection timelines and data return models will be provided for the initial 60 day lifetime and a possible extended mission. The EPISEM payload was specifically designed for CubeSats; leveraging heritage from the payload operating aboard Montana State University’s Hiscock Radiation Belt Explorer (HRBE), launched in October 2011. The EDSN project is based at NASA’s Ames Research Center, Moffett Field, California, and is funded by the Small Spacecraft Technology Program (SSTP) in NASA’s Office of the Chief Technologist (OCT) at NASA Headquarters, Washington. The EDSN satellites are planned to fly late 2013 as secondaries on a DoD Operationally Responsive Space (ORS) mission that will launch into space from Kauai, Hawaii on a Super Strypi launch vehicle. The EPISEM payload was designed, built, tested, and delivered to NASA Ames by the Space Science and Engineering Laboratory at Montana State University.

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**Application for RSO Automated Proximity Analysis and IMAGing (ARAPAIMA): Development of a Nanosat-based Space Situational Awareness Mission**

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ARAPAIMA is a proximity operations mission sponsored by the US Air Force Office of Scientific Research (AFOSR) and the Air Force Research Laboratory (AFRL), to perform the in-orbit demonstration of autonomous proximity operations for visible, infrared, and 3D imaging of resident space objects (RSOs) from a nanosat platform. The nanosat is of the 6U CubeSat class, with overall dimensions of 11x24x37cm, and has been selected as part of AFRL’s University NanoSat Program (UNP) Cycle 8. This paper describes the mission goals, concept of operations, science objectives and subsystem design and selection, with focus given to a detailed mission analysis and the requirements flow-down.

The nanosat carries a payload consisting of a FLIR Systems MLR2K laser rangefinder (LRF), a Goodrich Aerospace GA640C IR camera, and a monochrome high resolution camera, all chosen for their small size and relatively low power consumption. ARAPAIMA is equipped with a warm gas propulsion system, enabling it to perform orbital maneuvering and reaction control of attitude. Details on these, as well as the attitude determination and control system (ADCS), communications, electric power, operational modes and power, link, and mass budgets are presented at a Preliminary Design Review (PDR) level of readiness.

The complex series of events following the deployment of the nanosat from its launcher is detailed. Deployment of solar panels prior to de-tumble of the nanosat initiates the sequence. After de-tumble, the payload is pointed away from the sun, after which the second set of solar panels, which
serve as payload aperture covers, are deployed. Once the system has promoted into an operational mode, it will seek to acquire its spent upper stage and begin executing mission objectives.

The coupling between the top level mission requirements and the mission plan is addressed. The flow-down of these requirements to subsystem and component requirements is presented in minute detail. A detailed mission plan is developed to reduce risk and define success criteria for each phase of the mission.

Mission objectives will be achieved in steps of increasing complexity. First, ARAPAIMA is commanded by ground control to maneuver to within LRF range of the RSO and acquire a relative orbit. Next, the nanosat will maneuver autonomously to reduce the size of the relative orbit to a distance of 250 meters. The third step will perform visible and IR passive and active imaging of the RSO. The final mission objective will be to close to within 100 meters and evaluate the ability of the nanosat to match attitude and remain in a constant position with respect to the RSO.

By demonstrating robust, affordable, and responsive rendezvous of a nanosat with an uncooperative RSO, successful completion of the ARAPAIMA mission will validate a range of technologies for space-based space situational awareness (SSA), debris removal from Low Earth Orbit (LEO) and nanosat asteroid characterization. In addition, the mission will validate a set of key technologies at a system level, such as miniaturized commercially available sensors, a miniaturized warm gas propulsion system for CubeSat applications, as well as advanced relative navigation and proximity operations algorithms implemented on a nanosat. Integrated, in-orbit testing of these technologies will advance the technology readiness levels for future space-based SSA missions performed by inexpensive, agile nanosats.

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Small Satellite Constellations for Earth Geodesy and Aeronomy
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Drag-free nano-satellite constellations can improve the sensitivity and spatial and temporal resolution of Earth aeronomy and geodesy measurements relative to a single satellite or a satellite pair. It is clear that multi-satellite systems improve the frequency with which data can be collected for a given location over the Earth. Nonetheless, a broad quantitative assessment has not been performed for the particular applications of Earth geodesy and aeronomy. This research is necessary to produce a meaningful cost/benefit analysis for this class of nano-satellite constellations.

The enabling technology is a precision small-scale drag-free system, called the Drag-free CubeSat, currently under development at the University of Florida and Stanford University. Drag-free satellites provide autonomous precision orbit determination, accurately map the static and time varying components of Earth's mass distribution, aid in our understanding of the fundamental force of gravity, and will ultimately open up a new window to our universe through the detection and
observation of gravitational waves. At the heart of this technology is a gravitational reference sensor, which (a) contains and shields a free-floating test mass from all non-gravitational forces, and (b) precisely measures the position of the test mass inside the sensor. A feedback control system commands thrusters to fly the “tender” spacecraft with respect to the test mass. Thus, both test mass and spacecraft follow a pure geodesic in spacetime. By tracking the position of a low Earth orbiting drag-free satellite we can directly determine the detailed shape of geodesics and, through analysis, the higher order harmonics of the Earth’s geopotential. The commanded thrust, test mass position and GPS tracking data can also be analyzed to produce the most precise maps of upper atmospheric drag forces and, with additional information, detailed models that describe the dynamics of the upper atmosphere and its impact on all satellites that orbit the Earth. This paper will focus on the performance of drag-free CubeSat constellations for measuring Earth’s geoid and upper atmospheric winds and density. Advances in the development of the Drag-free CubeSat hardware and control software will also be described.