Cubesat
Literature Survey Report

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1 Introduction

In this report we have conducted a literature survey on possible scientific goals for formation flying missions. We have also looked at sensors and actuators for guidance, navigation and control of Cubesats.

2 Mission Concepts

2.1 NSF Programs

Below is a list of 3 programs which have been awarded by the NSF and are in the field of cubesats. These are current ongoing programs.

2.1.1 CubeSat: Cubesat investigating Atmospheric Density Response to Extreme driving (CADRE)

This project is a coordinated science program, whose main instrument is a 3-Unit (3U) CubeSat named Cubesat investigating Atmospheric Density Response to Extreme driving (CADRE). The planned science investigation addresses fundamental issues related to ion-neutral coupling, including neutral wind morphology and dynamics that are key to understanding how the thermosphere reacts to energy input and the role this plays in magnetosphere-ionosphere coupling. Being carried out by Aaron Ridley at UMich currently. The link to the NSF award.

2.1.2 CubeSat: Colorado Student Space Weather Experiment

The objective of this three-year cross-disciplinary team effort is to build and operate a tiny, so-called CubeSat, spacecraft. The purpose of the 3U Cubesat carrying an energetic particle sensor is to address fundamental space weather science questions relating to the relationship between solar flares, energetic particles, and geomagnetic storms in the near Earth space environment. The particle instrument is the Relativistic Electron and Proton Telescope integrated little experiment (REPTile). REPTile is designed to measure directional differential flux of energetic protons, 10-40 MeV, and electrons, 0.5 to $>$ 3 MeV. The specific science objectives for the project are to investigate the relationships between solar energetic particles, flares, and coronal mass ejections, and to characterize the variations of the Earth's radiation belt electrons. Being carried out by Xinlin Li at University of Colorado at Boulder. The link to the NSF award.

2.1.3 Collaborative Research: CubeSat–Composition Variations in the Exosphere, Thermosphere, and Topside Ionosphere (EXOCUBE)

This project is for a 3U CubeSat mission named EXOCUBE to measure the densities of all significant neutral and ionized species in the upper atmosphere on a global scale. The project will provide the first in-situ global neutral density data in more than 25 years, including the first direct measurements of Hydrogen densities using the mass spectrometer technique. An important science objective for EXOCUBE is to provide observational constraints for physical models of the upper atmosphere. Additionally, the measurements will be used to test and validate newly developed experimental techniques to obtain neutral and ionized composition and densities from radar and optical observations. Being currently done by John Noto at Scientific Solutions Incorporated. The link to the NSF award.

2.2 Small Satellite Conference 2012

The next topics have been taken from the small satellite conference conducted by KISS. The first few missions listed are all interplanetary missions. Two tables are also given at the end of the section which describe some other missions as well.

2.2.1 Mineral Mapping of Asteroids

The proposed mission overview is 6U CubeSat launched on a GEO satellite or Mars-bound mission as a secondary payload. There is a solar sail to reach near Earth asteroids. The proposed science objectives is to map surface composition of 3 asteroids at 1-20 m spatial resolution.

Required instrumentation: spatial IFOV of 0.5 mrad, spatial sampling 0.5 m -10 m depending on the encounter range, Spectral sampling 10 nm, Imaging Spectrometer, 0.4 – 1.7 μm. Perhaps extend to 2.5 μm w/ HOT-BIRD or other advanced detector and achievable cooling.

2.2.2 Solar system escape

The plan is to use use large area/ low mass spacecraft for high speed trajectory with Low perihelion which would Explore interplanetary environment, heliosheath and perhaps heliopause. It is also aimed to Test communications, power, pointing and miniaturized instrument technologies.

Required Instrumentation: Plasma, solar wind, Energetic particles & cosmic rays, Magnetometer, Cameras to observe sail interaction with environment.

2.2.3 Earth-Sun Sunward-of-L1 Solar Monitor

The aim of this concept is to measure strong Coronal Mass Ejections or other space weather from Sunward-of-L1 position to provide additional warning time to Earth. The science objective is to obtain Plasma and magnetometer readings of solar wind from sunward-of-L1 position to compare with L1 values from ACE or follow-on.

2.2.4 Solar Polar Imager CubeSat Constellation

6 S/C in highly inclined constellation. Out-of-Ecliptic Vertical Orbit, 0.99 AU. Use solar sail to reach high inclination. The proposed science mission is Dynamo: Helioseismology & magnetic fields of polar regions. Polar view of corona, CMEs, solar radiance, Link high latitude solar wind & energetic particles to coronal sources.

The required instrumentation of the 6 satellites are:

- S/C1: Plasma + Mag Field
- S/C2: Energetic Particles + Mag Field
- S/C3: Cosmic Rays,
- S/C4: Magnetograph/Doppler Imager

- S/C5: EUV Imager
- S/C6: Coronagraph

2.2.5 Radio Quiet Lunar CubeSat

The aim is to assess radio quiet volume in shielded zone behind the Moon for future 21 cm cosmology missions. The proposed science mission is to find the usable volume behind the Moon for high sensitivity 21 cm cosmology observations which determines utility of lunar surface vs. orbiting missions.

The other missions provided with no further information are given below.

- Sub-L1 Space Weather Monitor
- Bright AGN (blazar) monitoring
- Lunar water mapper
- QSO survey in NIR
- Jupiter Aurora (UV) monitor
- X-ray spectroscopy of ISM, solar wind charge exchange

These missions were taken from the presentations given by Stephen Murray from Space Telescope Science Institute and John Hopkins University and another presentation given by Robert Staehle at JPL.

The two tables below show some other possible concepts for multiple agents and their required science missions. These were given by Dayton Jones.

Mission Concepts

SCIENCE AREA	SINGLE CUBESAT	FEW CUBESATS	~20 CUBESATS	~100 CUBESATS	>> 100 CUBESATS
Dark Ages	DARE follow-on (lunar orbit)	DARE extension? (lunar orbits)	N/A	N/A	Tomography
EoR	Probably will be done from ground				
Extragalactic	N/A	N/A	Image individual strong sources	All-sky mapping	Deep, high dynamic range imaging
Galactic	Integrated spectra (RAE 2 done properly)	N/A	Image individual strong sources	All-sky mapping	Deep, high dynamic range imaging
Exoplanets	N/A	N/A	Initial LF searches	Deeper searches	Useful upper limits
Interplanetary Magnetic Fields	L4, L5 beacons for Faraday rotation	In-situ (sunward of L2 w/solar sails)	Faraday rot. with S/C along Earth orbit	High-res. Faraday rot. tomography	In-situ throughout inner heliosphere
Solar system Objects	Giant planet burst spectra (lunar orbit)	Giant planet source sizes (lunar orbit)	Localization & size of giant planet bursts	Imaging & det. of weak bursts	High quality imaging of solar system
Solar bursts	Solar AKR analog??	Type II trajectories?	CME shock tracking	Source morphology	Fainter & farther imaging & tracking
Discovery	Ant. Directivity modulation	Lunar ionosphere (via absorption)	Strong transients	Var. sources	???

Figure 1: Mission concepts for multiple agent systems

2.3 Constellations of Small Satellites

2.3.1 Planet Labs' Remote Sensing Satellite System (2013)

Planet Labs combines imaging capability with state-of-the-art big-data and cloud-computing technologies to enable easy access to this data by those who need it most. We describe the system under construction, the technical specifications of the satellites, the ground station network and the product. Satellite missions planned for launch in 2013.[1]

2.3.2 Can a Constellation of CubeSats Create a Capability? Satisfying Australia's Future Need for Multi-Spectral Imagery (2013)

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 identifies future satellite imagery requirements of the Australian economic region in the 2015 timeframe. A need was identified for multi-spectral coverage of the entire Australian landmass every day. This means medium spatial resolution and high temporal resolution. This paper estimates the gap in

Science Requirements

SCIENCE AREA	FREQ RANGE	NO. OF ANTENNAS	ANG. RESOLUTION
• **Cosmology**			
– Integrated EoR, Dark Ages spectral signals	50-150, 20-50 MHz	1 or more	> steradian
– EoR power spectrum	50-150 MHz	> 1000	2 arcmin to ~ 2 degrees
– Dark Ages power spectrum	20-50 MHz	> 10,000	2-20 arcmin
– EoR tomography	50-150 MHz	> 100,000	1-10 arcmin
• **Extragalactic**			
– Fossil radio lobes, AGN duty cycles	~ 10 MHz	~ 300	1 arcmin
• **Galactic**			
– SNR as sites of cosmic ray acceleration	3-30 MHz	> 10,000	< arcmin
– Map emissivity of interstellar medium	1-30 MHz	~ 100	< 1 arcmin
– Extrasolar planets	1-30 MHz	~ 10,000	< 1 arcmin
• **Transient Sources**			
– Fast transients & pulsars (<< 1 second)	> 100 MHz	~ 100	Arcmin
– Slow transients, ISS (> 1 second)	10-100 MHz	> 100	Arcmin
• **UHE Particles**			
– Radio bursts from Moon	~ 10 MHz	1-100	Degrees
– Radio bursts from terrestrial atmosphere, ice caps	~ 10 MHz	10-100	Degrees
• **Solar System**			
– Jupiter, Saturn LF emission	< 10 MHz	~ 10	Arcmin
– Interplanetary turbulence	1-30 MHz	~ 1000	Arcmin
• **Heliophysics**			
– Track type II & type III bursts	0.1-30 MHz	~ 10-50	Degrees
– Map interplanetary magnetic field lines	0.1-30 MHz	~ 10-50	Degrees
• **Earth**			
– Image magnetosphere response to CMEs	0.1-1 MHz	> 10	Degrees
– Auroral Kilometric Radiation	0.1-0.5 MHz	~ 10	Degrees

Figure 2: Science Requirements for above missions

required imagery that will remain in 2015 when new public good satellites are operational. It then describes a modification of the 6U cubesat system proposed 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. 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.[2]

2.3.3 Simultaneous Multi-Point Space Weather Measurements using the Low Cost EDSN CubeSat Constellation (2013)

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 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. 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 mission.[3]

2.3.4 Small Satellite Constellations for Earth Geodesy and Aeronomy (2013)

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. Multi-satellite systems improve the frequency with which data can be collected for a given location over the Earth. 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.[4]

2.3.5 A 6U CubeSat Constellation for Atmospheric Temperature and Humidity Sounding (2013)

We are currently developing a 118/183 GHz sensor that will enable observations of temperature and precipitation profiles over land and ocean. The 118/183 GHz system is well suited for a CubeSat deployment as ~10cm antenna aperture provides sufficiently small footprint sizes (~25km). We will take advantage of past and current technology developments at JPL viz. HAMSR (High Altitude Microwave Scanning Radiometer), Advanced Component Technology (ACT'08) to enable low-mass and low-power high frequency airborne radiometers. In this paper, we will describe the design and implementation of the 118 GHz temperature sounder and 183 GHz humidity sounder instrument on the 6U CubeSat. In addition, a summary of radiometer calibration and retrieval techniques of the temperature and humidity will be discussed.[5]

2.4 Formation Flying Small Satellites

2.4.1 NASA's Four Spacecraft Magnetospheric Multiscale Mission (2013)

The Magnetospheric Multiscale (MMS) mission is a Solar Terrestrial Probes Program mission within NASA's Heliophysics Division. The mission consists of four identically-instrumented spin-stabilized satellites that will be placed, with surgical accuracy, into the heart of Earth's magnetic reconnection regions. A mono-propellant propulsion system with 12 thrusters on each 1250 kg spacecraft will execute both small formation maintenance maneuvers and large apogee raise maneuvers – achieving controlled interspacecraft separations down to 10 km at mission-phased Earth-constellation distances eventually reaching 160,000 km. An attitude control system keeps the spacecraft to within $\pm 0.5°$ of the desired orientation using on-board closed loop maneuver control.

Scientifically, the MMS mission will utilize Earth's natural plasma laboratory to conduct the first sufficiently detailed measurements to solve the microphysics of magnetic reconnection. Magnetic reconnection is a fundamental plasma physical process that taps the energy stored in a magnetic field and explosively converts it to particle kinetic energy. This process occurs in star-accretion disk interactions, neutron star magnetospheres, pulsar wind acceleration. It is implicated in the acceleration of ultra-high-energy cosmic rays in active galactic nuclei jets and occurs in solar flares and solar Coronal Mass Ejections producing energetic charged particles that rain down on Earth's environment. Launch will be in October 2014 on an Atlas-V 421 Launch Vehicle.[6].

2.4.2 EDSN Update (2013)

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.[7]

2.4.3 The CanX-4&5 Formation Flying Mission: A Technology Pathfinder for Nanosatellite Constellations (2013)

Future nano- and microsatellite constellations will require highly precise absolute and relative position knowledge and control; intersatellite communications; high-performance attitude determination and control systems; and advanced, compact propulsion systems for orbit maintenance. The dual spacecraft CanX-4&5 mission - slated to launch in the late 2013 / early 2014 on India's Polar Satellite Launch Vehicle (PSLV) - will demonstrate all of these capabilities at the nanosatellite scale: both as standalone subsystems, and in concert, to accomplish autonomous formation flight with sub-meter relative position control and centimeter-level relative position determination. Each spacecraft is identical, and formation flight is enabled by each satellite having a GPS receiver, on-board propulsion system, S-Band inter-satellite link, and fine guidance and control (GNC) computer. The two spacecraft will share on-board position, velocity, and attitude data wirelessly over their intersatellite link, and one of the two spacecraft will perform propulsive maneuvers to achieve and maintain a series of autonomous formations. The technologies and algorithms used on CanX-4&5 are extensible to a broad range of missions and satellites at the nano- and microsatellite scale, and this ambitious technology demonstration will serve as a pathfinder for several formation flight and constellation applications.[8]

2.4.4 Small Satellite Cluster Inter-Connectivity (2013)

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. 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. There are three different formation flying patterns under study:

Table 1: Small Satellite Inter-Connectivity Evaluation

Formation	Throughput (%)	Access delay	End-to-end delay
Leader-Follower	23	Less than Cluster	Less than Cluster
Cluster	11	More than Cluster	More than Cluster
Constellation	under study	under study	under study

The decision of which formation flying pattern has to be used depends on the mission architecture, e.g. number of satellites, orbits, power, etc. Inter-satellite communication eliminates the use of expensive ground relay stations and ground tracking networks. 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. This presentation aims to propose and validate inter-satellite communication protocols for distributed small satellite networks.[9]

2.4.5 Enabling Radio Crosslink Technology for High Performance Coordinated Constellations (2013)

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. 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. [10]

2.4.6 From Single to Formation Flying CubeSats: An Update from the Delft Programme (2013)

[11] 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 OLFAR have been proposed for this purpose. This paper provides an update of the Delfi programme of the Delft University of Technology (TU Delft). Two CubeSats named Delta and Phi are going to be launched to demonstrate autonomous formation flying. This paper consists of three parts:

- 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 and satellite design.
- 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.
- Payloads of DelFFi that enable the autonomous formation flying. Here the technology developments are threefold:
  - communicating, which concerns on inter-satellite communication and ranging
  - processing, which utilizes multi-agent based artificial intelligence technology for cooperative control
  - 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.

2.4.7 Astronomical Antenna for a Space Based Low Frequency Radio Telescope (2013)

The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) project is investigating an orbiting low frequency radio telescope. Due to strong ionospheric interference and Radio Frequency Interference (RFI) found at frequencies below 30 MHz, such an instrument is not feasible on Earth, hence the proposed solution of a swarm of autonomous nano-satellites sent to a remote location in space. On each satellite, the astronom- ical antenna consists of three orthogonal dipoles designed to work within the constraints of a nano-satellite. Due to mechanical constraints, the dipoles are not optimally integrated into the nano-satellites from an antenna point of view. Unfortunately, the operational band of 0:3 MHz to 30 MHz and the dimensions of the astronomical antenna of just under 5:0 m prohibit tests within the controlled environment of an anechoic chamber; ergo, a scale model is required. This work describes the design, simulation and measurement of such a scale model.[12]

2.4.8 Design of Nano-satellite Cluster Formations for Bi-Directional Reflectance Distribution Function (BRDF) Estimations (2013)

The bidirectional reflectance distribution function (BRDF) of the Earth's surface describes the directional and spectral variation of reflectance of a surface element. It is required for precise determination of important geophysical parameters such as albedo. BRDF can be estimated using reflectance data acquired at large 3D angular spread of solar illumination and detector directions and visible/near infrared (VNIR) spectral bands. This paper proposes and evaluates the use of nanosatellite clusters in formation flight to achieve large angular spreads for cheaper, faster and better estimations that will complement existing BRDF data products. In this paper, the technical feasibility of this concept is assessed in terms of various formation flight geometries available to achieve BRDF requirements and multiple tradespaces of solutions proposed at three levels of fidelity – Hill's equations, full sky spherical relative motion and global orbit propagation. Preliminary attitude control requirements, as constrained by cluster geometry, are shown to be achievable using CubeSat reaction wheels.[13]

2.4.9 Operations, Orbit Determination, and Formation Control of the AeroCube-4 CubeSats (2013)

Three satellites of the AeroCube-4 series built by The Aerospace Corporation were launched in September 2012 from Vandenberg Air Force Base. These satellites were each equipped with an on-board GPS receiver that provided position measurements with a precision of 20 meters and enabled the generation of ephemerides with meter-level accuracy. Each AeroCube was also equipped with two extendable wings that altered the satellite's cross-sectional area by a factor of three. In conjunction with the GPS measurements, high-precision orbit determination detected deliberate changes in the AeroCube's drag profile via wing manipulation. The AeroCube operations team succeeded in using this variable drag to re-order the satellites' in-track configuration. A differential cross-section was created by closing the wings of one satellite while the others' remained open, and the relative in-track motion between two AeroCubes was reversed. Over the course of several weeks, the satellites' in-track configuration was re-ordered, demonstrating the feasibility of CubeSat formation flight via differential drag.[14]

2.5 Missions in which Formation Flying may be beneficial

2.5.1 Design and Analysis of a Nanosatellite Platform for Orbital Debris Mitigation through Launch of Space Tether in Low Earth Orbits (2013)

Orbital debris disposal, particularly in low Earth orbits, has been identified as a serious concern by NASA and other space agencies around the world. To mitigate future overgrowth of the problem, guidelines have been developed and proposed by these space agencies. However, much of the research and development of established systems for de-orbiting of satellites is focused on larger spacecraft, and efforts to reduce the existing space debris in the low Earth orbit has been limited. This paper will present a design and analysis of an approach to tether existing space debris through a nanosatellite platform by solving Lambert's problem in real time. The platform will host a tether launching system as its payload. The tether launching system is designed to accommodate two Terminator Tape tethers from Tethers Unlimited. The nanosatellite, when in orbit, will identify a nearby space debris object with support from ground control. Through estimation of its orbital position and prediction of orbital position of the space debris object, the nanosatellite will perform a launch maneuver according to Lambert's problem to "sling" the onboard Terminator Tape onto the debris object. The nanosatellite bus will largely be designed around commercial off the shelf components.[15]

2.5.2 CubeSats – Have They Reached Their Explorer-1 Moment? (2013)

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. 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. [16]

2.5.3 PanelSAR: A Smallsat Radar Instrument (2013)

A novel and low-cost solution for Synthetic Aperture Radar from space. The paper focuses on a solution based on low power SAR principles (FMCW/iFMCW), already proven in airborne SAR applications, that can be embarked on a commercially affordable small satellite. The system architecture is presented, showing how features such as modularity, reliability, low power and low mass are achieved to provide a low-cost end-to-end solution. Also the "new space" approach adopted in the development of the smallsat miniSAR is addressed.[17]

2.5.4 Deployable Mirror for Enhanced Imagery Suitable for Small Satellite Applications (2013)

High spatial resolution imagery and large apertures go hand in hand but small satellite volume constraints place a direct limit on monolithic aperture mirror systems. Deployable optical systems hold promise of overcoming aperture size constraints and greatly enhancing small satellite imaging capabilities. The Space Dynamics Laboratory (SDL) is currently researching deployable optics suitable for small spacecraft and has developed a passively aligned deployable mirror. The team recently built a proof-of-principle mirror and a single parabolic mirror segment or "petal" measured for deployment repeatability. They measured elevation (tilt) and azimuth (tip) angular alignment repeatability to be 0.6 arcseconds or 2.9 μrad (1 sigma) in each axis after a ten deployment sequence. Excellent image quality is possible in the short wave infrared (SWIR) to long wave infrared (LWIR) bands. [18]

2.5.5 Versatile Structural Radiation Shielding and Thermal Insulation through Additive Manufacturing (2013)

The use of Commercial Off-The-Shelf (COTS) components in SmallSat platforms enable operational mission capabilities within affordable program costs, although these components must either be isolated from the space environment or be expected to have short lifetimes. In this paper, we present results of our work adapting additive manufacturing technologies to create multifunctional structures that provide tailored isolation from the radiation and thermal environments of space. "Versatile Structural Radiation Shielding" (VSRS™) are structures that incorporate integral graded-Z radiation shielding, as well as "Structural Multi-Layer-Shielding" (SMLI ™), components that incorporate integral thermal insulation. These methods enable responsive fabrication of spacecraft structures with complex geometries, such as avionics enclosures, conformal covers, and even satellite 'exoskeleton' with tailored radiation shielding, thermal isolation, heat dissipation, and EMI shielding.[19]

2.5.6 Collapsible Space Telescope (CST) for Nanosatellite Imaging and Observation (2013)

Nanosatellites have gained broad use within the university and scientific communities for a variety of applications ranging from Space Weather, Space Biology and Astrobiology. There is great interest to develop high-quality nanosatellite imaging applications to support Earth Observations, Astrophysics and Heliophysics Missions. NASA Ames Research Center is developing a low cost, deployable telescope that, when coupled with the appropriate imager, will provide high-resolution imaging for Earth and Space Observations. The collapsible telescope design is a Strain Deployable Ritchey Chrétien Cassegrain telescope that can fit within the volume of 1U x 4U portion of a 6U nanosatellite platform. Additional telescope optical prescriptions compatible with the same deployable architecture are being explored. Our prototype instrument backend is a remote sensing compact spectropolarimeter with no moving parts, currently under development. The ability to integrate a deployable Cassegrain telescope into a nanosatellite platform matches desires outlined within the TA08 Remote Sensing Instruments/Sensors Technical Area Roadmap and represents game changing technologies in small satellite subsystems to include the potential for swarm missions with distributed apertures. [20]

2.5.7 Asteroid Prospector (2013)

This paper presents the overall design of a small reusable spacecraft capable of ying to an asteroid from low earth orbit, operating near the surface of the asteroid and returning samples to low earth orbit. The spacecraft is in a 6U CubeSat form factor and designed to visit near asteroids as far as 1.3 AU from the sun. Deep space missions are traditionally large and expensive, requiring considerable manpower for operations, use of the Deep Space network for navigation, and costly but slow rad-hard electronics. Several new technologies make this mission possible and affordable in such a small form factor: a 3 cm ion engine from Busek for the low-thrust spirals, an autonomous optical navigation system, precision miniature reaction wheels, high performance and nontoxic green propellant (HGPG) thrusters, and Honeywell's new Dependable Multiprocessor technology for radiation tolerance. A complete spacecraft design is considered and the paper includes details of the control and guidance algorithms. [21]

2.5.8 FTS CubeSat Constellation Providing 3D Winds (2013)

A novel small satellite constellation utilizing a Fourier Transform Spectrometer (FTS) instrument onboard 6U CubeSats would allow weather forecasters to have unprecedented understanding of global tropospheric wind observations from space; enabling more accurate, reliable, and longer-term weather forecasts. Three FTS CubeSats flying in formation and separated by a known time delay would provide cooperative measurements and overlay scenes necessary to compile vertical profiles of the wind field. A constellation of formation-flying FTS CubeSats would allow measurement of the global wind field; providing unparalleled coverage and allowing longer-term weather forecasts. This paper will describe the recent advancements in CubeSat capabilities and future work required to meet the objectives of the FTS mission. The innovative approach the Exelis/University of Michigan team is taking to power, attitude determination and control, communications, and constellation formations will also be discussed. [22]

2.5.9 Real-Time Geolocation with a Satellite Formation (2013)

Space-borne geolocation with a small satellite formation could provide accurate tracking of a Mars rover, a redundant navigation system in a jammed GNNS environment, or a cost-effective system for autonomously locating distress signals. In this study we demonstrate how a cluster of two or three Low Earth Orbit (LEO) satellites performing sequential time difference of arrival measurements could accurately determine the position of a terrestrial source emitting electromagnetic pulses. Whereas TDOA geolocation algorithms have been presented before, this study provides a theoretical basis for achieving optimal positioning performance, while solving for the initial position ambiguity through recursive filtering techniques.[23]

2.6 CubeSats developed by students

2.6.1 The SwissCube: Results and Lessons Learned After 4 Years of Operations in Space (2013)

SwissCube is the first Swiss built nanosatellite. Here we will present results from more than 3 years of operations in space, including results from the payload. In this paper we present a general description of the hardware used for SwissCube, giving a particular attention to the tests done before and after flight, describing the payload mounted and the results achieved. We will detail our analysis of the Attitude Control and Determination subsystem, which is based on a B-dot controller using magento-torquers, gyros, magneto-meters, sun-sensors and thermometers. [24]

2.7 Interesting papers

2.7.1 Findings of the KECK Institute for Space Studies Program on Small Satellites: A Revolution in Space Science (2013)

The Keck Institute for Space Studies (KISS) is a "think and do tank" established at Caltech where a small group of not more than 30 persons interact for a few days to explore various frontier topics in space studies. The primary purpose of KISS is to develop new planetary, Earth, and astrophysics space mission concepts and technology. The first workshop identified novel mission concepts where stand-alone, constellation, and fractionated small satellite systems can enable new targeted space science discoveries in heliophysics, astrophysics, and planetary science including NEOs and small bodies. The second workshop then identified the technology advances necessary to enable these missions in the future. In the following we review the outcome of this study program as well as the set of recommendations identified to enable these new classes of missions. [25]

2.7.2 The Next Little Thing: Femtosatellites (2013)

The original CubeSat vision was to enable simple, meaningful missions that universities could undertake. CubeSats were later adopted by industry and government agencies. The community focus on miniaturization has been costly in our endeavor to do more with less. Femtosatellites, defined as having a mass less than 100 grams, turn this scenario on its head by forcing a do less with more mentality; individual spacecraft will be less capable, but coordinated operation of massively distributed femtosatellites can achieve the required overall mission capability. [26]

2.7.3 Autonomous Assembly of a Reconfiguarble Space Telescope (AAReST) – A CubeSat/Microsatellite Based Technology Demonstrator (2013)

Future space telescopes with diameter over 20 m will require in-space assembly. High-precision formation flying has very high cost and may not be able to maintain stable alignment over long periods of time. We believe autonomous assembly is a key enabler for a lower cost approach to large space telescopes. The mission will involve two 3U CubeSat-like nanosatellites ("MirrorSats") each carrying an electrically actuated adaptive mirror, and each capable of autonomous un-docking and re-docking with a small central "9U" class nanosatellite core, which houses two fixed mirrors and a boom-deployed focal plane assembly. [27]

2.7.4 NASA's GRAIL Spacecraft Formation Flight, End of Mission Results, and Small-Satellite Applications (2013)

The Gravity Recovery and Interior Laboratory (GRAIL) mission was composed of twin spacecraft tasked with precisely mapping the gravitational field of Earth's Moon. GRAIL science collection required that the two spacecraft operate in the same orbit plane and with precise relative separation and pointing, which evolved through the primary and extended mission Science phases. [28]

2.8 Predicting Earthquakes through Ionosphere Monitoring

2.8.1 Mission Concept

Fluctuations in the ionosphere occur hours or days before large earthquakes as given here. The formation may help to mitigate measurement errors. Ionosphere measurement is also a target for other missions, if one of them is adopted, this could be a secondary objective. Something similar is scheduled to be launched by the Chinese in 2014, though not a formation.

2.8.2 Abstract

Earthquake Forecast Science Research with a Small Satellite (2002-Session 9)[29] Reliable, repeatable Earthquake forecast is a subject surrounded by controversy and scepticism. What is clear, is that reliable forecast could be the single most effective tool for earthquake disaster management. Roughly a third of the world's population live in areas that are at risk and, every year since the beginning of the twentieth century earthquakes have caused an average of 20,000 deaths. The economic loss in the 1995 Kobe, Japan earthquake was greater than US$100 billion . Substantial progress has been made on the development of methods for earthquake hazard analysis on a timescale of a few decades. However, the forecast of specific earthquakes on timescales of a few years to a few days is a difficult problem. It has been proposed that satellites and ground-based facilities may detect earthquake precursors in the ionosphere a few hours or days before the main shock. This hypothesis is now backed by a physical model, derived by the Russian Academy of Sciences from statist ical studies, and an understanding of the main morphological features of seismoionospheric precursors - which allows them to be separated from background ionospheric variability. The main problems now are lack of regular global data and limited funding for what is considered to be financially risky research. Low -cost, small satellites offer a solution to these problems. A 100 kg class SSTL enhanced microsatellite, carrying a RAS topside sounder and complimentary payload, will be used to make regular measurements over seismically active zones around the globe. The low cost of the spacecraft offers a financially low -risk approach to the next step in this invaluable research. The spacecraft will make ionospheric measurements for systematic research into the proposed precursors. The aims will be to confirm or refute the hypothesis; define their reliability and reproducibility; and enable further scientific understanding of their mechanisms. In addition, forecasting of the magnitude of the events, as well as an indication of the seismic centre may also be possible. These mission data should also lead to improved knowledge of the physics of earthquakes, improved accuracy for GPS-based navigation models, and could be used to study the reaction of the global ionosphere during magnetic storms and other solar-terrestrial events. The paper presents an overview of the scientific basis, goals, and proposed platform for this research mission.

Dynamic Ionosphere Cubesat Experiment (DICE) (2010- Session 3) (2012- Session 11) [30, 31] The Dynamic Ionosphere Cubesat Experiment (DICE) mission has been selected for flight under the NSF "CubeSat-based Science Mission for Space Weather and Atmospheric Research" program. The mission has three scientific objectives: (1) Investigate the physical processes responsible for formation of the midlatitude ionospheric Storm Enhanced Density (SED) bulge in the noon to post-noon sector during magnetic storms; (2) Investigate the physical processes responsible for the formation of the SED plume at the base of the SED bulge and the transport of the high density SED plume across the magnetic pole; (3) Investigate the relationship between penetration electric fields and the formation and evolution of SED. The mission consists of two identical Cubesats launched simultaneously. Each satellite carries a fixed-bias DC Langmuir Probe (DCP) to measure in-situ ionospheric plasma densities, and an Electric Field Probe (EFP) to measure DC and AC electric fields. These measurements will permit accurate identification of storm-time features such as the SED bulge and plume, together with simultaneous co-located electric field measurements which have previously been missing. The mission team combines expertise from ASTRA, Utah State University/Space Dynamics Laboratory (USU/SDL), Embry-Riddle Aeronautical University and Clemson University.

Conducting Science with a CubeSat: The Colorado Student Space Weather Experiment (2010- Session 12)[32] Energetic particles, electrons and protons either directly associated with solar flares or trapped in the terrestrial radiation belt, have a profound space weather impact. A 3U CubeSat mission with a single instrument, the Relativistic Electron and Proton Telescope integrated little experiment (REPTile), has been selected by the National Science Foundation to address fundamental questions pertaining to the relationship between solar flares and energetic particles. These questions include the acceleration and loss mechanisms of outer radiation belt electrons. The Colorado Student Space Weather Experiment operating in a highly inclined low earth orbit, will measure differential fluxes of relativistic electrons in the energy range of 0.5-2.9 MeV and protons in 10-40 MeV. This project is a collaborative effort between the Laboratory for Atmospheric and Space Physics and the Department of Aerospace Engineering Sciences at the University of Colorado, which includes the integration of students, faculty, and professional engineers.

Nanosatellites for Earth Environmental Monitoring: The MicroMAS Project (2012- Session 1)[33] The Micro-sized Microwave Atmospheric Satellite (MicroMAS) is a dual-spinning 3U CubeSat equipped with a passive microwave spectrometer that observes nine channels near the 118.75-GHz oxygen absorption line. The focus of this MicroMAS mission (hereafter, MicroMAS-1) is to observe convective thunderstorms, tropical cyclones, and hurricanes from a near-equatorial orbit. The MicroMAS-1 flight unit is currently being developed by MIT Lincoln Laboratory, the MIT Space Systems Laboratory, and the MIT Department of Earth and Planetary Sciences for a 2014 launch to be provided by the NASA CubeSat Launch Initiative program. As a low cost platform, MicroMAS offers the potential to deploy multiple satellites than can provide near-continuous views of severe weather. The existing architecture of few, high-cost platforms, infrequently view the same earth area which can miss rapid changes in the strength and direction of evolving storms thus degrading forecast accuracy. The 3U CubeSat has dimensions of 10 x 10 x 34.05 cm3 and a mass of approximately 4 kg. The payload is housed in the "lower" 1U of the dualspinning 3U CubeSat, and is mechanically rotated approximately once per second as the spacecraft orbits the Earth. The resulting cross-track scanned beam has a FWHM beam width of 2.4^{o}, and has an approximately 20-km diameter footprint at nadir incidence from a nominal altitude of 500 km. Radiometric calibration is carried out using observations of cold space, the Earth's limb, and an internal noise diode that is weakly coupled through the RF front-end electronics. In addition to the dual-spinning CubeSat, a key technology development is the ultra-compact intermediate frequency processor (IFP) module for channelization, detection, and analog-to-digital conversion. The payload antenna system and RF front-end electronics are highly integrated, miniaturized, and optimized for low-power operation. To support the spinning radiometer payload, the structures subsystem incorporates a brushless DC zerocogging motor, an optical encoder and disk, a slip ring, and a motor controller. The attitude determination and control system (ADCS) utilizes reaction wheels, magnetorquers, Earth horizon sensors, peak power tracking, a magnetometer, and a gyroscope. The communications system operates at S-band using the Open System of Agile Ground Stations (OSAGS) with a 2.025—2.120 GHz uplink and 2.200—2.300 GHz downlink at 230 kbps. MicroMAS-1 uses a Pumpkin CubeSat Motherboard with a Microchip PIC24 microcontroller as the flight computer running Pumpkin's Salvo Real Time Operating System. Thermal management includes monitoring with thermistors, heating, and passive cooling. Power is generated using four double-sided deployable 3U solar panels and one 2U bodymounted panel with UTJ cells and an electrical power system (EPS) with 30 W-hr lithium polymer batteries from Clyde Space. Tests with the MicroMAS-1 Engineering Design Model (EDM) have resulted in modifications to the spinning assembly, stack and ADCS system and have informed the development of the flight model subsystems.

2.9 Earth Imaging for Science Applications in Emerging Countries

2.9.1 Mission Concept

A satellite imaging cluster would give less advanced parts of the world access to scientific data on things like resource consumption, pollution, and climate. The formation could do the imaging with each satellite operating a different camera type.

2.9.2 Abstract

NanoObservatory: Earth Imaging for Everyone (2002- Session 3)[34] Earth imaging has traditionally been the domain of large governments and expensive satellites. Progress in earth imaging satellite technology has focused on driving down image resolutions, decreasing re-visit times, and expanding spectral coverage. While imaging capability has increased, costs have grown exponentially, pricing many would-be science applications out of the market. Many scientific groups, especially those in countries with emerging economies, have a compelling need for earth imaging to monitor the use of natural resources, measure changes in climate, quantify and track pollution, and assist in natural disaster warning and recovery—without the high cost of a dedicated system or the restrictions imposed by sharing data from another country's system. NanoObservatory, shown in Figure 1, is a low-cost solution for users wanting basic earth imaging for science applications. It provides multi-spectral imaging (red, green, blue) with a ground sampling distance (GSD) of 10m, and can be customized to image in other spectral ranges as necessary. The satellite resides in a 600km circular orbit between 0º and 38º inclination. From this vantage point, the satellite images a 50km x 50km area and can store consecutive images to create a seamless view. The satellite uses innovative designs for attitude determination and control (ADCS) and communications to deliver the best performance for the lowest cost. A single, off-the-shelf ground station transmits commands to the satellite and downloads images while it is overhead. The real breakthrough with NanoObservatory is not in capabilities but in cost. Weighing only 25kg, NanoObservatory can ride as a secondary payload on other missions, lowering the cost of launch. NanoObservatory takes advantage of the low radiation environment in LEO by using commercial offthe- shelf parts in novel ways, which lowers nonrecurring engineering costs. In addition, the satellite's simple command and control system requires only a basic ground station and PC for operation, making its on-going costs a fraction of competing earth imaging systems. Many science applications do not require highresolution imaging, but could benefit from a low-cost, dedicated Earth imaging platform. NanoObservatory fills this gap and delivers the benefits of space-based remote sensing to a new segment of underserved customers. NanoObservatory is a breakthrough technology that makes earth imaging for everyone.

Microsatellites at Very Low Altitude (2006- Session 2)[35] An approach of using a very low flying orbit for a microsatellite to achieve a low cost imaging mission, and its demonstration in the Israeli - French VENμS program scheduled to be launched in 2009, are presented. At low satellite altitude, a smaller and less expensive payload can be used to obtain the performance of another one that operates at a higher altitude. This is true for the optical payload (of the present concern), and is even much more conspicuous when an RF payload is involved. More savings in mission cost are achieved due to the impact of the payload size on the satellite and on the launch cost. The main problem of flying at such altitudes is the orbital rapid loss of energy due to the drag. This is compensated for by a fuel efficient Hall Effect electrical thruster, and by proper low-drag configuration design. The electrical thruster's high specific impulse (of about 1350 sec. in our case) can provide the microsatellite with several years of mission duration at the low altitude, using acceptable amount of Xenon propellant. This concept is scheduled to be demonstrated in the Israeli - French VENμS (Vegetation and Environment New μSatellite) program. The VENμS mission is composed of two portionsa scientific one and a technological one. The scientific mission consists of multispectral Earth monitoring for vegetation and water resources quality, from a Sun-Synchronous 2-day Earth repeating circular orbit, with a mean altitude of 720 km. The technological mission has several goals, one of which is to simulate a satellite flying in a high drag environment and performing an enhanced mission. In the VENμS program the enhanced mission is the same scientific mission mentioned before, only that it is carried out at a mean altitude of 410 km, thus providing a spatial resolution almost twice as good, while maintaining the 2-day repeating ground track. The required orbit corrections do not interfere with the Earth monitoring task. The VENμS platform, not designed to fly at high air density environment, has over 2.7 m2 average cross section area to the wind. Its mission at 410 km represents a mission at much lower altitude (less than 300 km) of a different microsatellite, configured especially for high drag environment. The paper describes the low altitude microsatellite concept and analysis, the VENμS mission with emphasis on its technological portions, and the Israeli Hall Effect thruster which is especially designed to be used by small satellites. Main design issues, such as electrical power supply and environment disturbances, are also addressed.

Micro Satellite Bus for Stand-alone Earth Imaging / Space Science Payloads (2006-Session 4)[36] ISRO has launched series of satellites for Earth Imaging for natural resource applications. These applications are being served by various large satellites. Some of the payloads with required swaths & resolutions, which can serve the applications separately in the areas of agriculture, forestry, geology, water resources, land-use, infrastructure build-up, pollution monitoring etc., can be launched on small or micro satellites on stand-alone basis. With the experience of design, development, fabrication and on-orbit operation of earth imaging satellites from IRS-1A to Cartosat-1, the small/micro satellites are planned with advanced technology. The small satellite project is envisaged to provide platform for stand-alone payloads for earth imaging and science missions. The current paper focuses on the first satellite. The satellite is a three axis stabilized bus with two deployed solar panels. The bus carries a miniature dual head star sensor, four micro reaction wheels and micro gyros. The bus can operate in sun-pointing and earth pointing modes and provides good attitude pointing and stability. The details of mission, configuration, and the bus capability details are presented.

VENμS Program: Broad and New Horizons for Super-Spectral Imaging and Electric Propulsion Missions for a Small Satellite (2008- Session 3)[37] Vegetation and Environment New Micro Satellite (Venμs) is a joint venture of the Israeli and French space agencies for development, production, launching, and operating a new space system. Venμs is a Low Earth Orbit (LEO) small satellite for scientific and technological purposes. The scientific mission includes vegetation monitoring and water quality assessment over coastal zones and inland water bodies. It will be specifically suitable for precision agriculture tasks such as site-specific management and/or decision support systems. For this purpose the satellite has apparatus for high spatial resolution (5.3 m) and for high spectral resolution (12 spectral bands in the visible and near infrared wavelengths), as well as orbit for high temporal resolution (2 days revisit time). The satellite's orbit is a near polar sun-synchronous orbit at 720 km height. The satellite will acquire images of sites of interest all around the world. The satellite will be able to be tilted up to 30 degree along and across track; however, each site will be observed under a constant view angle. The technological mission consists of space verification and validation by mission enhancement capability demonstration of a newly developed Israeli Hall Effect Thruster (IHET) system, used as a payload. IHET is developed and manufactured by Rafael and this will be its maiden flight. The heart of the IHET is the HET-300 thruster, which produces about 15 mN thrust, operating at 300W anodic power. This thruster and the based-on Electrical Propulsion System (EPS), is specifically developed for usage onboard micro or small satellites, which can supply as little as 300 to 600 watts for operation. The technological mission will be targeted to qualify the IHET in space as well as validate it by demonstrating orbit transfer and strict orbit keeping in a high drag environment. The Venμs satellite is currently in manufacturing phase, its launch weight is 260 kg, and it is planned to be launched in 2010. This paper will present Venμs system with emphasis on the two main missions (scientific and technological) of Venμs and the respective payloads along with main design considerations of the electrical propulsion system.

MISC – A Novel Approach to Low-Cost Imaging Satellites (2008- Session 10)[38] By severely limiting satellite size and weight, the popular CubeSat nanosatellite standard realizes noticeable cost savings over traditional satellites in the areas of design, manufacture, launch and operations. To date, there has been limited commercial utilization of CubeSat systems due to the widespread perception in industry that a 10 cm x 10 cm x 30 cm form factor is too constrained for payloads in support of useful missions. In this paper, we argue against this perception by presenting MISC, a 3U CubeSat capable of providing 7.5 m GSD multispectral imagery from a circular orbit of 540 km. Over an anticipated operational lifetime of 18 months, each MISC will be able to image over 75 million km2, equivalent to approximately half the Earth's landmass. MISC's novel design combines a robust miniature imager module payload with an existing CubeSat Kit-based bus and a distributed ground station architecture. With anticipated order-of-magnitude cost savings when compared to current commercial offerings, MISC's lifetime system cost should represent an extremely attractive proposition to consumers of satellite imagery that wish to own and operate their own assets. MISC satellites will be available for commercial purchase in mid-2009.

TINYSCOPE: The Feasibility of a 3-Axis Stabilized Earth Imaging CubeSat from LEO (2008-Session 10)[39] The idea of a nano-sat for tactical imaging applications from LEO is explored. On the battlefield, not every tactical situation requires something as high-tech as an FA-18 dropping a GPS-guided weapon within a couple of meters of the target to get the desired results - sometimes a grenade or a mortar will do the trick. In the same way, a nano-sat imaging from LEO may be a better solution than a national imaging asset for some applications. These spacecraft may be used as short-term low-cost independent elements, for instance; or perhaps in support of traditional large imaging space systems as free-flying "targeting telescopes". They may also be deployed as elements of a LEO constellation or cluster (think swarm), which would allow for quick re-targeting opportunities over a large portion of the Earth. Tactical Imaging Nano-sat Yielding Small-Cost Operations and Persistent Earth-coverage (TINYSCOPE) is a preliminary investigation using analytical modeling and laboratory experimentation to determine the potential performance and the feasibility of using a 5-U CubeSat as an imager. Emphasis is placed on three-axis attitude stabilization and slewing (for target acquisition and tracking) and performance of various optics hardware configurations. Numerical simulations will be conducted to support the study, in particular on spacecraft dynamics and control.

WNISAT - Nanosatellite for North Arctic Routes and Atmosphere Monitoring (2010 - Session 2)[40] WNISAT is a 10kg weight nanosatellite of the sun-synchronous low earth orbit, currently being developed by Weathernews Inc. and AXELSPACE, and waiting for the launch with PSLV of India until the year of 2011. Weathernews Inc. is the largest private weather service company headquartered in Japan, which have many sea liners as their customers. Currently, the north arctic ice region reaches the lowest level every year, and sea liners have great interest for this because the north arctic routes means very short distance compare to other routes. Many approaches have been suggested for the monitoring of north arctic routes, and constellation of small satellites is one of the best ways considering efficiency. From this reason, Weathernews Inc, decided to develop small satellites in close collaboration with AXELSPACE. AXELSPACE is a university venture company established in 2008, all engineers have considerable experience in the field of small satellites of nano-class through many projects of their universities. There are two major missions for WNISAT, the first mission is earth observation of commercial use as like explained already. It is challenging to provide with the ice coverage information over high latitude oceans including NIR spectral ranges. And the second mission is atmosphere monitoring for environmental issue, the density of carbon dioxide in atmosphere using a laser application. The bus system of spacecraft and the first mission development are being led by AXELSPACE. The laser application for the second mission is under development by Weathernews Inc. The object of this WNISAT is to show the feasibility of nanosatellite for two major missions, especially the commercial use of small satellites of nano-class. After this WNISAT, several satellites are scheduled for the practical and commercial use within three or five years. At first, this paper will review progress in the development of WNISAT. And, the entire structure of spacecraft and the sub-systems are presented for the review and the detail explanation. After that, it will review the relevance of WNISAT's technology to advanced sensing concepts, reliable and efficient remote sensing and issues of atmospheric carbon dioxide content monitoring. Finally, future schedule after WNISAT is also briefly presented.

NovaSAR: Bringing Radar Capability to the Disaster Monitoring Constellation (2012-Session 1)[41] Small satellites are playing an increasing role in addressing applications in Earth Observation for scientific, civil and military applications. With all optical systems, this leads to some obvious limitations to the time of day targets can be imaged, which geographic latitudes can be covered, and to a dependency on cloud cover. For some applications this limits the utility of space systems unless low-light and through-cloud imaging information can be obtained in a timely fashion by other cost-effective means. Typically, space based radar systems are significantly more complex, more expensive, and data is more difficult to utilise than equivalent optical systems. Existing radar satellite systems therefore predominantly address scientific and military needs, leaving room for smallsat systems that address commercial needs, maritime security, and disaster monitoring. Advances in new technologies now have permitted a step performance improvement in radar systems, which will now be implemented in the NovaSAR mission which is under construction at SSTL. Gallium Nitride RF transistors enable high efficiency power amplifiers to be employed, reducing the power demand from solar panels, thus enabling a smaller radar satellite to be constructed. System innovations are also included to facilitate satellite operation in constellations, and in orbits other than the traditional dawn-dusk orbits. The spacecraft will also include an operational mode to operate in a maritime detection mode instead of imaging mode. In November 2011 the UK government announced that they are investing in the first satellite in a NovaSAR radar constellation, allowing the construction of the first 400kg satellite to commence to be ready for launch in 2014. This paper will provide details on the satellite and payload design trades, results from airborne trials of the payload, and provides an overview of the planned mission applications.

Commissioning of the NigeriaSat-2 High Resolution Imaging Mission (2012- Session 11)[42] The manufacture of the NigeriaSat-2 spacecraft was completed in 2010, and was successfully launched in August 2011. This is a state-of-the-art small satellite Earth observation mission including several innovations not previously seen on small spacecraft, which will provide high duty cycle imaging of the Earth in high resolution. It will be used by the Nigerian government for mapping and to monitor a number of environmental issues within the country. The key requirements of this mission are to provide high volume mapping data, coupled with highly accurate image targeting and geolocation, and sufficient agility to enable a wide range of complex operational modes. This paper focuses on the challenges associated with designing a spacecraft system that can meet these requirements on a satellite with a mass of less than 270kg. The paper will describe how the stereo, mosaic and other imaging modes can be employed using the agility of the spacecraft. Inertia calibration and on-board navigation techniques used to give the required targeting accuracy are discussed, and the interaction between the attitude control system and the mechanical design is detailed. The payload isolation system used to ensure image quality and geolocation performance is also described. An overview of the final test and launch campaign, and first in-orbit results from the satellite commissioning are provided.

2.10 Pinpointing the Source of Gamma Ray Bursts

2.10.1 Mission Concept

The formation could be used to source GRBs through precise triangulation. If we could get the measurements of inter-satellite distance and GRB incident time accurately enough, we could potentially increase the accuracy of GRB detection and positioning.

2.10.2 Abstract

The Space System for the High Energy Transient Experiment (1992-Session 2)[43] The High Energy Transient Experiment (HETE) is an astrophysics project funded by NASA and led by the Center for Space Research (CSR) at the Massachusetts Institute of Technology (MIT). It has for principal goal the detection and precise localization of the still mysterious sources of gamma ray bursts. The project is original in many respects. HETE will provide simultaneous observations of bursts in the gamma, X-ray and UV ranges from the same small (250 Ibms) space platform. A network of ground stations around the world will diffuse in real time key information derived from HETE observations to many ground observatories, allowing quick follow-on observations with ground instruments. The whole project is entirely managed by MIT, under top level NASA supervision, and satellite and ground stations will be remotely operated from CSA. The HETE system development is conducted with a small budget and under a short schedule.

2.11 Observing Gamma Rays Emitted by Thunderstorms

2.11.1 Mission Concept

Look for gamma rays emitted by thunderstorms. NASA's Fermi telescope has observed the phenomenon, but it could possibly do with more study and happen in conjunction with the GRB monitoring. [http://www.nasa.gov/mission_pages/GLAST/news/fermi-thunderstorms.html]

2.11.2 Abstract

A Small/ Micro/ Pico Sat Program for Investigating Thunderstorm- Related Atmospheric Phenomena (1998- Session 7)[44] A low cost, multi-satellite program for conducting novel atmospheric science is described. The program exploits simple visual and radio frequency sensing in order to investigate atmospheric phenomena induced by thunderstorms. The science instrumentation is supported by a variety of standalone and collaborative small, micro-, and picosatellite vehicles in order to meet the program's science requirements while also exploring a spectrum of small satellite approaches for conducting meaningful science. This multi-mission program is being developed jointly by student design teams at Stanford University and Santa Clara University.

2.12 Tracking Asteroids and Satellite Debris

2.12.1 Mission Concept

Search for Earth-Approaching Asteroids and potentially hazardous debris satellites. Could act as a guard dog for the ISS.

2.12.2 Abstract

NESS: Using a Microsat to Search for and Track Satellites and Asteroids (2000- Session 2)[45] The Near Earth Space Surveillance (NESS) mission is being developed by Dynacon and a team of asteroid scientists, supported by the Canadian Space Agency (CSA) and the Canadian Department of National Defence (DND). NESS uses a single satellite to perform a dual mission: searching for an tracking Earth-approaching asteroids, and tracking satellites in Earth orbit. There are aspects of both of these activities that are best accomplished using an orbiting observatory. The concept presented here is to implement NESS using a small imaging telescope mounted on a lowcost microsatellite-class platform, based on the design developed for the MOST stellar photometry microsatellite mission.

Space-Based Radar to Observe Space Debris (1998- Session 12)[46] Space debris of 1÷3mm size is known to be hazardous for astronauts and space vehicles. At the same time the possibility to notice such objects by ground based optical and radar devices in the nearest future is rather problematic. Here we propose an idea of space radar for observation of cicumterrestrial space debris. The radar works in short wave part of millimetre band, which is mostly suitable for this purpose. The radar provides detecting and tracking of 1mm size objects within 40000m2 area. The radar antenna is Phased Array Antenna with 2m diameter. The radar's weight is about 100kg, the consumed power - 2.5kW.

How Can Small Satellites be used to Support Orbital Debris Removal Goals Instead of Increasing the Problem? (2010- Session 2)[47] Orbital debris is a serious concern for the NASA, DARPA, Air Force organizations and the commercial space industry. Since 2005, the space debris environment has been unstable and began a collision cascade effect per NASA. A recent International Orbital Debris Conference focused on the need to find solutions for Orbital Debris Removal and manage any space debris increase potential. The purpose of this paper is to explore what orbital debris issues can be address by Small Satellites. The paper will discuss a technology supported by Small Satellites to resolve the Orbital Debris problem. It will concentrate on mitigation of debris sizes from 1cm to 10cm, which are unable to be tracked by current ground systems capabilities but can cause serious damage or destroy spacecraft. Requirements will be for the LEO orbit, where there are known significant numbers of debris of this size. A Method will be proposed, by which a small spacecraft can be used to sweep volumes of specific orbits to remove or collect debris.

Sapphire: A Small Satellite System for the Surveillance of Space (2010- Session 2)[48] The tracking of man-made objects in Earth orbit is a crucial function of the Canadian Space Surveillance System (CSSS). This system will contribute information to the United States Space Surveillance Network (SSN) which maintains a global catalog of orbit elements for Resident Space Objects (RSOs). RSOs include active and inactive satellites, spent rocket bodies, and other pieces of orbital debris created by decades of human activity in space. Sapphire is a small satellite system that will form the centerpiece of the CSSS, providing an operationally flexible space-based platform for the precise tracking and identification of RSOs covering orbit altitudes in the range from 6000 km to 40000 km. The Sapphire system, including a satellite, ground segment, launch, and operations, is currently being developed by MDA for the Canadian Department of National Defence (DND), with satellite launch scheduled for 2011. This paper describes the Sapphire design. Sapphire must meet demanding performance requirements for RSO detection and pointing determination accuracy as well as system responsiveness and imaging task throughput. Sapphire will provide continuous service over a mission life of at least five years. The paper discusses the approaches used to build a robust capability into a small satellite package, including the extensive use of flight-proven heritage in the satellite subsystems. In addition, the paper discusses the role of the satellite with respect to the ground system elements and summarizes some of the major system-level tradeoffs from the design process.

2.13 Monitoring Atmospheric Plasma Depletion to Predict Outages in GPS and Communications

2.13.1 Mission Concept

Depletion in ionospheric plasma can disrupt signal transferrance, and not much is known about the depletion zones. The formation would study how the depletions change and propagate so that scientists can create a model and further their understanding of the phenomenon.

2.13.2 Abstract

Target of Opportuinty Multipoint in Situ Measurements with Falconsat-2 (2002- Session 9)[49] This paper describes the FalconSAT-2 mission objectives to take advantage of targets of opportunity to make multipoint in situ measurements of ionospheric plasma depletions simultaneously with other spacecraft. Because these plasma depletions are known to interfere with radio transmissions over a broad range of frequencies, including 100-1000 MHz, the international space weather community is investigating the instigation, temporal evolution, and spatial propagation of these structures in the hopes that a prediction tool may be developed to warn operators of outages in communications or navigation. FalconSAT-2 will be launched into a low altitude (360 km), medium inclination (52 degrees) orbit with sensors designed to measure in situ suprathermal plasma spectra at a rate of 10 samples per second. The primary mission objectives are to 1) investigate F region ionospheric plasma depletion morphology relative to geomagnetic activity, and 2) demonstrate the utility of the Miniature Electrostatic Analyzer (MESA) in measuring energy-resolved spectra of ionospheric electrons over a dynamic range such that plasma density depletions down to 0.1% of the background may be resolved at a rate of 10 Hz. Simultaneous in situ multipoint observations of ionospheric plasma depletions are designated as a secondary objective since FalconSAT-2 consists of a single spacecraft, and opportunities to make these simultaneous measurements with other spacecraft in compatible orbits are not in our control. Both deep and shallow bubbles, frequently observed in the pre- and post-midnight sectors, respectively [Singh at al., 1997], are known to exhibit magnetic field-aligned behavior [Fagundes et al., 1997]; thus, there is the expectation (to first order) that multiple spacecraft entering a magnetic flux tube simultaneously have the opportunity to observe a depletion structure at different points within the structure. This observation would provide insight into the plasma depletion extent along the field line. Other conjunction types, such as non-simultaneous intersection of a flux tube or crossing of orbital paths simultaneously in different magnetic flux tubes, provide insight into other aspects of depletion structure, such as constraining the plasma depletion extent and propagation speed along the magnetic field line, or plasma depletion vertical extent. With this paper, a statistical analysis of the probability that FalconSAT-2 will intersect a magnetic flux tube during eclipse simultaneously with other spacecraft capable of measuring thermal electrons is presented.

Low-Resource CubeSat-scale Sensorcraft for Auroral and Ionospheric Plasma Studies (2010- Session 1)[50] Explicitly separating variations in space from variations in time over a large volume is a current unmet challenge for in situ studies of the ionosphere and aurora. We propose that arrays of many (_ 10) low-resource sensorcraft can address this scientific and technical challenge. We are developing a suborbital CubeSat, RocketCube, to enable low-cost multipoint measurements for orbital and sub-orbital scientific missions. The graduate student-designed RocketCube showcases a new scientific instrument, the Petite Ion Probe (PIP), and an FPGA-based instrumentation and payload bus system designed specifically with the ionosphere in mind. The PIP, a retarding potential analyzer, measures thermal plasma parameters to characterize the ionosphere. In addition to control and data handling, RocketCube's bus system will allow synchronization of PIP activity between payloads in an array to the order of _1 μs from timing provided by a qualified GPS. As of this writing (June 2010), RocketCube may be repackaged and manifested as a deployable subpayload on the Cornell University MICA (Magnetosphere-Ionosphere Coupling in the Alfvn Resonator) mission scheduled for a winter 2012 sounding rocket launch. Additionally, RocketCube is enabling us to be currently proposing our next scientific sounding rocket mission, called Probe Array Lattice to Investigate Spatial Auroral DEnsity Structuring (Palisades), to NASA's G/LCAS (Geospace Low Cost Access to Space) program. Palisades will feature an array of 12 subpayloads containing our bus system and two PIPs per payload to study the auroral driving of the ionosphere. This paper provides an overview of RocketCube's purpose, design, and current status including details of the PIP instrument.

Sensitivity of Ionospheric Specifications to In Situ Plasma Density Observations Obtained From Electrostatic Analyzers Onboard of a Constellation of Small Satellites (2012- Session 4)[51] Our ability to specify and forecast ionospheric dynamics and weather at low- and mid-latitudes is strongly limited by our current understanding of the coupling processes in the ionosphere-thermosphere system and the coupling between the high and low latitude regions. Furthermore only a limited number of observations are available for a specification of ionospheric dynamics and weather at these latitudes. As shown by meteorologists and oceanographers, the best specification and weather models are physics-based data assimilation models that combine the observational data with our understanding of the physics of the environment. Through simulation experiments these models can also be used to study the sensitivity of the specification accuracy on different arrangements of observation platforms and observation geometries and can provide important information for the planning of future missions. For example, these studies can provide information about the number of spacecraft needed to improve the specification or evaluate the impact of different observation geometries on the accuracy of the specification. Here we have used the Global Assimilation of Ionospheric Measurements Full-Physics model (GAIM-FP) to study the sensitivity of ionospheric specifications on in situ plasma density observations obtained from electrostatic analyzers (ESA) onboard of a constellation of small satellites. The model is based on an Ensemble Kalman filter technique and a physics-based model of the ionosphere/plasmasphere (IPM), which covers the altitude range from 90 to 20,000 km. The data assimilation model can, in addition to the ESA observations, assimilate bottom-side Ne profiles from ionosondes, slant TEC from ground-based GPS stations, in situ Ne from DMSP satellites, occultation data from several satellites, and line-of-sight UV emissions measured by satellites. Simulation studies have been performed using various ESA constellation arrangements and their impact on the ionospheric specification has been evaluated. The results from this study will be presented with an emphasis on the number of satellites and their orbital geometries needed to improve ionospheric specifications and forecasts.

2.14 Space-Based Ocean Monitoring

2.14.1 Mission Concept

Monitor the health of the oceans, rivers, lakes, etc, through multi-spectral imaging. Better understand the effects of tides on ocean color. The mission described is extremely aggressive, ours would be much much smaller.

2.14.2 Abstract

'Charybdis' – The Next Generation in Ocean Colour and Biogeochemical Remote Sensing (2012- Session 4)[52] Within the field of Space-based Maritime observation, there exists an opportunity in the form of high spatial, high temporal resolution multi-spectral imaging to map coastal and inland waterway colour and biogeochemistry. Information provided would help environmental agencies and the scientific community to better understand patterns and evolution of ecological systems, sediment suspension in river estuaries and the effects of anthropogenic processes on our water systems. In addition, monitoring of these colour patterns with respect to the well understood tidal sequence would provide significant benefits to our understanding of the way in which tidal forcing affects ocean colour. This paper describes the astrodynamic properties of a tidal-synchronous satellite trajectory and the system-level design of a multi-platform CubeSat constellation capable of high resolution, multispectral imaging. The constellation, named 'Charybdis', is envisaged to be dedicated to providing unprecedented levels of data (high temporal and spatial resolution) of coastal regions and inland waterway colour and biogeochemistry. Analyses of two alternative missions are presented; one providing bi-hourly, global coverage from 115 nanosatellites and a second providing bi-hourly regional coverage over the UK mainland from 30 nanosatellites.

2.15 Interferometry and Synthetic Aperture Radar Formation Flying

2.15.1 Mission Concept

A formation of >2 CubeSats will work together to create a digital terrain model

2.15.2 Abstract

Possible Orbit Scenarios for an InSAR Formation Flying Microsatellite Mission (2008- Session 6)[53] Multistatic interferometric synthetic aperture radar (InSAR) is a promising future payload for a small satellite constellation, providing a low-cost means of augmenting proven "large" SAR mission technology. The Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies is currently designing CanX-4 and CanX-5, a pair of formation-flying nanosatellites slated for launch in 2009. Once formation flight has been demonstrated, a future multistatic InSAR formation-flying constellation can exploit sub-centimeter inter-satellite baseline knowledge for interferometric measurements, which can be used for a myriad of applications including surface deformation, digital terrain modeling, and moving target detection. This study evaluates two commonly proposed InSAR constellation configurations, namely the Cartwheel and the Cross-Track Pendulum, and considers two 'large' (~kilowatt) SAR transmitters (C- and X-band) and one microsatellite transmitter (X-band, 150W). Each case is evaluated and assessed with respect to the available interferometric baselines and ground coverage. The microsatellite X-band transmitter is found to be technically feasible, although the lower available transmitter power limits the operating range. The selected transmit band determines the maximum allowable cross-track baseline between receiver satellites in the constellation. Additionally, the Cartwheel and Cross-Track Pendulum configurations offer different available baselines and ground coverage patterns, namely, the Cartwheel eliminates the near-zero cross-track baseline component that contributes to DEM height errors but adds a coupled along-track baseline, while the Cross-Track Pendulum offers the advantage of independent cross-track and along-track baseline components. Ultimately, the primary application for the InSAR data will dictate the transmit band used, the desired baselines, and the receiver constellation configuration.

WiSAR: A New Solution for High-Performance, Smallsat-Based Synthetic Aperture Radar Missions (2008- Session 6)[54] To date, high performance Synthetic Aperture Radar (SAR) satellites have typically featured massive power generation, storage and distribution subsystems, together with complex, heavy and rigid deployable SAR antenna structures. The result is an expensive, heavy satellite. MDA's Wireless Synthetic Aperture Radar (WiSAR) is a new SAR payload design that offers leading-edge performance in both X- and C-band at a significantly lower cost than the conventional state of the art. The key technology breakthrough is a modular, low mass phased array antenna technology that enables high performance multi-mode SAR imaging from a smallsat platform. The WiSAR solution uses proven off-the-shelf technologies from the automotive and terrestrial wireless communication industries to enable an innovative space-fed active lens architecture that replaces the heavier and bulkier constrained feed design of traditional high performance SAR payloads. Key elements of the WiSAR payload include: self-contained active antenna nodes; low cost RF radiators; thin, lightweight, easily deployed antenna panels; and RF ranging for dynamic antenna distortion compensation. This paper describes the WiSAR™ payload technology in various configurations; a High Resolution X-Band Smallsat SAR, a Dual Aperture X-Band GMTI SAR, a High Performance C-Band SAR, and a C-Band Smallsat SAThe results of a project to build, test and operate a fully functioning C-band prototype WiSAR phased array antenna are presented, along with current developments in X-Band.

2.16 Testing Satellite Tether Deployment and Operations

2.16.1 Mission Concept

Hardware test for satellite tether, can be used to create artificial gravity to aide in long term human missions.

2.16.2 Abstract

The Kyushu/US Experimental Satellite Tether (QUEST) Mission, A Small Satellite to Test and Validate Spacecraft Tether Deployment and Operations (2000- Session 7)[55] In recent years, an increased effort to design, build, and operate small satellites has taken place in universities and laboratories all over the world. These microsatellites provide numerous flight opportunities for science experiments at a fraction of the cost of larger traditional missions. In addition, there has been an increasing trend towards international cooperation on space projects. From the International Space Station to joint commercial ventures, the future of space progress will be shared by countries around the world. Tomorrow's engineers must prepare for this challenge. This paper provides an overview of the Kyushu/US Experimental Satellite Tether (QUEST) mission, a joint project between Kyushu University (KU), Arizona State University (ASU), and Santa Clara University (SCU). This mission will develop and test new technologies related to space tether deployment and operation. In particular, it will attempt to show very small space platforms can be used for significant tether deployments. If successful, it will provide valuable data for tether designers as well as cost and weight savings on future missions. In addition, progress on system design, ground station development, orbital simulations and related testing are reviewed.

A Small-Satellite Demonstrator for Generating Artificial Gravity in Space via a Tethered System (2002- Session 3)[56] It is well-known that prolonged exposure in humans to a microgravity environment leads to significant loss of bone and muscle mass; this presents a formidable obstacle to human exploration of space, particularly for missions requiring travel times of several months or more, such as a 6 to 9mon th trip to Mars. Artificial gravity may be produced by spinning a spacecraft about its center of mass, but since the g– force generated by rotation is equal to "omega-squared times r" (where omega is its angular velocity and r is the distance from the center of rotation), we have that unless the distance from the center of rotation is several kilometers, the rotation rate required to generate "1 - g" would induce vertigo in the astronauts as they moved about the capsule (e.g. if the distance from the center of rotation is 10 meters, the required rotation rate for 1 - g would be 9.5 rpm). By tethering the crew capsule to an object of nearly equal mass (such as the spent final rocket stage) at a distance of 1 to 2 kilometers, the necessary rotation rate would be sufficiently small as to not cause discomfort for the astronauts. For example, if the distance from the center of rotation is 2 kilometers, the required rotation rate for 1-g would be 0.67 rpm; at 1 kilometer the rate is still only 0.95 rpm. 1 rpm is considered an acceptable spin rate for the human body to withstand for extended periods of time. This paper gives an overview of the Tethered Artificial Gravity (TAG) satellite program, a 2-part program to study the operation and dynamics of an artificial-gravity-generating tethered satellite system. Phase I of the program will culminate in a flight of a model spacecraft in a non-ejected Get-Away-Special (GAS) Canister on the Space Shuttle. It is to be operated under the aegis of the Texas Space Grant Consortium. The purpose of the Phase I flight is to test key components of the system to be flown in Phase II of the program. Phase I will also involve detailed modeling and analysis of the dynamics of the spacecraft to be flown in Phase II of the program; the Phase II spacecraft will be a small, 65 kg, tethered satellite system which will be boosted into low-earth orbit, deployed and then spun-up to produce artificial gravity. In addition to a description of the TAG program, results of parametric studies related to TAG will be presented in this paper.

2.17 Studying Sub-dwarf Stars Using a Small Telescope

2.17.1 Mission Concept

Use the satellites to study distant sub-dwarf stars. Formation seems unnecessary.

2.17.2 Abstract

MOST- Microsat Mission: Canada's First Space Telescope (1998- Session 6)[57] The MOST (Microvariability and Oscillations of STars) astronomy mission has been chosen by the Canadian Space Agency's Small Payloads Program to be Canada's first space science microsatellite, and is currently planned for launch in late 2001. The MOST science team will use the MOST satellite to conduct long-duration stellar photometry observations in space. A major science goal is to set a lower limit on the age of several nearby "metal-poor sub-dwarf" stars, which may in turn allow a lower limit to be set on the age of the Universe. To make these measurements, MOST will incorporate a small (15 cm aperture), high-photometric-precision optical telescope to be developed by UBC. The MOST bus and ground stations are being developed by Dynacon and the University of Toronto, in collaboration with AMSAT Canada. Several of the bus subsystems are based on similar designs that have been flown on past AMSAT microsatellites. However, the MOST attitude control system is unusual for a microsatellite, requiring highly-accurate (<30 arc-seconds) three-axis inertially-fixed stabilization, far better than can be achieved using the gravity-gradient boom stabilization approach typical of many past microsatellites. Dynacon will provide the MOST ACS, based on its Miniature Reaction Wheel (MRW) and High Performance Attitude Control (HPAC) products. MOST's HPAC capability will enable it to be one of the first operational space science microsatellites.

DISC Experiment Overview and On-Orbit Performance Results (2012- Session 11)[58] The Digital Imaging Star Camera (DISC) experiment has successfully imaged star fields from the International Space Station (ISS). DISC is a Naval Research Laboratory (NRL) led payload developed jointly by NRL and the Utah State University Space Dynamics Laboratory (SDL) to advance miniaturized technology for accurate precision pointing knowledge in space which is a critical mission requirement for many scientific and operational payloads. The low size, weight and power (<10x10x10 >cm, <1kg, <1 W) sensing platform that will provide an enhanced pointing capability for nano- and pico- satellite busses. It is flying on the ISS as part of the Air Force Space Test Program STP-H3 flight to provide a proof of concept for DISC experiment. This technology represents a key transition from large, high cost, long-timescale programs to small, low-cost, rapid response science enabling sensing platforms. This paper will focus on the instrument design and on-orbit mission performance.

2.18 Completing the Map of the Earth's Electric Field

2.18.1 Mission Concept

This project would use a system of small satellites to observe the Earth's electric field with radar measurements. It would appear that other systems already make these measurements, but there are still areas of poor coverage that could be addressed as given here.

2.18.2 Abstract

Microspacecraft and Earth Observation: The Electrical Field Measurement Project (1990- Session 8)[59] Past attempts to map the earth's electrical field have been severely limited by the lack of simultaneous global measurements. Previous measurements have been made by sounding rocket and satellite borne sensors, but these measurements have covered only singular points in the field. These satellite observations are augmented by ground radar (incoherent scatter) plasma drift measurements; however, only six ground-based installations are producing such local electrical field maps. The expansion of this ground-based radar network to meet a global objective is politically and financially impossible. Global electrical field maps constructed by forcing mathematically formulated models to fit this limited set of data points are not only inaccurate, but the degree of inaccuracy is impossible to evaluate. This paper discusses the design of a global electrical field sensing system to be deployed in a constellation of microspacecraft. Each microspacecraft incorporates a deployable sensor array (5 m booms) into a spinning oblate platform. Global deployment of 48 spacecraft is achieved through perturbation-driven dispersion of multiple spacecraft launched from eight Pegasus launch vehicles. The mass of each spacecraft is less than 25 kg, and the power requirements are less than 10 W; all the required power can be generated by solar cells covering the exterior of the spacecraft. The program costs are estimated to be less than $100 million.

2.19 Raman Spectroscopy to investigate the atmosphere

2.19.1 Mission Concept

Create a more in-depth model of the upper atmosphere using Raman Spectroscopy from multiple sources in a formation to achieve a 3D (or at least more comprehensive) map. The main obstacle here would be finding a detector array that would fit in our size constraints.

2.19.2 Abstract:

Raman Spectroscopy to investigate the atmosphere (1988- Session 3)[60] Raman Spectroscopy is an active remote sensing method that can map planetary mineral and chemical abundances and their distributions. Raman spectroscopy can also be used to study the chemical composition of various planetary atmospheres. The remote raman technique utilizes a low power laser to stimulate raman scattering at the substance and a spectrometer receives the returned raman spectrum at the spacecraft. The returned spectrum contains the shifts in frequency, shifted from that of the incident laser light, that are characteristic of the substance. The intensity of the raman spectrum lines is proportional to the amount of the substance present. Thus, with raman spectral information, the identification of a substance and an estimate of its volumetric concentrations can be achieved. The baseline remote raman instrument system utilizes a 10 W krypton laser and a RIRIS spectrally sensitive detector array, cassegran optics, has a mass of 200 Kg, and consumes

1 KW of electrical power. This paper explores the basic concepts of remote raman spectroscopy and postulates an instrument package that is compatible with the mass and size constraints of a small satellite. Various solar system exploratory missions using raman spectroscopy are discussed including the study of the surface of the moon, Earth's upper atmosphere, the atmosphere of Mars, the atmosphere of Jupiter, and the rings of Saturn.

2.20 Formation Flying to Sample Volume of Magnetosphere

2.20.1 Mission Concept

Use the formation of cubesats to create a more detailed 3D model of the magnetosphere. This may not be necessary because of the twin satellites launched by NASA in Fall 2012. Also several earlier missions acheived similar results, not using formations but I doubt the information is still needed. [http://www.ucl.ac.uk/news/news-articles/1009/10090204]

2.20.2 Abstract

Picosat Free Flying Magnetometer Experiment (1996- Session 2)[61] Individual satellites have been measuring the Earth's magnetic field since 1958. Measurements taken in this way have led to some interesting discoveries about the earth's magnetosphere. However, they have also raised many questions about the magnetosphere's finer texture and dynamic nature. Researchers at JPL have proposed a mission where a single larger satellite ejects several picosatellites in order to simultaneously sample a volume of space. Each picosat is to carry a small, two axis, fluxgate magnetometer, several photo detectors for spin rate detection, a micro processor and a high frequency transmitter. After launch from the main satellite, each picosat will transmit its sensor readings back to the main satellite where the data will be stored for retrieval. Issues addressed in this paper are related to the design, manufacture, and planned flight test of the picosatellite on OPAL, a Stanford University Student Spacecraft

2.21 Formation Flying Educational Platform

2.21.1 Mission Concept

This is essentially what we are doing. We would test out our formation flying algorithms, then open the platform to outside universities or scientists to test their algorithms.

2.21.2 Abstract

Design of Small Satellite for Use in Astronautics Education (1988- Session 2)[62] The Naval Academy is pursuing a small satellite project to give midshipmen hardware and ground control experience. The concept is for a lightweight, gravity-gradient stabilized satellite to be deployed from a Get Away Special cannister; the payload would be two small, low-resolution imagers (one visible and one infrared). The 40 foot diameter ground station antenna being installed at the Naval Academy can receive a power of 10 milliwatts from a satellite that uses an omnidirectional antenna and is in a typical Space Shuttle orbit. Approximately 5 to 7 watts of power is constantly available to the payload of up to 10.4 Ib (4.7 kg). Thermal control is largely passive, but some heating will be required during the longest eclipses. Once in orbit, the spacecraft would be used in astronautics courses for such assignments as orbit determination, decoding telemetry, and processing images.

2.22 Conclusions

Formation Flight CubeSats are capable of great contributions to science and technology as:

1. To avoid spacial and temporal ambiguities
    - Multipoint measurement of plasma density
    - Multipoint measurement of electric y magnetic fields (geomagnetic storms)
    - Multipoint measurement of proton and electron fluxes
    - Planetary Atmospheric espectroscopy
2. Earth monitoring (a constellation should be enough)
    - Agriculture and vegetation management
    - Weather prediction models
    - Oceanographye
    - Disasters assesment
    - Measurements of compounds on the atmosphere
    - Pollution
    - CO_2 or H_2O cycle (or any other compound)
    - Doppler sensing of winds
    - Temperature sensing
3. Testbed for mobile phone electronics for satellite intercommunications or satellite-ground communications
4. To carry a web and remove space junk
5. To maneuver with solar sails
6. To explore asteroids (spider cubesat swarm, could be the basis to industrialize asteroids)
7. Automated 3D mapping (google maps or any other applications)
8. Observation of gravitational waves
9. Interferometry
    - Exoplanet detection
    - Infrared telescopes
    - Gamma-ray telescopes
    - X-ray telescopes
    - Visual spectrum telescopes
    - Radio Telescopes

3 Actuators and Sensors

Below are attached the images that have been found regarding this. They are taken from the presentations given by J. Mueller and Matt Bennett.

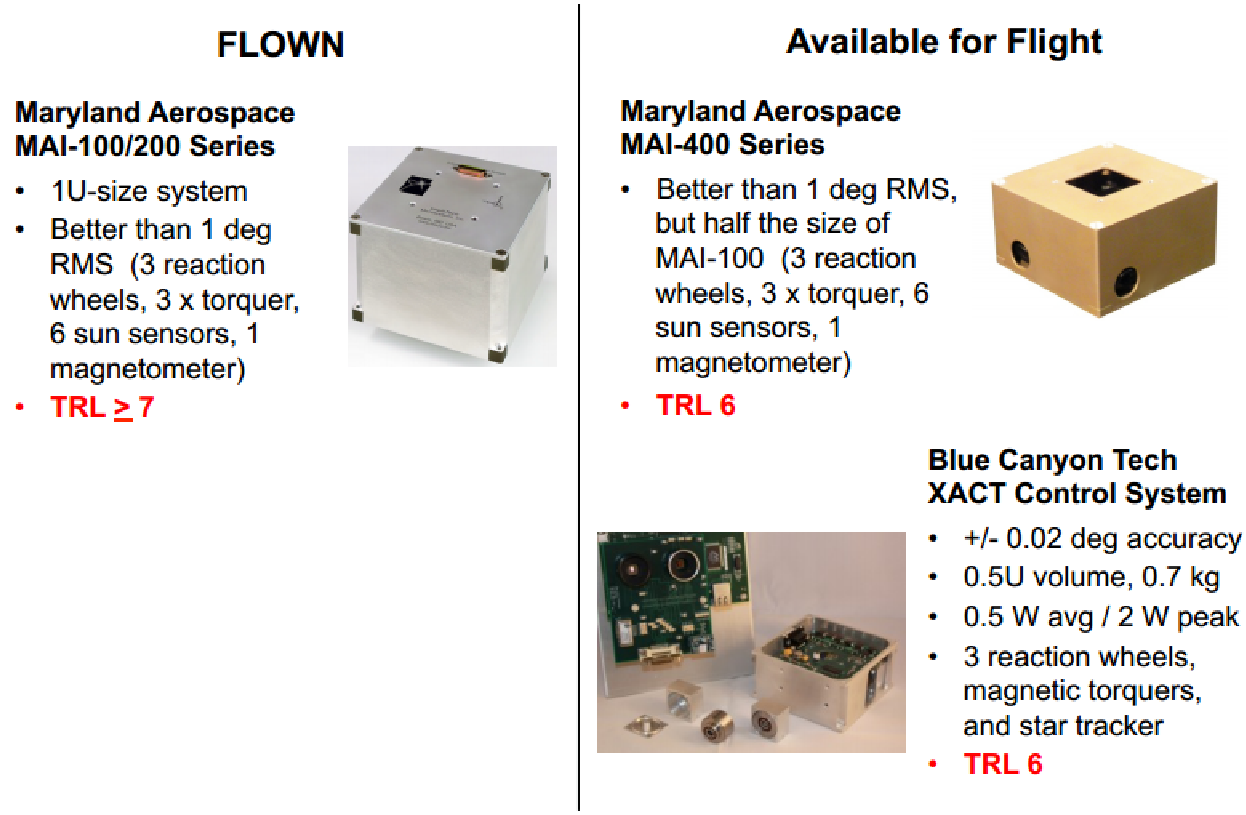
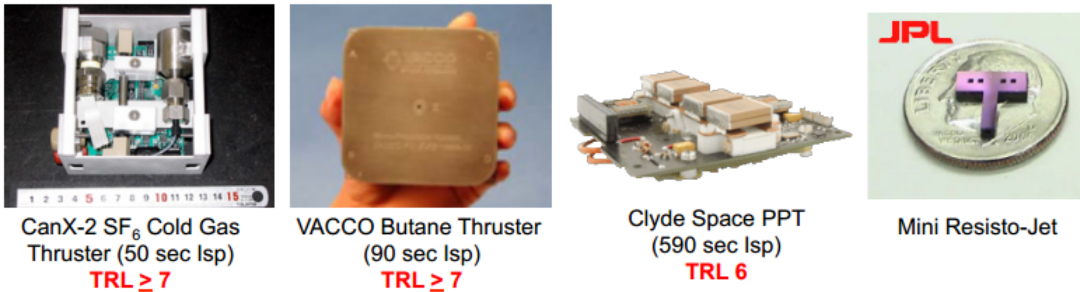
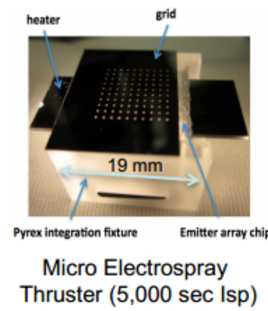


Figure 3: Current attitude control sensors and actuators



Thruster Type	Resisto-jet	PPT	FEEP (Indium)	FEEP (Cesium)	Colloid	Miniature Ion
Thrust (mN)	0.1 - 10	0.002 - 0.7	0.001 - 1	0.001 - 1.4	0.001 - 1	0.5 - 3
Isp (sec)	75-150	500 - 1500	6,000 - 9,000	6,000 -9,000	100 - 1,500	3000 (typ.)
Ibit (Ns)	10^{-6}	10^{-4} - 10^{-6}	10^{-8} (est.)	10^{-8} (est.)	10^{-8} (est.)	TBD
Specific Power (W/mN)	1-5	70 - 100	60	60	1	30
Propellant	Water	Teflon	Indium	Cesium	Glycerol, Ionic Liquids, Formamide	Typ. Xenon



These technologies now enable CubeSats to perform proximity operations, deep space maneuvers, or orbit changes from initial deployment orbits

Figure 4: Current thrusters

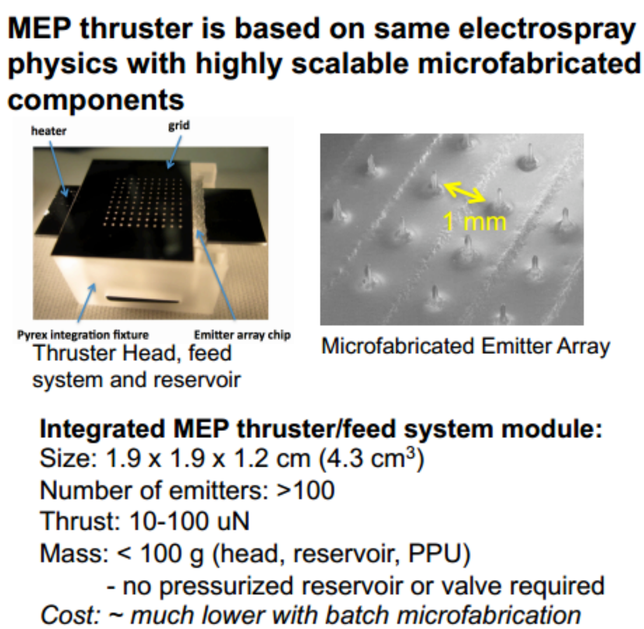


Figure 5: Micro-Electric Propulsion specifications

This is not available of the shelf as of now. They had said it will take 1-2 years in December 2012. It will be a TRL 6 when it becomes available.

Given below is a table showing what can be achieved using the state of the art controllers and actuators(as on December 2012).

Typical Parameter	1U	3U
Mass	1.3 kg	4 kg
Volume (Before Deployment)	10x10x10cm	10x10x34cm
Solar Arrays	Fixed (few deployable)	Fixed Deployable and Articulated
Power	~3 W avg fixed	~8W avg body-fixed ~25W avg deployed
Battery	2200mAh	4400mAh (0.2U)
Antenna	Monopole / Dipole	Dipole, Turnstile, Patch 0.5m dish (1U)
Comms	UHF / VHF	S-Band, UHF/VHF
Data Rates	9600 kbps	3 Mbps demo'd
Attitude Control	~5 deg control (passive)	1-10 deg (torquer) ~0.02-1 deg (RW) (0.5U)
Attitude Determination	~3-4 deg (gyro, sun, mag)	<1 deg (horizon sensor) ~40 arcsec with star tracker (1 U)
C&DH	RISC, ARM Some Linux-based	RISC, ARM, Linux, FPGAs
Propulsion	None	Cold Gas, EP, Solar Sail (<100 m/s)
Deployables	Antenna	Antenna, Panels, Tethers, Boom (0.5m), Solar Sail (5m)
Demonstrated Lifetime	9 years + (XI-IV)	9 years + (Quakesat)
Payload Volume	0.5U max	0.5-2U

Figure 6: Current state of the art in all fields

A few of the other actuators and sensors found have been listed below along with their references.

- Uses GPS and ephemerides for position determination. Variable drag used to re-order satellites' in-track configuration [63].
- Surveys various cubesat type propulsion systems and develops method for evaluating performance of these propulsion systems [64].
- Describes approach to component selection and testing to meet the needs of cubesats [65].
- Attitude determination for spinning spacecraft: uses sun sensor and RF Doppler measurment received at ground stations. Good for low cost, resource-limited spacecraft with moderate attitude determination requirement [66].
- Cubesat attitude control system designed with sub-degree pointing accuracy using COTS miniature reaction wheels and a developmental micro-propulsion system [67].
- Precision attitude control (arc-second level), enabled by Blue Canyon Technologies Nano Star Camera-1 [68].

- Semi-passive actuator where solar cells drive a small magnetic torquier automatically when illuminated. Applications in obtaining sun-avoiding attitudes [69].
- Error of attitude of star trackers are systematic. Methods of taking into account systematic error and decreasing effect on accuracy [70].
- Attitude Determination and control system for 2-degree-accuracy surface track [71].
- Discusses antennas used in GNSS based precision orbit determination [72].
- Practical advice for handling and assembly of star trackers and discuss strategies for maximizing image quality over the sensor lifetime [73]
- Using reaction wheels and star tracker for ADCS [74].
- Development of a star tracker for CubeSat use [75].
- An Off-the-shelf Electric Propulsion System for CubeSats [76].
- Autonomous position and attitude determination of a swarm of satellites. Vision based system for attempting to dock. Attitude algorithms validated for distances up to 30 m and position determination tested for distances up to 50 m [77].
- Uses active magnetic bearings to support and tilt a spinning rotor to provide 3-axis attitude control using a single actuator [78].
- Reaction wheel for 2 to 20 kg spacecraft. Wheel fits in 5x5x4cm box, weighs 185 g and consumes 100mW at nominal speed [79].
- Uses commercially available GPS receiver for orbit determination. RMS value of range error is 0.6m from flight data [80].
- Low-cost visible imaging camera, radiation-hardened, 87x70x230 mm and 0.6kg [81].
- SS-411 maintains mean accuracy of 0.16 deg over entire field of view [82].
- Optical based system that weighs less than 1 kg and consumes $<$3W. Spacecraft attitude to within 100 arc-seconds and angular rate information over rates up to 15 deg/sec [83].
- Describes the Micro Sun Sensor (MSS), the result of the radiation test for commercial active pixel sensor and ground optical performance test of the MSS ground test model [84].
- Star Tracker 300 g, $<$1 W power, 100 arc-second or better pointing accuracy, pointing accuracies better than 0.25 degree [85].
- Attitude determination error of less than 1 degree from magnetometer and coarse sun sensor combination [86].
- 3U Atmospheric Satellite. Uses passive microwave spectrometer. reaction wheels, magnetorquers, Earth horizon sensors[87].
- 3U satellite. Demonstrate de-orbiting technology for LEO(drag sail). [88].

- 3.7-kg mass nanosatellite ejected from the Space Shuttle Atlantis during the final STS-135 mission on July 20, 2011. PSSCT-2 had a three-axis attitude control system to enable firing of solid rockets for orbit raising, pointing of solar cells normal to the sun for on-orbit performance monitoring, and pointing of a GPS antenna in the anti-flight direction for radio-occultation measurements.Hybrid Propulsion system. Pressure vessels are made using new high performance carbon-fiber reinforced polymer material. Hybrid propulsion is safer than solid, simpler than liquid.[89].

- Miniature ion electrospray thrusters. effort fits within 1/3 of one 1U cubesat and is designed to provide fine three-axis attitude control and precision thrusting, to deliver a total Delta-V in excess of 200 m/sec to 3U cubesats[90].

- Mission proposal to test Differential Optical Shadow Sensor (DOSS) on 2U Sat -position sensor[91].

- A stellar gyroscope for ADCS (higher update rate star tracker)[92].

- Two MEMS (Micro Electro Mechanical Systems) components suitable for small satellite propulsion applications. [93].

- Two cubesats with miniaturized propulsion system are used for the mission[94].

- Prototype SPT consists of 36 individual thrusters with chambers 1.5 mm in diameter and approximately 3 mm in length. 0.15 - 0.28 mN thrust range.[95].

- A new method for measuring performance of a micro-thruster with minimal calibration measurements.[96].

  overview of ultra-short baseline GPS attitude determination experiments[97].

- Presents GPS based ADS. uses three GPS antennas to achieve subcentimeter accuracy.[98].

- A survey is presented of existing technology driven by the following primary requirementsIbit less than 1mNs, mass less than 1kg, and size less than one 10cm cube unit.[99].

- ATSBTM CMOS horizon sensor has an RMS accuracy of better than 0.1^o, a mass of 560g and consumes only 550mW when imaging.[100].

- Discuss Vision-Based Attitude and Formation Determination System (VBAFDS), including hardware requirements, algorithm development, and simulation results[101].

- University of Illinois 2-cube CubeSat used vacuum arc thruster (VAT) propulsion system. 4 x 4 x 4 cm and 150 g. 1μN-s/pulse[102].

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