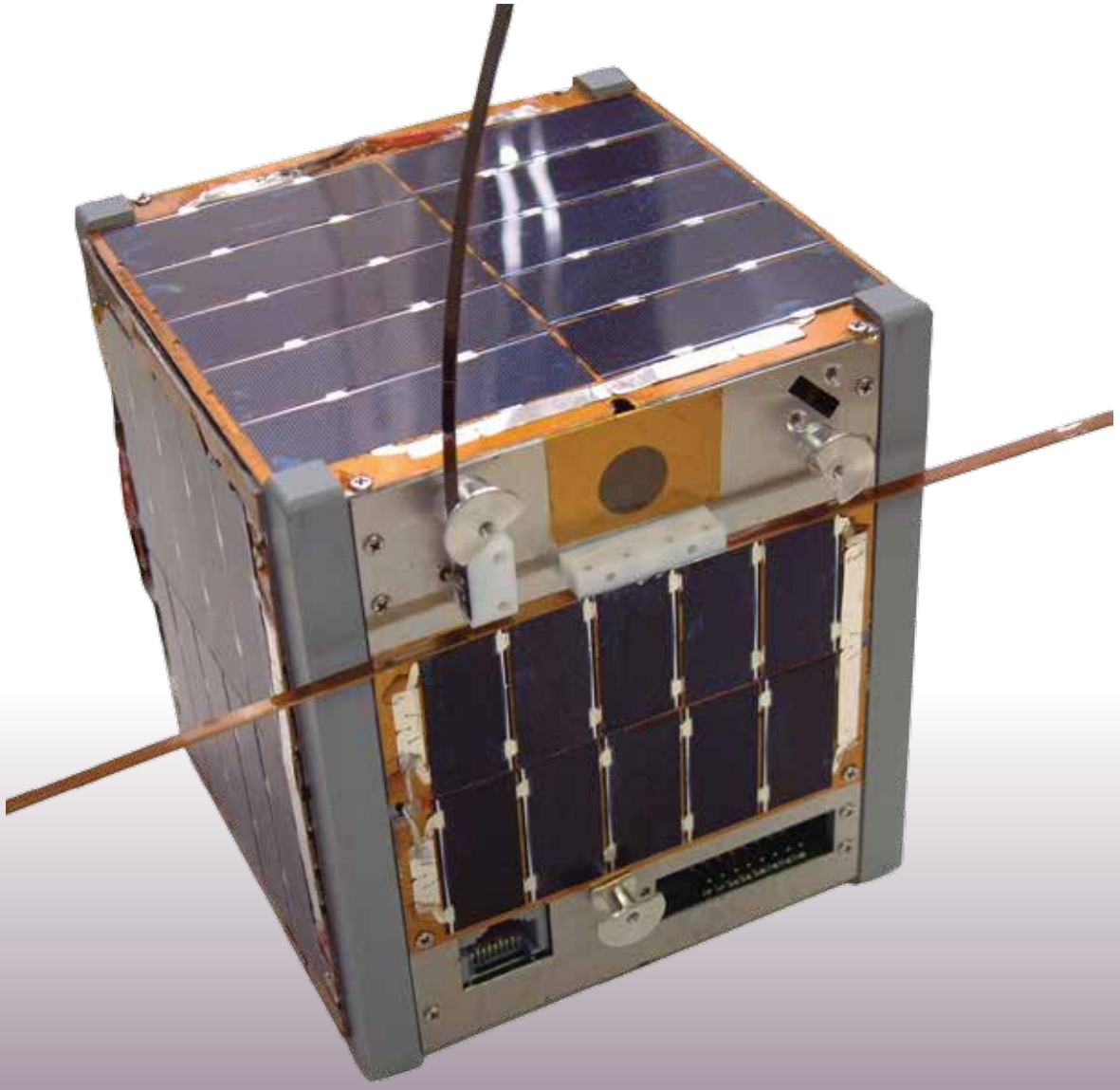
National Aeronautics and Space Administration



annual report

NATIONAL SCIENCE FOUNDATION (NSF) CUBESAT-BASED SCIENCE MISSIONS FOR GEOSPACE AND ATMOSPHERIC RESEARCH

October 2013

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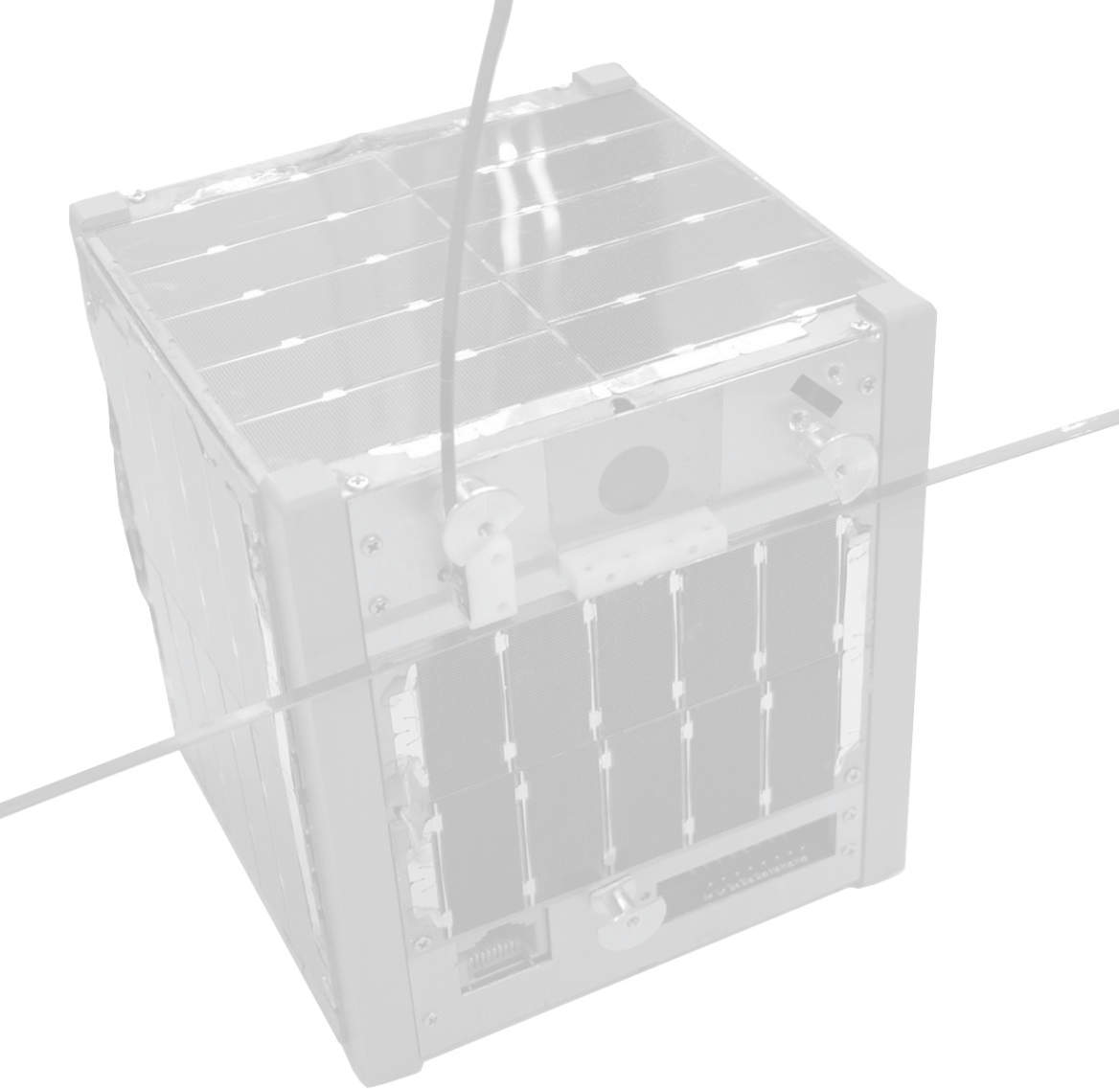

Contents

Letters of Support

The following are letters of support from Dr. Richard Behnke, National Science Foundation, Head, Geospace Science Section, and Mr. Bill Wrobel, NASA Goddard Space Flight Center (GSFC), Director, Wallops Flight Facility (WFF).

NATIONAL SCIENCE FOUNDATION

4201 Wilson Boulevard
Arlington, VA 22230

DIVISION OF ATMOSPHERIC AND GEOSPACE SCIENCES

August 16, 2013

When the Geospace Section at NSF in 2007 began exploring the use of cubesats to conduct space weather research few people believed the miniature satellites would prove to be a useful scientific tool. However, as documented in this report, during the last five years, the NSF cubesat program has seen the highly successful implementation of creative and innovative missions that carry out important science experiments. Already, several projects in the program have delivered first-of-their-kind observations and findings that have formed the basis for high profile engineering and science publications. Many more exciting and promising projects are currently under development. Inarguably, the results from the program have now established beyond doubt the scientific value of cubesats and have proven them as a viable option for space missions that should be taken seriously.

Clearly demonstrated in the program is also the tremendous educational value of cubesat projects. Each mission involves more than 20 students, both under graduate and graduate level, and several of them many more. Real tangible effects on their future career options and advancements of having worked on one of these cubesat projects are starting to materialize for the students involved as evidenced both in the numbers and the stories in the report.

From the outset, the partnership with NASA's Wallops Flight Facility has formed a key component of the program, providing critical technical and management support to the project teams. The outcomes of this joint program, so far, have been truly amazing, establishing the program in a leadership position, nationally as well as internationally, in promoting and supporting university-class cubesat missions. I very much look forward to the further progression of cubesat technology, science missions, and training that is certain to result from our continued collaboration on this program.

Sincerely,

Richard Behnke

Dr. Richard Behnke

Head, Geospace Science Section

National Aeronautics and Space Administration

Goddard Space Flight Center
Wallops Flight Facility
Wallops Island, VA 23337-5099

August 22, 2013

Reply to Attn of: 802

Dr. Richard Behnke
Head, Geospace Science Section
National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230

Dear Dr. Behnke:

NASA Goddard Space Flight Center's Wallops Flight Facility (WFF) is proud of our partnership with the National Science Foundation (NSF), and their selected University faculty and student teams. The enclosed report outlines a number of recent successes of exciting space weather research with CubeSats.

We endeavor to work together, leveraging WFF's engineering and facility strengths, for increasing the science return, technology advancement, and educational value of the NSF CubeSat-based science experiments.

We are especially looking forward to new and exciting projects. Questions of a technical nature may be addressed to Mr. Scott Schaire, Technical Manager, in the Advanced Projects Office, by phone at 757-824-1120 or by e-mail at scott.h.schaire@nasa.gov.

Sincerely,

William A. Wrobel
Director of Wallops Flight Facility

Enclosure

cc:
802/Mr. Schaire

Contacts

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NSF Program Objectives

The National Science Foundation (NSF) is an independent federal agency that was created by Congress in 1950 "to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…" With an annual budget of about $7 billion, NSF funds approximately 20% of all federally supported basic research conducted by the nation's colleges and universities. Most of the grants awarded by NSF go to individuals or small groups of investigators for limited-term specific research projects that have been judged the most promising by a rigorous and objective merit-review system. Currently NSF issues about 11,000 new awards per year, with an average duration of 3 years.

Since 2008, the Division of Atmospheric and Geospace Sciences at NSF has run a program to support CubeSat-based Science Missions. This program implements a new and very different approach to providing the scientific measurements in and from space that are critical for advancing discovery and understanding in many areas of science. It builds on recent engineering and system developments of CubeSat technology that have established the technical feasibility of tiny spacecraft missions that can be launched as secondary payloads at very low cost and rapid time scales as they pose virtually no risk to the launch vehicle or its primary payload. This makes space measurements achievable within the scope of the traditional NSF grants programs and greatly enhances the participation of the larger university community in space activities. In addition, doing space in new ways with Cubesat missions spurs science innovation and creativity and also motivates and inspires engineering inventions and advances. Equally importantly, CubeSat projects offer extraordinary educational benefits. They allow students, through hands-on work on real, exciting, end-to-end projects, to develop the necessary skills and experience needed to succeed in Science, Technology, Engineering, and Mathematics (STEM) careers. CubeSat projects are also an effective tool to broaden the participation amongst underrepresented groups in STEM research and education. The projects stimulate widespread excitement and involve a uniquely diverse set of skills and interest. Therefore they appeal to a broader range of participants than more traditional science and engineering projects.

The Oxygen Photometry of the Atmospheric Limb (OPAL) mission consists of one 3U Cubesat.

Building on this strong motivation, the NSF CubeSat program pursues a dual goal: to promote original and stimulating STEM education and workforce development as well as frontline, interdisciplinary scientific research and technology advances by exploring untraditional, creative, and low-cost ways to provide space measurements for scientific research. Specifically, the main objective of the current program is to execute small scientific satellite missions to advance space and atmospheric research. An additional objective is to provide essential opportunities to train the next generation of experimental space scientists and aerospace engineers. To this end, the program supports the development, construction, launch, and operation of small satellite systems as well as the distribution and analysis of the science data from the missions. To facilitate launch of the satellites as secondary payloads, the focus currently is on CubeSat-based satellites. Launches are not part of the program but are provided by the DOD on a collaborative or reimbursable basis and by NASA through their Educational launch program (ELaNa).

Proposals are submitted to the program through an annual solicitation; based on scientific and technical peer review one to two new projects are selected each year for implementation out of a pool of roughly 25 proposals. The selected projects particularly excel in each of the following aspects:

Compelling science case
The uniqueness and importance of the observations and measurements they obtain for addressing key outstanding science questions.

Exceptional Student training
The extensive and outstanding education and training opportunities they offer and the high level of student involvement in all of the various aspects of the missions.

Technical ingenuity and feasibility
The significant degree to which they advance and make use of emerging technologies while demonstrating satisfactory technological readiness or heritage

Strong team building and management
The soundness of their plans for collaboration, management, scheduling, and risk reduction throughout the development, operations, and science phases of the mission, respectively.

So far, the program has carried out 4 competitions resulting in a total of 10 projects. Typically, the grants awarded are in the amount of $900,000 and of 3 years duration. Over the first 5 years of the program (2008-2012), the total funding in the program was just below $10 million, including a one-time infusion of $2.8 million from the American Reinvestment and Recovery Act in 2009.

The program employs a management approach that is unusual for satellite programs: Minimal directives and oversight obligations are imposed on the management of the projects during their implementation, with the only strict requirements being the ones that are dictated by launch acceptance. This implies that the Principal Investigators of the projects are fully responsible for conducting the missions, including scheduling, reviews, testing, documentation, and risk management, and for meeting the requirements for any of this set by the launch provider. However, technical and management support, including access to test and ground-station facilities, is provided to the teams, as needed, through the collaboration with NASA Wallops Flight Facility (WFF). Although, by design, limited in scope this support is a crucial element of the program. It contributes essential engineering and mission management expertise and capabilities that are critical for ensuring that all of the missions are successfully qualified for launch and completed. Open inter-team discussions as a means to promote transfer of knowledge and provide continuity between the individual projects constitute another untraditional management tool that the program applies. To jointly develop and implement best practices for these groundbreaking small satellite projects is an important auxiliary goal for the program at NSF and for the collaboration with WFF.

GSFC WFF Objectives

The very first CubeSat launched in the United States was a 3U Cubesat called GeneSat-1, manifested on the Tacast-2 launch out of GSFC Wallops in Dec. 2006. WFF manifested CubeSats with the Tacsat-3 launch on a Minotaur-1 launch vehicle which launched in May of 2009.

It was during this TacSat-3 project that WFF learned quite a bit about object debris analysis, safety, and the required CubeSat and P-POD testing.

Mainly because of WFF experience with the low-cost, small payload, responsive, sounding rocket and balloon programs, and working with principal investigators, WFF is ideally suited to support CubeSat endeavors.

In 2008, the National Science Foundation (NSF) chose NASA GSFC Wallops Flight Facility (WFF) to collaborate with their CubeSat activities. WFF continues to support their CubeSat program. Some of the services that WFF has been providing to the NSF and their CubeSat teams include the following:

- Mentoring to CubeSat developers and support of reviews from the WFF engineering staff
- Use of lab test facilities such as GPS simulation, antenna testing and vibration testing
- Interfacing with the launch vehicle provider
- Ground station support with a 60-foot dish. This allows the CubeSat to transmit at up to 300 times the typical data rate.

NASA GSFC Wallops UHF Groundstation.

There is a Radar at WFF that is being used as a satellite telemetry ground station. In the past the Radar had been used for tracking and study of reentry wakes in the upper troposphere. In support of CubeSats, the UHF Radar with its high gain antenna provides a government-licensed frequency allocation that enables high data rates (3.0 Mbit/Sec). This presents a huge improvement over the 9.6 Kbit/s data rates otherwise available.

The UHF CubeSat groundstation answers a growing need for high data rate from CubeSats over a government licensed frequency. Government funded CubeSats using amateur radio frequencies may violate the intent of the amateur radio service and it is a violation of National Telecommunications Information Administration (NTIA) rules for a government funded groundstation to use amateur radio frequencies to communicate with CubeSats.

The success and wide community support for the NSF CubeSat Program combined with the increasing number of NASA proposals that utilize CubeSats demonstrates the maturation of the CubeSat platform.

The primary vision of GSFC WFF is to be a national resource enabling responsive low-cost aerospace science and technology research.

GSFC WFF supports the following NASA mission themes:

1) **Enabling Scientific Research:** Support the Science Mission Directorate by providing low-cost, highly capable suborbital and orbital carriers, mission management, and mission services to enable Earth and space science research.

A. Provide research carriers and science platform missions, including sounding rockets, balloons, aircraft, and carriers for orbital missions, and provide brokering services for other carriers such as Uninhabited Aerial Vehicles (UAV's) and non-NASA aircraft

B. Develop new technologies and applications for WFF carriers such as use of balloons for planetary and Earth science missions, and sounding rockets for planetary entry demonstrations

C. Develop, manage, and implement small orbital science missions

D. Provide specialized mission services through use of the WFF Test Range

E. Conduct Earth science measurements supporting global climate change and coastal research

F. Lead the application of balloon technology to planet Exploration missions as selected or assigned

Wallops balloon prepares for launch with payload to search for antimatter and other cosmic particles.

Student team working on their sounding rocket experiment.

2) **Enabling Aerospace Technology and Facilitating the Commercial Development of Space:** Support the Aerospace Technology and Exploration by providing advanced aerospace technology development, testing, operational support, and facilitation of the commercial launch industry to enable frequent, safe, and low-cost access to space.

A. Serve as a NASA test site for demonstrating space launch technologies

B. Support development advanced range technologies that improve safety and reduce launch costs

3) **Enabling Education, Outreach, and Innovative Partnerships:** Support other NASA goals and objectives by providing science and technology education and outreach programs including innovative partnerships with academia, other Government agencies, and industry.

A. Provide student flight projects to teach students the processes associated with conducting aerospace and scientific research.

B. Seek new opportunities to collaborate with regional colleges and universities, especially Historically Black Colleges and Universities (HBCU's).

C. Continue efforts with WFF tenants and regional government organizations to create new business opportunities for WFF.

2013 and Prior Projects

This past year and prior years there were the following research projects:

- Radio Aurora Explorer (RAX-2) – University of Michigan, SRI International, see *http://rax.engin.umich.edu/ and http://rax.sri.com*

- Dynamic Ionosphere CubeSat Experiment (DICE) – Utah State University, Embry-Riddle Aeronautical University, Clemson University, see *http://www.sdl.usu.edu/programs/dice*

- Colorado Student Space Weather Experiment (CSSWE) - University of Colorado, see *http://lasp.colorado.edu/home/csswe*

- Cubesat for Ions, Neutrals, Electrons, MAgnetic fields (CINEMA) – University of California, Berkley, Kyung-Hee U., Imperial College, Applied Physics Lab, Inter-American University of Puerto Rico, see *http://newscenter.berkeley.edu/2012/07/31/cinema-among-tiny-cubesats-to-be-launched-aug-2/*

- Firefly/Firestation – GSFC, Hawk Institute for Space Sciences, Siena College, Firefly is manifested to launch in Nov. 2013, see *http://www.nasa.gov/topics/universe/features/firefly.html. Firestation launched to the ISS on August 3, 2013, see http://www.nasa.gov/content/goddard/firestation-to-international-space-station/*

- Firebird – Montana State University, University of New Hampshire, Aerospace Corporation, manifested to launch in Dec. 2013, see *https://ssel.montana.edu/category/cubesat/*

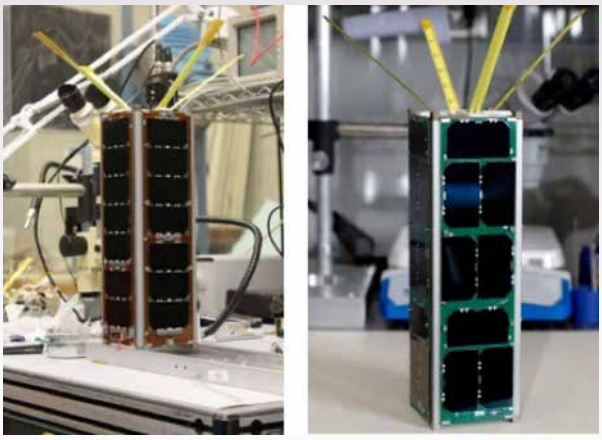
GSFC/Naval Research Labs Winds-Ion-Neutral Composition Suite (WINCS) Instrument slated to fly on CADRE.

Radio Aurora Explorer (RAX)

Project Description

Ionospheric plasma turbulence occurs in response to intense solar and magnetospheric forcing. The turbulence consists of sub-meter to decameter-scale electron density irregularities that impact communication and navigation signals, such as GPS. A small misalignment of ionospheric irregularities from the geomagnetic field results in wave-generated parallel electric fields that dissipate significantly more energy per mV/m than the perpendicular electric fields that are associated with large-scale ionospheric convection. Determining the magnetic-aspect sensitivity of the turbulence is critical, not only for quantifying electron heating and subsequent changes in the plasma chemistry, but also for quantifying the total amount of electromagnetic energy entering into the Earth's upper atmosphere due to solar and magnetospheric forcing.

Radio Aurora Explorer (RAX) is the first CubeSat funded by the NSF CubeSat-based Space Weather program. Its mission has been to reveal the micro-physics of ionospheric plasma turbulence by measuring Auroral scatter using a ground-to-space bistatic Radar geometry. It has been jointly conducted by SRI International and University of Michigan. Previously, Auroral scatter has been measured using ground-based coherent scatter Radars. However, due to near vertical magnetic field line geometry at high-latitudes, it has been difficult to achieve scatter perpendicularity. The unique Radar scattering geometry of a RAX experiment, composed of a transmitter on the ground and an orbiting receiver in space, enables unprecedented high-resolution measurements. Two RAX satellites were launched (see picture of RAX-1 and RAX-2 satellites). RAX-1 was launched in December 2010, through STP from Kodiak AK, to a polar circular orbit (650 km). The spacecraft was terminated due to the malfunctioning solar panels. RAX-2 satellite was launched in October 2011 from Vandenberg Air Force Base to a polar-elliptical orbit (400-820 km). The launch was provided by NASA's Educational Launch of Nanosatellites (ELaNa) program.



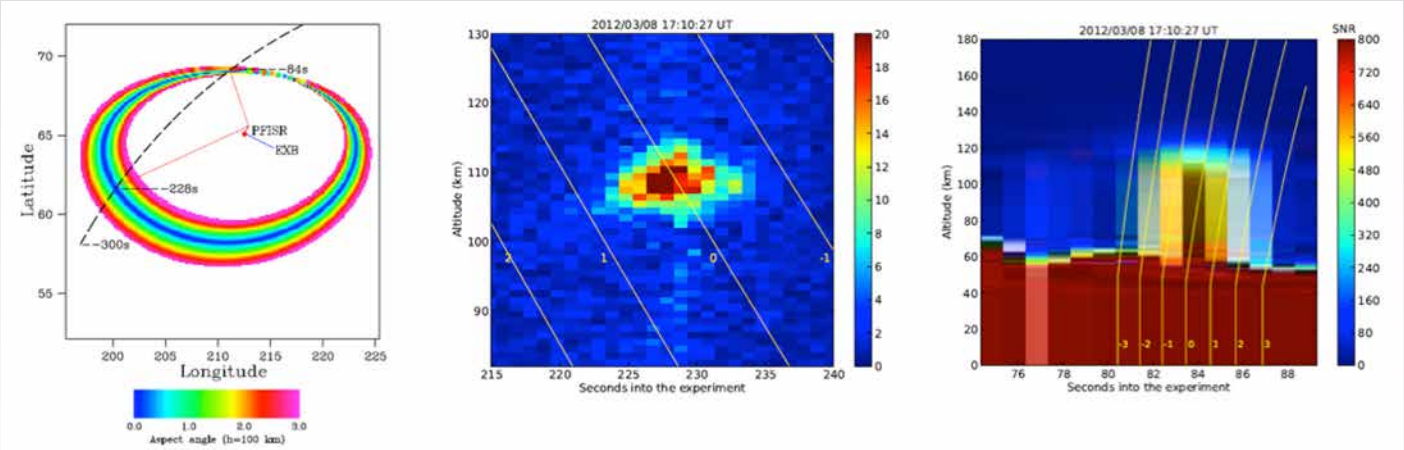
RAX-1 and RAX-2 Satellites.

RAX-2 completed its nominal 1-year science mission and produced a unique dataset, some of which has been analyzed and published in the scientific literature. Details regarding the RAX mission can be found on the team websites: http://rax.engin.umich.edu and http://rax.sri.com.

Scientific Accomplishments

RAX-2 completed more than 30 end-to-end experiments with the Advanced Modular Incoherent Scatter Radar (AMISR) chain of radars in Alaska, and Resolute Bay, Canada. Coherent Radar echoing occurred during four of the passes: three when electron drifts exceeded the ion acoustic velocity threshold and one during HF heating of the ionosphere by the HAARP heater. The small number of detections is expected because of the short window (300 s) of each experiment. Nevertheless, the detections span a large range of electrojet conditions (EXB drifts from 700 m/s to 1600 m/s) and this enabled observations of plasma turbulence for a large dynamic range of magnetospheric forcing.

RAX-2 has provided the highest combined resolution for altitude and magnetic aspect angle measurements of Auroral electrojet scatter thus far. The aspect angle graph shows the experimental geometry for the pass 1017 that coincided with the solar storm of March 8, 2012. In the Radar echoes figure, the mapping of Radar data on altitude and magnetic-aspect angle shows that the turbulent backscatter is observed when the spacecraft was crossing the loci-of-perpendicularity shown in the aspect angle graph. In fact, we see that the scattering plasma structures are aligned with the magnetic field within a fraction of a degree and are localized at the altitude of approximately 110 km. This altitude is exactly where most of the electrojet-driven electron temperature enhancements were measured previously.



Experimental geometry showing the loci of perpendicularity for scattering at the spacecraft.

Radar echoes mapped to altitude aned magnetic aspect angle/time coordinates for the first (left) and second (2) crossings of the loci perpendicularity. The echoing is observed very close to the 0^0 contour.

Based on this and other sets of compelling backscatter events, RAX data showed that sub-meter-scale irregularities in the Auroral E region are more strongly aligned with the geomagnetic field than previously thought, and the turbulence is confined to a narrow (~5 km) altitude range centered near 110 km. These findings are important for accurate mathematical modeling of E region plasma heating and chemistry.

RAX-2 findings suggest that the parallel electric fields of sub-meter scale waves propagating at larger angles from the main EXB flow direction (secondary waves) are too small to contribute to E region electron heating. It is possible that the dynamics of those sub-meter scale waves propagating in the EXB direction (primary waves) or the dynamics of longer wavelengths explain anomalous electron heating in the Auroral electrojet.

Technology

The project helped advance CubeSat and CubeSat-based payload technology for more effective instrumentation of the space environment. The first-time successful operation of a UHF receiver payload on a CubeSat is a technology demonstration that elevates the Technology Readiness Level (TRL) of this particular payload to 9. Most importantly, the demonstration opens the way for proliferation of similar radio payloads as distributed sensors in space, enabling more effective characterization of the ionosphere. Enormous effort has been spent to build a CubeSat bus that would support the rigid power, thermal, attitude, and electromagnetic interference requirements of the payload. RAX-2 bus successfully met the expectations by

fulfilling its nominal mission lifetime. RAX-2 design will serve a basis for future CubeSat developments and the lessons learned will surely be carried forward to build more robust ones.

Education

The RAX project demonstrated a major educational impact in the field of aerospace engineering by engaging a large number of students during the development and operation of the spacecraft (see Figure of RAX team members). Dozens of undergraduate and graduate students studied under this project and went on to careers in space sciences and aerospace engineering. Some of the students have graduated and are currently working for NASA on larger spacecraft.

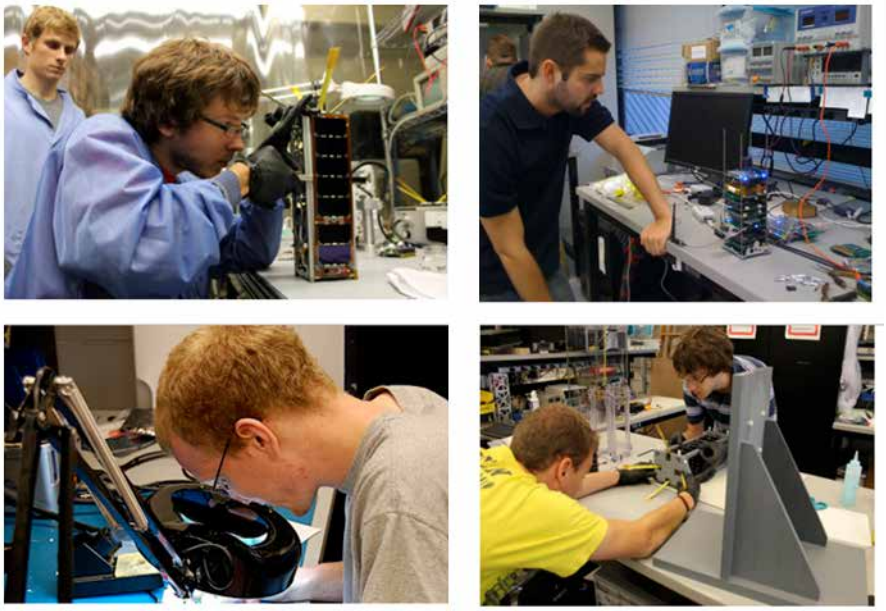
Publications

Journals

1. Bahcivan, H., J. W. Cutler, J. C. Springmann, R. Doe, and M. J. Nicolls (2013), Magnetic aspect sensitivity of high-latitude E region irregularities measured by the RAX-2 CubeSat, *J. Geophys. Res.,* in review, 2013.

2. J. C. Springmann, B. P. Kempke, J. W. Cutler, and H. Bahcivan (2013), Time keeping on the RAX Spacecraft, *Acta Astronautica.,* in review, 2013.

3. James W. Cutler, Hasan Bahcivan, The Radio Aurora Explorer – A Mission Overview, *AIAA Journal of Spacecraft and Rockets,* Published online June 25, 2013, 10.2514/1.A32436.



Some of the RAX team members in the Michigan Exploration Labortory (MXL) of Professor James Cutler.

4. Sara C. Spangelo, Matthew W. Bennett, Daniel C. Meinzer, Andrew T. Klesh, Jessica A. Arlas, James W. Cutler, Design and Implementation of the GPS Subsystem for the Radio Aurora Explorer, *Acta Astronautica,* Volume 87, June-July 2013, Pages 127-138, ISSN 0094-5765, 10.1016/j.actaastro.2012.12.009.

5. Bahcivan, H., J. W. Cutler, M. Bennett, B. Kempke, J. C. Springmann, J. Buonocore, M. Nicolls, and R. Doe (2012), First measurements of radar coherent scatter by the Radio Aurora Explorer CubeSat, *AGU Geophysical Research Letters,* 39, L14101, 10.1029/2012GL052249.

6. J.C. Springmann, A.J. Sloboda, A.T. Klesh, M.W. Bennett, J.W. Cutler, The attitude determination system of the RAX satellite, *Acta Astronautica,* Volume 75, June–July 2012, Pages 120-135, ISSN 0094-5765,10.1016/j.actaastro.2012.02.001.

7. J.C. Springmann and J.W. Cutler, "Attitude-Independent Magnetometer Calibration with Time-Varying Bias," *AIAA Journal of Guidance, Control, and Dynamics,* Volume 35, Number 4, July–August 2012, pages 1080-108810.2514/1.56726.

8. H. Bahcivan and J.W. Cutler, "Radio Aurora Explorer: Mission Science and Radar System," *Radio Science,* Volume 47, Number 2, RS2012, 10.1029/2011RS004817.

9. H. Bahcivan, M.C. Kelley, and J.W. Cutler (2009), Radar and rocket comparison of UHF radar scattering from auroral electrojet irregularities: Implications for a nanosatellite radar, *J. Geophys. Res.,* 114, A06309,10.1029/2009JA014132.

Conference Publications

1. J. C. Springmann, "On-Orbit Calibration of Photodiodes for Attitude Determination," AIAA/ *USU Small Satellite Conference,* Logan, UT, August 2013.

2. R. Burton, S. Rock, J. Springmann, J. Cutler, "Online Attitude Determination of a Passively Magnetically Stabilized Spacecraft", Proceedings of the 23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii, February 2013.

3. R. Burton, S. Rock, J. Springmann, J. Cutler, "Dual Attitude and Parameter Estimation of Passively Magnetically Stabilized Spacecraft", Proceedings of the 63rd International Astronautical Congress, Naples, Italy, October 2012.

4. J. C Springmann, B.P. Kempke, J.W. Cutler, H. Bahcivan, "Initial Flight Results of the RAX-2 Satellite", Proceedings of the 26th Small Satellite Conference, Logan, Utah, August 2012.

5. J. C Springmann, B.P. Kempke, J.W. Cutler, H. Bahcivan, "Development and Initial Operations of the RAX-2 CubeSat", The 4S Symposium, Portoroz, Slovenia, June 2012.

6. J. C Springmann, J.W. Cutler, "Attitude-Independent Magnetometer Calibration with Time-Varying Bias", The 4S Symposium, Portoroz, Slovenia, June 2012.

7. J. Arlas and S. Spangelo, "GPS Results for the Radio Aurora Explorer 2 CubeSat Mission," AIAA Region 3 Student Conference, Ann Arbor, MI, March 2012.

8. J. Springmann, J. Cutler, H. Bahcivan, "Initial Flight Results of the Radio Aurora Explorer," Proceedings of the 62nd International Astronautical Congress, Cape Town, South Africa, October 2011.

9. J. Cutler, H. Bahcivan, J. Springmann, S. Spangelo, "Initial Flight Assessment of the Radio Aurora Explorer", Proceedings of the 25th Small Satellite Conference, Logan, Utah, August 2011.

10. J. Springmann, "Attitude-Independent Magnetometer Calibration with Time-Varying Bias," Proceedings of the 25th Small Satellite Conference, Logan, Utah, August 2011.

11. J. Springmann, J. Cutler, "Initial Attitude Analysis of the RAX Satellite", Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, Girdwood, Alaska, August 2011.

12. Geeyong Park, Sheryl Seagraves and N. Harris McClamroch, "A Dynamic Model of a Passive Magnetic Attitude Control System for the RAX Nanosatellite" AIAA Guidance, Navigation, and Control Conference, 2-5 August 2010 in Toronto, Ontario, Canada.

13. S. Spangelo, A. Klesh, and J. Cutler, "Position and Time System for the RAX Small Satellite Mission," AIAA/AAS Astrodynamics Specialist Conference Proceedings, Toronto, Ontario, Canada, August 2010.

14. J. Springmann, J. Cutler, H. Bahcivan, "Magnetic Sensor Calibration and Residual Dipole Characterization for Application to Nanosatellites," AIAA/AAS Astrodynamics Specialist Conference Proceedings, Toronto, Ontario, Canada, August 2010.

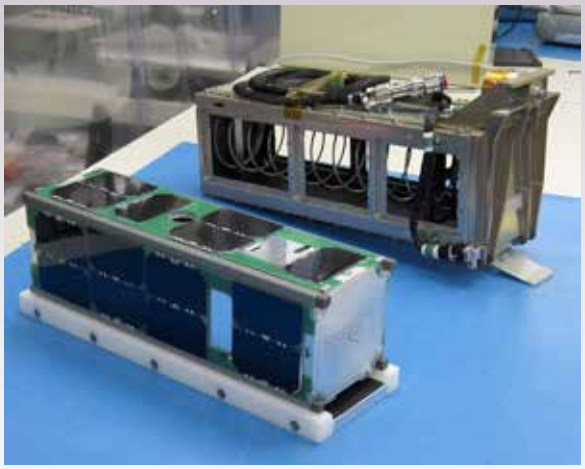
15. James Cutler, Matthew Bennett, Andrew Klesh, Hasan Bahcivan, Rick Doe, "The Radio Aurora Explorer – A Bistatic Radar Mission to Measure Space Weather Phenomenon," In Proceedings of Small Satellite Conference, August 2010.

16. Klesh, Andrew, S. Seagraves, M. Bennett, D. Boone, H. Bahcivan, J. Cutler, "Dynamically Driven Helmholtz Cage for Experimental Magnetic Attitude Determination," AAS/AIAA Astrodynamics Specialist Conference, 09-311, Pittsburgh, PA, 2009.

Colorado Student Space Weather Experiment (CSSWE)

Project Description

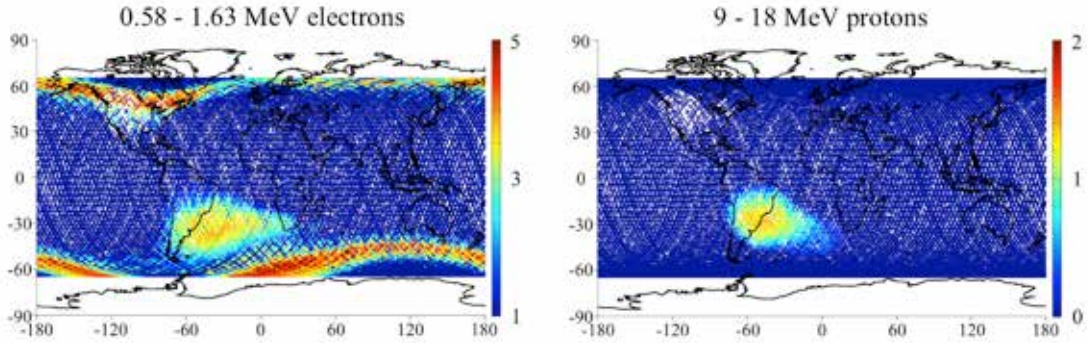
The Colorado Student Space Weather Experiment (CSSWE) is a 3U CubeSat designed, built, and operated by students at the University of Colorado, Boulder. It was inserted into a low altitude, high inclination orbit on Sept 13 2012 as a secondary payload on an Atlas V through the NASA Educational Launch of Nanosatellites (ELaNa) program. The science payload, the Relativistic Electron and Proton Telescope integrated little experiment (REPTile), a miniaturized version of the REPT instrument onboard the NASA/Van Allen Probes, provides differential measurements of MeV electrons and protons trapped in the radiation belts and from solar energetic particle (SEP) events. Having completed its nominal 90-day science mission, CSSWE continues to operate and return valuable data today, almost a year later. Details regarding the CSSWE mission can be found on the team website: http://lasp.colorado.edu/home/csswe/.



The CSSWE CubeSat delivered in January 2012 next to its Poly-Picoset OrbitalDeployer (P-POD).

Scientific Accomplishments

The REPTile instrument onboard CSSWE has been making valuable measurements of the near-Earth radiation environment since the commissioning period was completed in early October 2012. The Energetic Electrons and Protons figure illustrates the measurements recorded from the first 20 days of science operations. There are a number of scientific papers in development using CSSWE data to study the complicated dynamics of the radiation belts, including energy and pitch angle dependencies of electron acceleration and loss. A full list of publi cations to date can be found at the end of this report. These results have also been presented at numerous scientific conferences including the Geospace Environment Modeling (GEM) workshop 2013, Meeting of the Americas 2013, European Geophysical Union 2013, and Fall American Geophysical Union 2012. Additionally, papers studying REPTile data, in combination with



Energetic electron and proton fluxes color-coded by logarithm and organized by spacecraft position in geographic latitude and longitude. MeV protons and electrons from the inner radiation belt are visible as CSSWE files through the South Atlantic Anomaly (SAA) while electrons from the outer radiation belt are . . .

measurements from the NASA/Van Allen Probes and 2013 BARREL balloon campaign are in preparation and submitted to the Journal of Geophysical Research and Geophysical Research Letters. CSSWE is a prime example of how small inexpensive CubeSats can be used to complement larger missions and greatly enhance their scientific return.

Technology

There have also been a number of technological achievements and lessons learned from CSSWE. These were presented at the CubeSat Developers' Workshop/Small Satellite Conference this past August 2013, will be published in the Journal of Small Satellites, and were highlighted in a recent news article (http://www.newspacejournal.com/2013/08/11/can-cubesats-do-quality-science-for-one-group-yes/). Contact with CSSWE was established on its first pass over Boulder after launch, and amateur radio operators across the world have helped track and decode beacons. On-orbit performance has been in line with expectations from predictions and testing, with interior temperatures within the ranges of the thermal vacuum testing performed before delivery, and the passive magnetic attitude control system (PMACS) converging to the local magnetic field within ~ one week. A number of lessons learned have been documented and passed on to future CubeSat missions both at the University of Colorado as well as other institutions. These include keeping the design and overall system as simple as possible to minimize risk while still meeting requirements. Additionally, integrated system testing was crucial to characterizing the system performance and preparing for on-orbit results.

Education

The CSSWE CubeSat was designed, built, tested, delivered, and operated by a team of students under advising from professionals at the University of Colorado and the Laboratory for Atmospheric and Space Physics (LASP) as well as others in the community. Over 60 students, both graduate and undergraduate, from disciplines ranging from electrical, mechanical and aerospace engineering to astrophysics and computer science, worked on CSSWE over the project lifetime. The results of the mission will be incorporated into the dissertations of three PhD students, two focusing on the energetic electron measurements from REPTile and one on the passive magnetic attitude control (PMACS) system. These students have presented CSSWE work in the Frank J. Redd Annual Student Scholarship Competition held at the Small Satellite Conference and placed in the top three for three different papers. The CSSWE team picture from Spring 2010 shows the team holding an engineering model of the REPTile instrument (front center) well as the CubeSat outer shell (back row). The project has allowed students the rare experience to be involved in all stages of a satellite mission lifetime, from preliminary design and testing through to operations and data analysis phases.

CSSWE team in Spring 2010.

Publications

Gerhardt, D., S. Palo, Q. Schiller, L. Blum, X. Li, and R. Kohnert *(submitted)*, The Colorado Student Space Weather Experiment (CSSWE) On-Orbit Performance, *Journal of Small Satellites*.

Li, X., Q. Schiller, L. Blum, S. Califf, H. Zhao, W. Tu, D. Turner, D. Gerhardt, S. Palo, R. Selesnick, S. Kanekal, D. N. Baker, J. Fennell, J. B. Blake, M. Looper, G. D. Reeves, and H. Spence *(submitted)*, First Results from CSSWE CubeSat: Characteristics of Relativistic Electrons in the Near-Earth Environment During the October 2012 Magnetic Storms, *Journal of Geophysical Research*.

Li, X., S. Palo, R. Kohnert, L. Blum, D. Gerhardt, Q. Schiller, and S. Callif (2013), Small Mission Accomplished by Students - Big Impact on Space Weather Research, *Space Weather Journal,* 11, doi:10.1002/swe.20025, 2013.

Li, X., S. Palo, R. Kohnert, D. Gerhardt, L. Blum, Q. Schiller, D. Turner, W. Tu, N. Sheiko, and C. S. Cooper (2012), Colorado Student Space Weather Experiment: Differential flux measurements of energetic particles in a highly inclined low Earth orbit, in Dynamics of the Earth's Radiation Belts and Inner Magnetosphere, *Geophys. Monogr. Ser.,* vol. 199, edited by D. Summers et al., 385–404, AGU, Washington, D. C., doi:10.1029/2012GM001313.

Li, X., S. Palo, and R. Kohnert (2011), Small Space Weather Research Mission Designed Fully by Students, *Space Weather Journal* 9, S04006, doi:10.1029/2011SW000668.

Lauren Blum, Quintin Schiller, with advisor Xinlin Li (2012), Characterization and Testing of an Energetic Particle Telescope for a CubeSat Platform, 26th Annual AIAA/USU Conference on Small Satellites.

Scott Palo, X. Li, D. Gerhardt, D. Turner, R. Kohnert, V. Hoxie and S. Batiste (2010), Conducting Science with a CubeSat: The Colorado Student Space Weather Experiment, 24th Annual AIAA/USU Conference on Small Satellites.

Quintin Schiller, Abhishek Mahendrakumar, with advisor Xinlin Li (2010), REPTile: A Miniaturized Detector for a CubeSat Mission to Measure Relativistic Particles in Near-Earth Space, 24th Annual AIAA/USU Conference on Small Satellites.

David T. Gerhardt with advisor Scott Palo (2010), Passive Magnetic Attitude Control for CubeSat Spacecraft, 24th Annual AIAA/USU Conference on Small Satellites.

Data Archive

Level 1 science data (electron and proton count rates) from the first six months of the mission have been made publicly available and can be downloaded at the following site: *http://lasp.colorado.edu/home/csswe/data/download/*.

The team is considering putting the data in the CEDAR database or the Virtual Solar Terrestrial Observatory as a long term archive as well.

Dynamic Ionosphere CubeSat Experiment (DICE)

Project Description

Funded by the NSF CubeSat and NASA ELaNa programs, the Dynamic Ionosphere CubeSat Experiment (DICE) mission consists of two identical 1.5U CubeSats deployed simultaneously from a single P-POD (NASA's Poly Picosatellite Orbital Deployer) into the same orbit.

The success of the DICE mission has required a very large team of people. The DICE Principal Investigator is Geoff Crowley, from ASTRA LLC. Charles Swenson, Space Dynamics Lab/Utah State University (USU/SDL), is the Deputy Principle Investigator. Chad Fish, USU/SDL and Virginia Tech, is the Program Manager and a science Co-Investigator. Science team Co-Investigators include Marcin Pilinski and Irfan Azeem from ASTRA and Aroh Barjatya from Embry Riddle Aeronautical University. The project lead engineer is Tim Neilsen, USU/SDL. ASTRA is leading the mission science analysis, with support from USU/SDL and Embry Riddle. The DICE engineering component was implemented at USU/SDL, with support from ASTRA and Embry Riddle. Major engineering industry partners include L-3 Communications, TiNi Aerospace, Clyde Space, ATK Aerospace, and Pumpkin Inc. GPS simulator testing occurred at the NASA Goddard Space Flight Center. Mission operations are conducted by USU/SDL, in collaboration with NASA Wallops Flight Facility and SRI International.

Both satellites are expected to remain on orbit for about 15 years and the goal was to get at least six months of scientific data from them. Each satellite carries two Langmuir probes to measure in-situ ionospheric plasma densities, a science and attitude magnetometers, and electric field probes to measure DC and AC electric fields. The Langmuir Probes are fully deployed, and data has been collected from them as well as from the science magnetometer. In addition to being a scientific pathfinder in terms of measuring electric fields from a distributed set of spacecraft in LEO, the DICE CubeSats have achieved science data downlinks unprecedented in previous CubeSat missions. Details regarding the DICE mission can be found on the team website: http://astraspace.net/research-development/dicecubesat-mission/.

Scientific Accomplishments

The following is a summary of major accomplishments resulting from the DICE CubeSat mission:

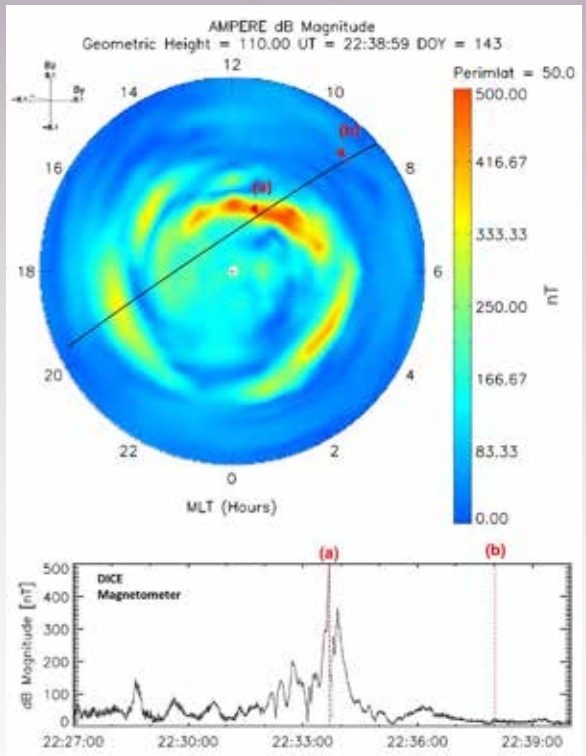
Left: The twin DICE spacecraft, Farkle and Yahtzee. Right: DICE CubeSat showing one of the Langmuir Probes in a deployed position.

- First in-situ SED observations from a satellite flying in the ionosphere
- First demonstration of Field Aligned Current (FAC) observations in the ionosphere using a body-mounted magnetometer on a CubeSat
- Development of a high-speed communications link for CubeSats with unprecedented data-rates for this class of spacecraft
- First CubeSat constellation funded specifically for scientific purposes
- Nearly two years of successful operations at the time of writing

The primary scientific accomplishments of the DICE mission to date have focused on the characterization of Storm Enhanced Densities (SEDs) in the ionosphere, and the detection of Field Aligned Currents (FACs) at high latitudes. The DICE team is currently submitting several research papers related to this work. The DICE team also worked with Millstone Hill and others

to orchestrate several Incoherent Scatter Radar (ISR) conjunction campaigns resulting in multi-instrument observations of the top-side and bottom-side ionosphere. Data from the joint ionospheric configuration measurements is currently being analyzed.

Field Aligned Currents: The DICE satellite has made the first observations of magnetic residuals attributed to FAC's using a CubeSat body-mounted magnetometer. The presence of strong FAC's in the vicinity of a DICE north-polar pass was confirmed by both AMIE and AMPERE and corresponds to the measured 400nT perturbation on May 22nd 2013 (see AMPERE dB magnitude Figure). While significant, such FAC's result in magnetic perturbations which are still only 1% of the Earth's magnetic field magnitude, making them difficult to detect. The DICE body-mounted magnetometer is able to detect significant FAC events (>100nT) and thus serve as cost-effective space-weather monitors.



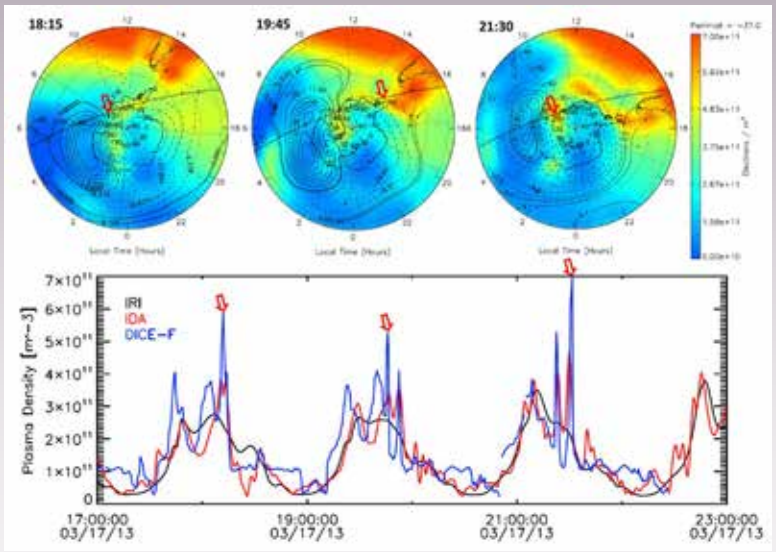
Ampere dB magnitude (top) with DICE dB measurements (bottom). The locations of the satellites are indicated with red triangles.

Ionospheric Storm Enhanced Densities: A geomagnetic activity on March 16-17, 2013 resulted in the generation of SED features in the northern and southern hemispheres. The southern hemisphere SED evolution was observed by the NSF DICE CubeSats. The DICE plasma observations figure compares DICE plasma density with IDA4D assimilation of the south polar ionosphere and AMIE convection patterns (contours). The AMIE convection patterns successfully located the dusk convection cell by assimilating data from DMSP ion-drift meters, SuperDARN radars and ground based magnetometers. The SED is shown to move towards the convection "throat" region near 14-15LT and is then convected across the pole as polar cap patches. This results in a horseshoe shape plasma formation in the southern polar cap which is observed as a double-peaked plasma-density enhancement by the DICE-F satellite (right hand side of DICE plasma observations Figure). The DICE observations on March 17th, 2013 represent the first CubeSat observations of SED's and complete an important scientific objective of the DICE mission. The local time and altitude coverage afforded by DICE represent a unique and complementary view relative to the topside observations by DMSP in the evening sector at higher latitudes. Furthermore, the in-situ DICE satellite data provides a unique validation of IDA4D plasma densities in the south-polar region, which is normally considered data-sparse. IDA4D reproduced many of the features associated with the SED and observed by DICE.

Technology

One of the major challenges for CubeSat missions has been downloading sufficient amounts of engineering and science data from the satellite to the ground. As a result of technology developed under the DICE program, the total on-board formatted data acquisition rate of

each DICE sensor-sat is > 6.8 Kbits/s when in 35 Hz science mode (11.8 Kbits/s in 70 Hz mode). ***These downlink rates are much greater (by a factor of 100-200) than those used on previous CubeSat missions.*** The total amount of housekeeping, attitude determination, and science data demodulated from both satellites since launch has been approximately 9GB during the course of the primary mission. To store and forward transmit this data to the ground from the DICE constellation on a daily cadence requires an on-board storage of ~ 1 Gbit/day and a downlink rate greater than 1.5 MBits/second (assumes approximately 7-10 minutes of overpass downlink time per sensor-sat per day). The on-board storage requirement is well within typical CubeSat technology specifications. Therefore, in collaboration with L-3 Communications, the DICE team developed the CadetU CubeSat radio to enable high downlink data rates and to operate in government assigned and regulated UHF bands for both uplink and downlink communications. The use of UHF bands avoids congested S-band operations, and provides better signal to noise levels over the same communication path. Each DICE sensor-sat contains a CadetU radio. CadetU is a 6.9 x 6.9 x 1.3 cm half-duplex modem weighing only 0.07 kg, and capable of 9600 kbps uplink (450 MHz) and 20 MBits/s of FEC encoded downlink (460-470 MHz). The DICE CadetU radios downlink at 3 MBits/s as that is more than ample bandwidth for the mission telemetry needs. Continuous receive operations consume ~ 200 mW of power on the DICE Cubesats, while transmission consumes ~9 W of power to produce up to 2 W of RF output power.



DICE plasma density observations compared with IDA4D assimilation of the south polar ionosphere and AMIE convection patterns (contours). Note that the enhanced densities observed by DICE (red arrows in the bottom plot) correspond to passes through a tongue.

Education

The DICE project involved major contributions from its two graduate and six undergraduate engineering students. Approximately 68% of DICE funding for labor hours supported student contributors. Students were integral to the assembly, integration and test (AI&T) process. Upon launch and deployment of the CubeSats, students were also involved in performing day-to-day operations, and analyzing the data returned from the DICE instruments. Students were also involved in testing data-recovery algorithms and recovering additional telemetry from the raw transmitted I/Q data. The specific duties of the students included Deputy Program Manager, Systems Engineer, Structural and Thermal Analysis, Mechanical Design, Electrical and Computer Analysis and Design, Software Design, Mission Ops, Development of Concepts of Operations (CONOPS), Communication Analysis and Design, Instrumentation Design, Assembly and Test, and Calibration.

Several Master's Theses were conducted during the course of the DICE project and one PhD dissertation is currently in progress. These documents include subjects such as Electric Field Boom Deployment from a CubeSat and CubeSat Systems Engineering. The DICE mission design was also the focus of a number of core classes at Utah State University, including Space Environments and Satellite Systems Engineering courses. This approach of integration of the CubeSat missions into core classes led to another mission study that was the technical impetus for the recently awarded NSF Optical Profiling of the Atmospheric Limb (OPAL) CubeSat mission.

DICE student team with professional advisors in January 2010.

The DICE engineering activity was implemented at Space Dynamics Lab (SDL), enabling direct interaction of the student core with full time program management and engineering professionals. This interaction provided real world aerospace experience and guidance for the DICE student team. Three DICE team students have since progressed to full time positions at SDL and continue to contribute in key design areas on a number of SDL associated CubeSat programs, including the NSF OPAL and Lower Atmosphere/Ionosphere Coupling Experiment (LAICE) missions as well as the NASA Hyper Angular Rainbow Polarimeter (HARP) mission.

The DICE student core engaged industry partners and managed development of key technology on DICE, including the CADET U high speed communications radio from L-3 Communications, the iCAST ground station and mission operations control center with L-3 Communications, and a miniaturized Frangibolt actuator from TiNi Aerospace. Subsequently a number of DICE students were invited as interns at L-3 Communications, with one acquiring permanent employment with L-3.

Additionally, the students from DICE are now actively supporting the development and enhancement of L-3 Communications high speed radios for future CubeSat missions. This effort, which is led by Drs. Jake Gunther and Charles Swenson and run by students, is executed out of the SDL CubeSat mission operations and high speed communications center which was developed on DICE.

Publications

Barjatya, A., M. Pilinski, C. Swenson, C. Fish, G. Crowley, The Langmuir Probe Instrument on the DICE CubeSat, in preparation, *Journal of Geophysical Research,* 2013.

Crowley, G., C. Fish, C. Swenson, R. Burt, T. Neilsen, A. Barjatya, G. Bust, M. Larsen Dynamic Ionosphere Cubesat Experiment (DICE), SSC10-III-7, Proceedings of the Small Satellite Conference, Logan, UT, August, 2010.

Crowley, G., C. Fish, C. Swenson, R.Burt, E. Stromberg, T. Neilsen, S. Burr, A. Barjatya, G. Bust, and M. Larsen, Dynamic Ionosphere Cubesat Experiment (DICE), SSC11-XII-6, Proceedings of the Small Satellite Conference, Logan, UT, August, 2011.

Crowley, G., M. Pilinski, C. Swenson, C. Fish, A. Barjatya, I. Azeem, et al., Modeling and
Observations Of Storm Enhanced Densities in the Ionosphere During The March 17th, 2013 Geomagnetic Storm, in preparation, Space Weather Journal, 2013.

Crowley, G., M. Pilinski, C. Swenson, C. Fish, A. Barjatya, I. Azeem, et al., Ionospheric Response to Geomagnetic Activity during March 2013, *in preparation,* Journal of Geophysical Research, 2013.

C.S. Fish, C. M. Swenson, G. Crowley, A. Barjatya, T. Neilsen, J. Gunther, I. Azeem, M. Pilinski,
R. Wilder, J. Cook, J. Nelsen, R. Burt5, M. Whiteley, B. Bingham, G. Hansen, S. Wassom, K. Davis, S. Jensen5, P. Patterson, Q. Young, J. Petersen, S. Schaire, C. R. Davis, M. Bokaie, R. Fullmer, R. Baktur, J. Sojka, M. Cousins, Design, Development, Implementation, and On orbit Performance of the Dynamic Ionosphere CubeSat Experiment Mission, manuscript in submission, Space Science Reviews, 2013.

The Mission Operations Center (MOC) is run by students at USU/SDL.

Fish, C., C. Swenson, T. Neilsen, B. Bingham, J. Gunther, E. Stromberg, S. Burr, R. Burt, M. Whitely, G. Crowley, I. Azeem, M. Pilinski, A. Barjatya, and J. Petersen, DICE Mission Design, Development, and Implementations: Success and Challenges, SSC12-XI-1, 26th Annual AIAA/USU Conference on Small Satellites, 2012.

Jandak, M., R. Fullmer, An Extended Kalman Smoother for the DICE Mission Attitude Determination Post Processing with Double Electrical Field Probe Inclusion, 2011, AAS 11-598.

Neilsen et al., The DICE Satellite Communications (Specifics of implementing high-speed communications on the DICE CubeSats), manuscript in preparation, 2013.

Pilinski, M., G. Crowley, C. Swenson, C. Fish, A. Barjatya, I. Azeem, et al., Field-Aligned Current Observations using the Dynamic Ionosphere CubeSat Experiment (DICE) Body Mounted Magnetometer, in preparation, Journal of Geophysical Research, 2013.

Ryan, K., R. Fullmer, S. Wassom, Experimental Testing of the Accuracy of Attitude Determination Solutions for Spin-Stabilized Spacecraft, 2011, AAS 11-599.

Swenson et al., DICE Communications System Overview, manuscript in preparation, 2013.

Data Archive

The DICE science data will be made publicly available online by ASTRA LLC and will be hosted on the ASTRA website. The following is a summary of DICE data products which will be made available in netcdf and ASCII formats. The L1 products include plasma densities, plasma temperatures, and magnetic residuals and will be made available with a resolution of approximately 1 degree latitude. The L0 data products will be made available at a cadence of 30Hz. Documentation will be provided on the ASTRA website which describes the data processing.

- Langmuir Probe Data
  - DC Langmuir Probe
    - L0 probe data
      - Date and time, Counts, latitude, longitude, altitude, spacecraft temperature, IRI density and temperature, IDA4D density and temperature
    - L1 normalized plasma densities
      - Date and time, Julian date, Density, latitude, longitude, altitude, IRI densities and temperatures, IDA4D densities

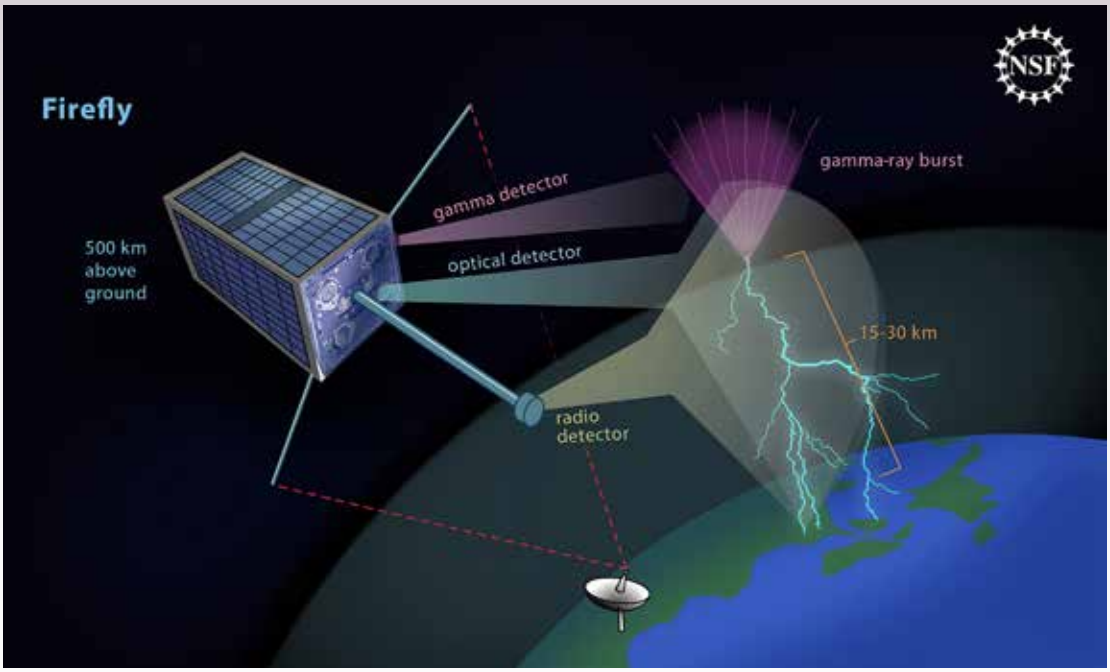
  - Sweeping Langmuir Probe
    - L0 sweep data
      - Date and time, Julian date, Sweep vector in counts, applied voltage vector, latitude, longitude, altitude, instrument temperature, IRI density and temperatures, IDA4D densities
    - L1 sweep data
      - Date and time, body-to-inertial frame quaternion, Julian date, Ion Density, Electron Density, Plasma Temperature, latitude, longitude, altitude, IRI densities and temperatures, IDA4D densities

- Magnetometer Data
  - Body-Mounted Magnetometer
    - L0 magnetometer data
      - Date and time, magnetometer vector in body reference frame, latitude, longitude, altitude, IGRF vector in geodetic reference frame
    - L1 magnetometer data
      - Date and time, magnetic residual vector in geodetic reference frame, latitude, longitude, altitude, IGRF vector in geodetic reference frame

Firefly and Firestation

Project Description

Lightning discharges represent the release of enormous amounts of energy and are associated with familiar and powerful manifestations near the Earth's surface: thunder, a bright flash, and powerful currents that can shatter trees and turn sand to glass. Lightning gives rise to



Firefly, a milk-carton-sized satellite, will study gamma-ray bursts that accompany lightning. Credit: Zina Deretsky, National Science Foundation.

x-ray and gamma-ray bursts, and unlike the well-known flashes of light and claps of thunder, these energetic rays are channeled upward and can be detected only from space. A CubeSat mission, called Firefly, sponsored by the National Science Foundation, will explore the relationship between lightning and these bursts of radiation called Terrestrial Gamma Ray Flashes (TGFs). Firefly demonstrates the capability of small missions such as CubeSats to do important, focused science, with abundant student involvement, and with a minimal budget and available resources. The Firefly Figure shows a cartoon of the processes involved in TGF generation.

Scientific Accomplishments

TGFs were first discovered by the Compton Gamma Ray Observatory in the mid-1990s. Since their discovery, the RHESSI, Fermi, and AGILE satellites have convincingly tied these events to lightning discharges, demonstrated that the gamma ray emissions extend up to millions of electron volts, and shown indirect evidence for energetic electrons and positrons that can escape the Earth's atmosphere and be magnetically trapped in the Van Allen radiation belts. These electrons are generated by secondary interactions of the TGF gammas with the upper atmosphere. However, none of these previous missions were dedicated to the study of TGFs and energetic electrons generated by thunderstorms. Firefly is the first dedicated mission to study TGFs, their link to lightning, and their effect in producing energetic electrons that may become stably trapped in the inner radiation belt.

TGFs are of inherent interest, as they result from the most powerful natural particle acceleration process on Earth, in which thermal electrons are energized to tens of millions of volts in less than one millisecond. By studying TGFs, we can learn fundamental physics critical in understanding not only lightning, but also solar flares, cosmic shocks, black holes, and even dust storms on Mars.

Inside the body of the Firefly CubeSat is the Gamma-Ray Detector (GRD). On the nadir side of the satellite are four photometers to optically detect lightning. Each photometer is angled slightly to obtain a general direction vector. The CubeSat is also equipped with a Very-Low Frequency (VLF) detector. Previous studies have shown correlation between ground-based VLF-detectors and TGFs.

Firefly is a small satellite (3.6 kg, 10x10x34 cm), that was designed, built, and tested as part of this NSF grant. The Firefly team is collaboration between Siena College and NASA. Students at all levels (grade-school to college) are involved in all aspects of the project, from design and development to mission operations and data analysis.

In addition to Firefly, a related mission called FireStation has been installed as part of the STP-H4 platform on the International Space Station (ISS). FireStation relies heavily on existing flight experience from the NSF-funded Firefly CubeSat mission, with some modifications to interface and sensors. FireStation consists of:

1) A sensitive miniaturized radio receiver, with onboard FFT capability, VLF search coil and VLF-MF (100 Hz to 30 MHz) electric antenna. The radio receiver has smart onboard processing, utilizing a new LEON in FPGA design independently developed by GSFC over the last year.
2) A novel phoswich energetic radiation detector, based on an ultrafast inorganic scintillator (GYSO:Ce), capable of dead times shorter than 1μs for high count rate applications. This detector represents the first flight of GYSO:Ce, which is similar to BGO, but provides a much faster response time, and has a very high radiation tolerance. The phoswich design of our energetic radiation detector also permits discrimination between energetic photons (X- and gamma-rays) and energetic electrons in the 100 keV to 5 MeV energy range.

3) A multi-channel photometer system, including multi-wavelength filters and high speed readouts, providing accurate localization of lightning flashes, as well as accurate timing at high resolution, and multi-wave length observation.

Technology

The gravity gradient boom provides attitude stabilization for Firefly as well as a sensitive VLF antenna. Early deployment testing in 2011 validated design but resulted in some need for

Instrument	Science products	Measurement range
Gamma Ray Detector (GRD)	Gamma Ray energy and time of arrival Energetic Electron energy and time of arrival Background spectra	50 keV to 20 MeV (photons) 100 keV to 2 MeV (electrons) count rates up to 100,000 / second
VLF receiver	ELF / VLF electric field waveforms	+/- 10 mV/m, sample rate 40 ksps, 16 bits
Optical Lightning Detector	Optical power waveform, some localization	98% of all lightning optical power, sample rate 40 ksps, 16 bits

rework of gearing, etc. Rework and testing of the GGB was accomplished in 2013. The instrument controller Field Programmable Gate Array (FPGA) was developed to support Firestation in 2012/2013 and then modified for the Firefly CubeSat in 2013. It connects the instrument to the flight software and flight computer.

Education

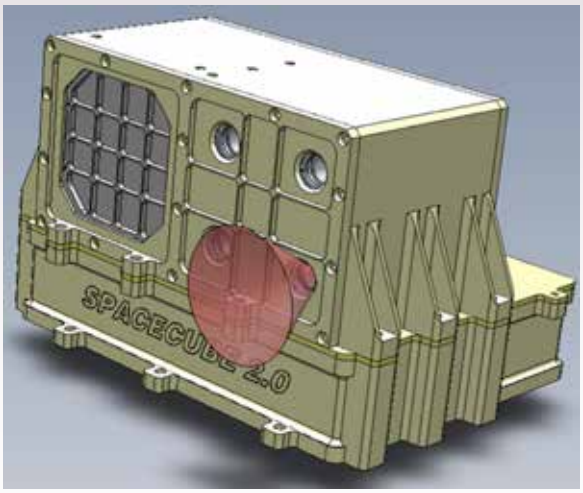
Both Firefly and Firestation have helped train undergraduates at Siena, obtaining hands-on experience designing, building, testing, and will train students on operating the spacecraft, as well as analyzing the data.

Specific course and tutorials at Siena College related to FireStation include:

- Orbital Dynamics
- Satellite Design and Engineering
- Spacecraft Instrumentation
- STK Certification

Students at Siena College worked on and/or started development of the following:

1) Experiment Expansion Modules, FFT, Filter bank, advanced triggering mechanisms
2) AWESOME VLF Receiver Development, Ground-based VLF support
3) GSE, MATLAB Instrument Control Toolbox
4) Instrument modeling, Optical photodiode collimator optimization
5) Data Processing and Analysis
6) LEGO Firefly Mission Development
7) Geographic Information System, Worldwide lightning network
8) STK, Satellite Toolkit Orbit Development



Firestation International Space Station Experiment.

Firestation being placed on the ISS.

AGU Student Presentations

- AE33B-0306. Firefly and FireStation: Missions to Study Terrestrial Gamma-ray Flashes, Kevin A. Melsert; Lindsay E. McTague; Nguyen Truong; Jack Sneeringer; Joshua DeJoy; Joseph T. Kujawski; Douglas E. Rowland; Allan T. Weatherwax

- SA31A-1958. A novel self-localization protocol for spacecraft clusters, Thaddeus Savery; Graziano Vernizzi; Joseph T. Kujawski; Riccardo Bevilacqua; Allan T. Weatherwax

Other Presentations

- Firefly: Understanding Earth's most Powerful Particle Accelerator, by A.T. Weatherwax et al., Fall Meeting of the Astronomical Society of New York, October 25, 2009.

- The Firefly CubeSat Mission, Doug Rowland et al., Dartmouth College Plasma Seminar Series, April 14, 2009.

- The Firefly CubeSat Mission, Doug Rowland et al., CubeSat Developers' Workshop, Cal Poly, San Luis Obispo, April 22-25, 2009.

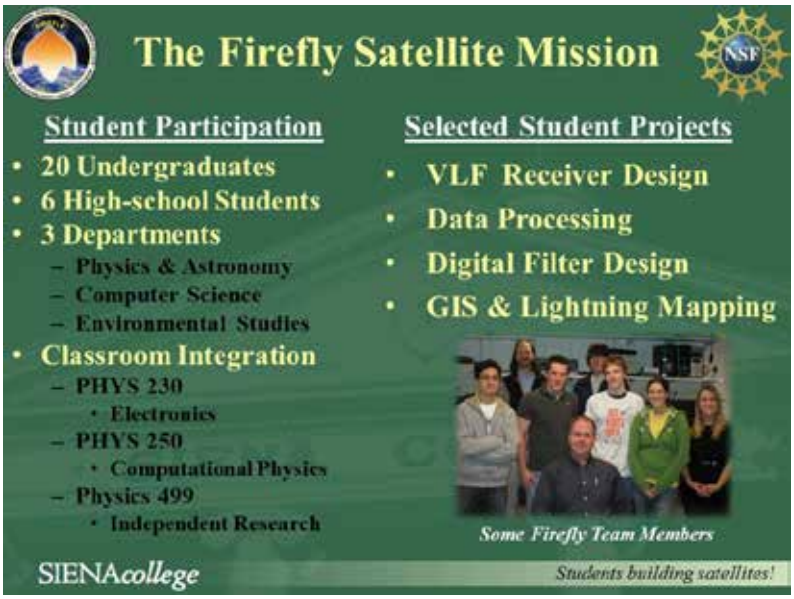
- The Firefly CubeSat Mission, A.T. Weatherwax et al., CEDAR CubeSat Workshop, 2009.

- The Link Between Lightning and Terrestrial Gamma Ray Flashes, Bill Wanamaker (high school student) et al., MA State Science Fair Finals at MIT, May 2009.

- Firefly: An NSF CubeSat Mission to Understand Earth's Most Powerful Natural Electron Accelerator by Allan Weatherwax (Siena College) and the Firefly Team, Union College Physics Seminar Series, September 17, 2009.

- The NSF Firefly Cubesat: Progress and status, Rowland, D. E., Weatherwax, A. T., Klenzing, J. H., Hill, J, AGU Fall Meeting 2009, abstract #SM42A-07

- FIREFLY: A CubeSat mission to study terrestrial gamma-ray flashes, Authors: Klenzing, J. H., Rowland, D. E., Hill, J., Weatherwax, A. T., American Geophysical Union, Fall Meeting 2009, abstract #SM33C-1577.



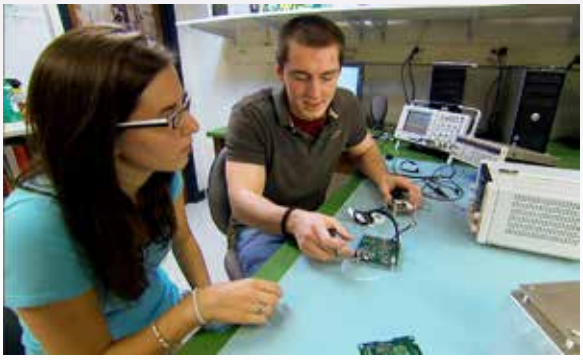
Students on Firefly and Firestation were involved in all aspects of spacecraft design and operation.

Student Profiles

High School student Josh Dejoy displays the CubeSat frame in the Siena Space Sciences Lab.

Josh Dejoy worked on Firefly and Firestation as part of a high school honors program for gifted and talented students. Josh competed in the Greater Capital Region Science and Engineering Fair at RPI and won several awards. He was also invited to compete in the National American Meteorological Science Fair. Josh graduated New Paltz high school first in his class in June 2013 and is currently a physics major at Geneseo College in New York.

Jack Sneeringer worked on Firefly and Firestation as part of the Shaker High School Research program. He competed in numerous New York science fairs where he won the Walter Eppenstein Astronomy/Physics Award and the American Meteorological Society Award for his efforts on preliminary Firefly data analysis. He is currently a computer science and physics major at Colgate University.



Jennifer Williams (left) and Robert Carroll are shown testing an early prototype of Firefly's photometer experiment.

Jennifer Williams graduated with a 3.73 GPA in physics at Siena College and is currently working on her Ph.D. in optics at Boston University and her O.D. at the New England College of Optometry. Robert Carroll, graduate with a 3.82 GPA as a physics major and is working on a Ph.D. in engineering at the College of Nanoscale Science and Engineering. Robert Carroll was student lead on the lightning photodetector design. A primary task was to calculate the field of view of the photodetector and the overlap function. Minimum and maximum field of view were calculated based on the geometry of the photodetector and collimator. As undergraduates, they were co-authors on the paper entitled, The NSF Firefly CubeSat mission: Rideshare mission to study energetic electrons produced by lightning, Aerospace, IEEE doi:10.1109 AERO.2011.5747231.

Jack Sneeringer worked on Firefly and Firestation.

Undergraduate physics major John DeMatteo lead the orbital mechanics effort. John was enrolled in the independent study course entitled "Orbital Mechanics", under the supervision of Professor Allan Weatherwax. In May, 2010, John became certified on the Satellite Took Kit (STK) software package from Analytical Graphics, Inc.

Lindsay McTague graduated Siena College in May 2013 with a B.S in physics and minors in mathematics and computer science. At Siena, Lindsay worked on both Firefly and Firestation

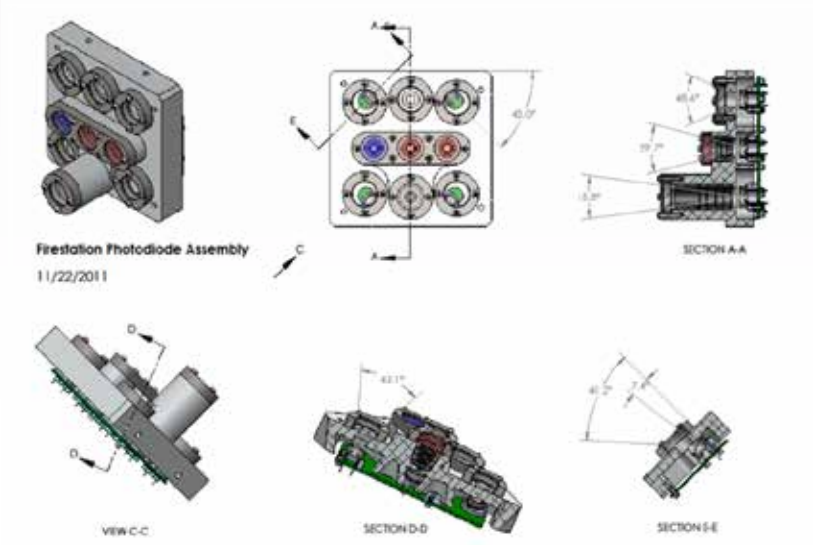
with support from the NSF. Lindsay primarily worked on the optical and mechanical design of the Firefly and Firestation photometer boards. She learned Solid Works and Matlab as part of research studies and helped construct the interface bracket for the photometer instrument that was recently deployed on the International Space Station. In addition, as part of her senior independent study project entitled, Space Mission Design Engineering & Operations, she became Satellite Tool Kit (STK) certified and worked on orbital analysis scenarios for both missions. Lindsay is currently enrolled at Duke University where she is pursuing a Ph.D. degree in electrical engineering.

Lindsay speaking at the NSF CubeSat panel.

Publications

- Rowland, D., A.T. Weatherwax, et al. (2011), The NSF Firefly CubeSat mission: Rideshare mission to study energetic electrons produced by lightning, Aerospace, IEEE doi:10.1109 AERO.2011.5747231.

(Left) Lindsay building Firefly in the Space Sciences Lab at Siena College. (middle) The photo-optical board that Lindsay helped design and build. (right) Firefly ready for launch!



The Firestation photodiode and optical assembly developed for the International Space Station. Undergraduate student Lindsay McTague was the lead on the mechanical design of this instrument.

Cubesat for Ions, Neutrals, Electrons and MAgnetic fields (CINEMA)

Project Description

The CINEMA spacecraft showing the MAGIC sensor and 1m stacer boom.

The Cubesat for Ions, Neutrals, Electrons and MAgnetic fields, or CINEMA, is a 3U spacecraft built by students at the Space Sciences Laboratory (SSL) at the University of California Berkeley (UCB). CINEMA carries two exciting new science instruments, one of which was developed explicitly for this project. The Supra-Thermal, Electrons, Ions and Neutrals (STEIN) detector is a 32-pixel silicon detector with a remarkable 2-4keV energy threshold and peak energy range of 200 keV. STEIN uses the same thin window technology that UCB pioneered for the STEREO-STE instrument, but combines it with a newly developed ASIC, provided by CEA-Saclay (The French Atomic Energy Agency) to expand from 4 channels to 32 while reducing the power and volume to the point where inclusion in a CubeSat became feasible. CINEMA also carries MAGIC, a magnetoresistive magnetometer that was provided by Imperial College-London. It has paired inboard-outboard sensors, the second placed on a deployed 1-meter stacer boom designed at Berkeley. This instrument is also remarkably sensitive (~nT) with development driven by the need to be low mass and low power. The MAGIC sensor head is ~1cm^3 and weighs 10g. The CINEMA project was extended to four spacecraft of roughly equivalent design through collaboration with Kyung-Hee University (KHU) of Seoul, Korea. KHU has built two additional copies of the CINEMA spacecraft and UCB has added a fourth copy with additional funding from NSF and Air Force research Labs. Together, MAGIC and STEIN are designed to provide high science quality observations of the earth's ring current, precipitating charged particles and the magnetic field in its orbit.

Scientific Accomplishments

CINEMA has been operating since its launch in September 2012, but science operations are only now ramping up. Two technical issues with the spacecraft bus have necessitated significant investigative effort and workarounds. As a result, after a year on orbit, the inboard and outboard MAGIC sensors can now successfully be operated, and the operations team is working to turn on the STEIN instrument shortly. The continuing efforts of the CINEMA team on the first spacecraft bus on orbit have allowed key design changes to be determined, progress that will be invaluable as the upcoming launch of CINEMA 2 and 3 approaches as well as the fourth copy. The first issue is command uplink reliability in the few percent range. This appears to be primarily interference between the UHF receiver onboard and other spacecraft systems. However, we have increased the antenna gain we use on our groundstation and modified our operations mode such that we have recently been getting significantly higher command throughput. This provides a path to resolve the second issue, involving a lockup of the primary data storage SD card. This issue is harder, as card reads/writes were tested thoroughly on the ground both before launch and on the engineering model post launch, with no success in recreating the issue in the lab. Workarounds for small volumes of data have been developed to allow commanded science data collection and these show initial success. The second through fourth 'copies' of CINEMA have improved software reliability, significantly better uplink margin and other smaller revisions to the original's design.

Technology

The CINEMA instrument payloads have attracted significant attention. In addition to the multiple future copies of CINEMA that are in the pipeline (KHU launches its pair of CubeSats late 2013), MAGIC has been adapted for inclusion in other CubeSats and STEIN has been adapted into an instrument that is slated to be launched on the European Space Agency's Solar Orbiter mission. Detectors that are more highly modified have been proposed for science areas as far ranging as understanding lunar surface features and shock accelerated plasmas at the sun. CINEMA additionally broke new ground for data rates on a CubeSat, utilizing the existing S-band infrastructure for downlink available at Berkeley. CINEMA's development and operational hurdles have proved instructive as well, with numerous lessons learned in the management and development of such a complex, multi-institution, multi-spacecraft project. Some of these lessons learned have been presented at the Cubesat Developers' Workshop, and all are being applied to the follow on CINEMA CubeSats, potential future CubeSats at UCB, partner institutions, and hopefully, throughout the CubeSat community. In particular the importance of handling student labor and student turnover on such a large project was recognized early and documentation requirements were implemented that made CINEMA's later years run far more smoothly than its early ones. The complexity of the system also demanded more system level testing than was scheduled or costed, partly because STEIN was such a large instrument development effort and took time from thorough spacecraft systems level testing. That said, CINEMA is a remarkable CubeSat effort.

The CINEMA student teams from Summer 2010 and 2011.

Education

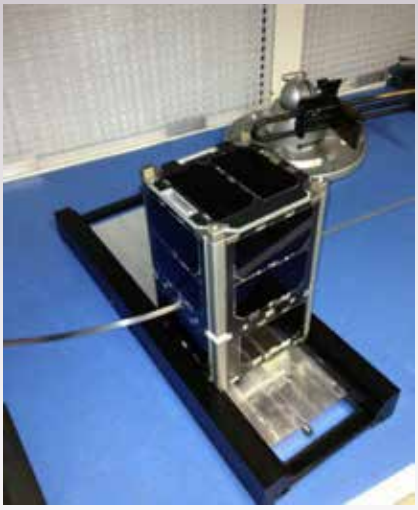
CINEMA involved 24 undergraduate students at UCB, four master's level students and one PhD candidate. The systems were primarily designed and implemented by the student workforce. Our four academic partner institutions employed more than the 16 students who visited Berkeley to help with various aspects of the development and take those lessons back to their own institutions. At least 10 of the UCB CINEMA students have gone on to early positions in aerospace engineering. A picture of the CINEMA teams from successive summers is included.

The CINEMA student teams from Summer 2010 and 2011.

Focused Investigations of Relativistic Electron Burst, Intensity, Range, an Dynamics (FIREBIRD)

Project Description

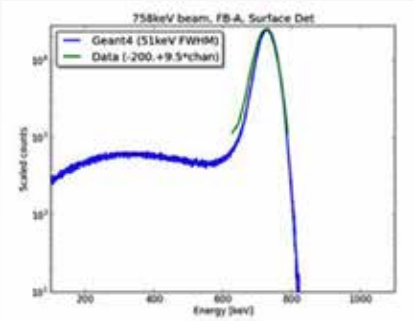
The mission a targeted, goal-directed, space weather Cubesat mission to resolve the spatial scale size and energy dependence of electron microbursts in the Van Allen radiation belts. Relativistic electron microbursts appear as short durations of intense electron precipitation measured by particle detectors on low altitude spacecraft, seen when their orbits cross magnetic field lines which thread the outer radiation belt. Previous spacecraft missions (e.g., SAMPEX) have quantified important aspects of microburst properties (e.g., occurrence probabilities), however, some crucial properties (i.e., spatial scale) remain elusive owing to the space-time ambiguity inherent to single spacecraft missions. While microbursts are thought to be a significant loss mechanism for relativistic electrons, they remain poorly understood, thus rendering space weather models of Earth's radiation belts incomplete.



FIREBIRD CubeSat.

Scientific Accomplishments

The FIREBIRD 1 CubeSat is launching in December, 2013 on NROL-39. It was delivered, integrated into the P-POD, integrated into the Naval Postgraduate School CubeSat Launcher (NPSCuL), attached to the Centaur Launch Vehicle (LV) upper stage, and stacked on the pad in September, 2013. The FIREBIRD 2 CubeSat is manifested to launch on a Delta II from Vandenberg in October, 2014, and will be delivered in July, 2014.



Beam Testing of FIREBIRD Instrument.

An engineering development unit (EDU) and two flight units were developed, and tested. Testing of the FIREBIRD instrument at Aerospace Corporation bracketed the full width at half-maximum (FWHM) of the electron beam. In March, 2013, the EDU passed a proto-qualification vibration test with a mass simulator. In April, 2013, FIREBIRD was presented at a Mission Readiness Review. IN May, 2013, the FIREBIRD instrument was successfully calibrated at Aerospace Corporation.

Education

FIREBIRD has provided unique opportunities for graduate students at Montana State University and the University of New Hampshire for hands-on education. One such student is Alex Crew. Crew, a Ph.D. candidate in the Space Science Center, at the University of New Hampshire Institute for the Study of Earth, Oceans, and Space (EOS), has spent three working on FIREBIRD. Crew presented a poster on FIREBIRD at a NSF workshop in Arlington, VA. He joined CubeSat project scientists, engineers, educators, and students from around the country to explore how CubeSat projects can enable scientific discoveries and engineering innovation and play a major role in helping solve critical societal problems related to, for example, climate change and space weather. See *http://www.eos.unh.edu/Spheres_0812/firebird.shtml*.

2014 PROJECTS

The following eight projects are planned to continue or begin in 2014:

Alex Crew holds FIREBIRD's full-size engineering unit, which contains twin particle detectors. The boxy structure to Crew's left is a copy of the miniscule FIREBIRD spacecraft. Photo by David Sims, UNH-EOS.

- Cubesat for Ions, Neutrals, Electrons, MAgnetic fields (CINEMA) – University of California, Berkley, Kyung-Hee U., Imperial College, Applied Physics Lab, Inter-American University of Puerto Rico, see *http://newscenter.berkeley.edu/2012/07/31/cinema-among-tiny-cubesats-to-be-launched-aug-2/*.

- Firefly/Firestation – GSFC, Hawk Institute for Space Sciences, Siena College, Firefly is manifested to launch in Nov. 2013, see *http://www.nasa.gov/topics/universe/features/firefly.html*. Firestation launched to the ISS on August 3, 2013, see *http://www.nasa.gov/content/goddard/firestation-to-international-space-station/*.

- Firebird – Montana State University, University of New Hampshire, Aerospace Corporation, manifested to launch in Dec. 2013, see *https://ssel.montana.edu/category/cubesat/*.

- Composition Variations in the Exosphere, Thermosphere, and Topside Ionosphere (EXOCUBE) – Scientific Solutions Inc., Cal Poly, University of Wisconsin, GSFC, scheduled for launch in October 2014, see *http://www.sci-sol.com/Exocube-Oct2011.pdf*.

- CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE) – University of Michigan, Naval Research Labs, manifested on an Atlas V, for launch in Oct., 2014, see *http://exploration.engin.umich.edu/blog/?page_id=961*.

- Oxygen Photometry of the Atmospheric Limb (OPAL) – Utah State University, University of Maryland, Eastern Shore (UMES), Hawk Institute for Space Sciences, Dixie State College of Utah.

- QB50/QBUS – Von Karman Institute (VKI) of Belgium, European Union (EU), see *https://www.qb50.eu/index.php/requirements-and-reviews/pdr-submission*.

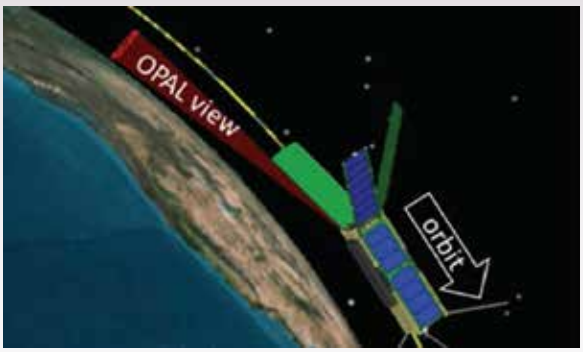
- Lower Atmosphere-Ionosphere Coupling Experiment (LAICE) – Virginia Tech, University of Illinois, Urbana, The Aerospace Corporation, Colorado Research Associates, see *http://www.space.vt.edu/news/articles/RockSat-X_Payload.html*.

Oxygen Photometry of the Atmospheric Limb (OPAL)

Project Description

The Oxygen Photometry of the Atmospheric Limb (OPAL) mission consists of one 3U CubeSat that is designed to understand the thermospheric temperature signals of the dynamic solar, geomagnetic, and internal atmospheric forcing. This mission can be addressed by remote sensing of the altitude temperature from the atmospheric limb from a mid- to high-inclination orbit (>50°) thus providing daytime observations of the mid- and low-latitudes. OPAL's team combines students, advisors, and professionals from Utah State University/Space Dynamics Laboratory, University of Maryland Eastern Shore, Hawk Instituted for Space Sciences, and Dixie State College to promote the training of the next generation of engineers and scientists.

Planned Scientific Accomplishments



OPAL instrument viewing the earth limb.

The OPAL temperature measurements in the lower thermosphere, and the scientific studies that can be conducted with them, are highly relevant to goals of the National Space Weather Program (NSWP), and to the NSF-sponsored community-wide Coupling, Energetics and Dynamics of Atmospheric Regions program. One of the main goals of the NSWP is "to mitigate the adverse effects of space weather by providing timely, accurate, and reliable space environment specifications." The lower thermosphere is an important element in this program because of its interface between the lower and upper atmosphere with variable solar forcing from above and dynamical wave coupling from below. Some of the tasks that are required to accomplish the primary goal of the NSWP include the development of a suite of sensors to provide the necessary observations, the development of data analysis algorithms, and scientific studies of space weather phenomena. OPAL addresses these elements.

The OPAL instrument is a high resolution imaging spectrometer that simultaneously collects spatially-resolved A-band spectra in multiple azimuthal directions and across the full altitude range of A-band emission. As the temperature increases, the relative intensity of the R branch (759 - 762 nm) increases and shifts to shorter wavelength while the P branch (762 - 770 nm) widens and shifts to longer wavelength. Thus, the neutral temperature (Tn) can be estimated from the qualitative shape of the A-band.

Over the next year, the team will complete the system requirements review, finalize the radiometric model, complete a Preliminary Design Review (PDR), and develop the engineering unit.

Planned Technology

The satellite bus will incorporate a number of unique features:

A. The satellite will point at the limb to within a few fractions of a degree and make lower thermospheric temperature measurements

B. The satellite will use the next generation high speed CADET radio link that will be supported primarily by the NASA WFF UHF station and secondarily by the DoD MC3 stations

C. The satellite bus is a COLONY2 bus

Planned Education

About 12 students will be involved from Utah State, University of Maryland Eastern Shore, and DIXIE State (in Utah). They will support development of the program in all areas, including science, instrument development, mission operations, test and calibration, and on-orbit operations.

QB50/QBUS

Project Description

QB50 is an international network of 50 CubeSats for multi-point, in-situ measurements in the largely-unexplored lower thermosphere and re-entry research. Led by the Von Karman Institute (VKI) of Belgium, the QB50 project is expected to be predominantly funded from the FP7 Grant by the European Union (EU). However, a funding gap exists, which is to be covered by the National Science Foundation.

QBUS efforts began in earnest in 2011 and received planning support from the National Science Foundation. Consortium members coalesced around a common architecture and design philosophy from broad community engagement during 2011 and member intuitions provided significant feedback and design efforts during regular workshops and telecoms.

In April of 2012, the consortium submitted a proposal to participate in QB50 for consideration to VKI. QBUS was notified that upon review the proposal was among the top of any proposing group from among 70+ proposals representing more than 25 countries.

In May of 2012, the consortium submitted a proposal to the National Science Foundation to help support the scientific investigations and broader impacts enabled by QB50 participation. Funding from NSF began in October 2013. The money from NSF allowed consortium student teams to begin building and testing the CubeSat buses. This also allowed teams to purchase Ion-Neutral Mass Spectrometer (INMS) instruments from the Mullard Space Science Laboratory (MSSL).

Planned Scientific Accomplishments

All 50 CubeSats will be launched together in April 2015 into a circular orbit at 320 km altitude, inclination 79°. Due to atmospheric drag, the orbits will decay and the CubeSats will be able to explore all layers of the lower thermosphere without the need for on-board propulsion, down to 90 or 100 km, depending on the quality of their thermal design. It is expected that the network will spread around the Earth within a month by deploying only one CubeSat during each orbit. The lifetime of the CubeSats from deployment until atmosphere re-entry will be less than three months.

The QBUS team will build four identical 2U CubeSat flight units, with participating members providing the usual satellite functions (attitude determination and control, uplink and downlink telecommunications, power subsystem including a battery and body-mounted solar cells, on-board data handling and storage by a CPU). The QBUS team has selected the Mullard Space Science Laboratory (MSSL) Ion-Neutral Mass Spectrometer (INMS) sensor from the three QB50 options. Each university on the QBUS team will provide a flight unit with the integrated payloads provided by QB50, which will be delivered to Draper Laboratory for final testing, checkout and ITAR compliant shipment. Furthermore, QBUS will procure additional components for qualification and testing during the build phase, providing additional risk mitigation, spare parts, and lowered costs (5+ component prices are significantly lower). Testing and delivery will be commensurate with the specified QB50 timeline.

This first-of-a-kind thermospheric constellation of CubeSats will allow the investigation of the transition region between 100 – 300 km. This area of the atmosphere ranges between well mixed, neutrally dominated forcing and heavily ionized, electrically dominated forcing. The change from pressure gradient driven responses to electric field driven dynamics provides a

source term for momentum and energy transfer that is highly dynamic and often unpredictable. This leads to uncertainty in the behavior of density, winds, and temperatures of both the ions and the neutrals. There is also a lack of understanding of atmospheric composition in this region due to scarcity of measurements as well the influence of background parameters, chemistry, and forcing from the lower thermosphere.

The INMS on each of the four QBUS CubeSats can uncover new information about the composition and variability of the lower thermosphere. When combined with the full suite of instrumentation in the QB50 constellation, both the ionized and neutral state parameters of the atmosphere/ ionosphere, its variability, response, and interconnections can be uncovered. In addition to curiosity-driven science that aims to determine the governing physics of the region, the QB50 mission will also provide a practical application for measurements related to satellite drag. In a time when satellite presence in LEO continues to expand and de-orbiting satellites have become more common, it is important to be able to predict where these satellites might re-enter the atmosphere to ensure human safety. This requires better characterization of the lower thermospheric mass density and winds.

Further, the lower thermosphere and ionosphere are highly dynamic, with auroral, solar and tidal inputs all mixing together. This means that it is crucial to have multipoint measurements if we are to understand how the system evolves over time. The constellation approach, both within the consortium and across the instrument suites on the QB50 CubeSats, will provide a new set of transformative measurements that will lead to an enhanced understanding of the region as well as new predictive capabilities.

Planned Technology

Each of the 2U CubeSats for QBUS will have a University of Michigan (UM) structure with two deployed solar panels to form "wings", allowing more solar energy to be collected, as shown in the figure. The two fundamental requirements of the QB50 satellites are to fly the instrument package facing in the ram direction and to minimize the drag to allow for longer lifetime. Therefore, the QBUS CubeSats will be flown with the instrument pointed into ram and the "top" rotated in such a way to maximize solar collection, allowing us to maximize the operation the instruments in each orbit. Each of the proposed QBUS CubeSats is designed to carry an INMS package. Communication with the ground will occur via a Lithium UHF radio, which has flown on many of the NSF missions. The power system will be the previously flown University of Michigan (UM) designed system (blend of the RAX, RAX-2 and M-Cubed EPS systems). The on-board computer will be the MSP430, which has flown on a wide variety of missions, and has a large software base designed for it from UM and University of Colorado (CU). The attitude determination and control system (ADCS) will be a magnetic torque rod only system with heritage from UM (through CADRE) or the MAI-QB50 single wheel system. The UM system is baselined, but the viability of the MAI-QB50 will be investigated in terms of cost, mass and complexity by the preliminary design review (PDR).

QBUS Cubesat cut-away layout.

Planned Education

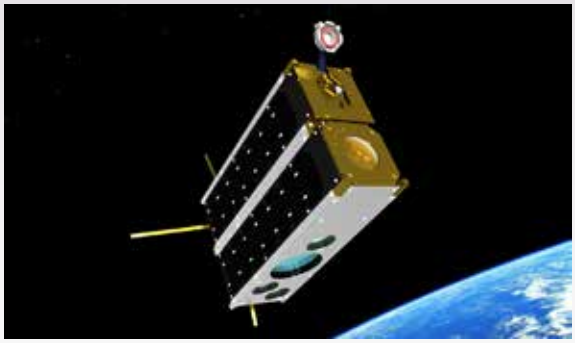
Currently, QBUS (QB50 US) is a consortium of seven US institutions (three research universities, one Hispanic minority undergraduate university and two national laboratories, and 1 small business) all with significant CubeSat and science experience.

QBUS enables students' science and hands-on engineering experience within a University/ Laboratory consortium expanding access to participation and provides valuable professional contacts. The goal is to have over 200 participating students. This will include a large number of unrepresented grounds, such as Hispanic students from a minority serving undergraduate institutions in Puerto Rico.

Lower Atmosphere/Ionosphere Coupling Experiment (LAICE)

Project Description

LAICE is a low Earth orbit (LEO) CubeSat mission focused on understanding how waves generated by weather systems in the lower atmosphere propagate and deliver energy and momentum into the mesosphere, lower thermosphere, and ionosphere (MLTI). These waves are a vitally important but under-explored facet of atmospheric physics. They strongly influence the dynamics of the media through which they travel by modifying the structure of the atmosphere at altitudes well above their source regions, and they may seed the development of plasma instabilities that scintillate and disrupt radio propagation. Our experiment will be the first global satellite investigation to focus entirely on these waves, and to attempt to connect their causes and effects in three widely different altitude ranges. In-situ instrumentation aboard LAICE will measure the perturbations the waves produce in both neutral and ion densities at F-region heights, while on-board photometers will simultaneously measure the wavelengths and amplitudes of the wave fields in the upper mesosphere. Subsequent modeling coupled with meteorological data will reveal the connections between tropospheric storms and the MLTI system using state-of-the-art ray tracing techniques that include the effects of wave dissipation.

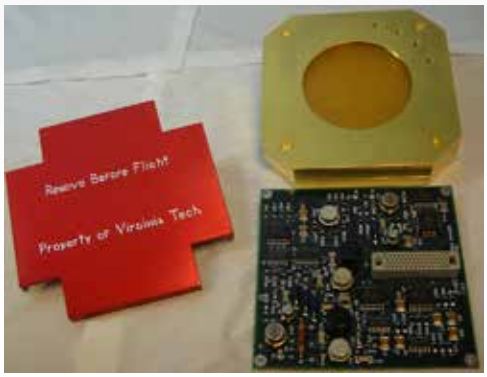


LAICE in Orbit.

Planned Scientific Accomplishments

The preferred orbit for LAICE is circular at 375-400 km altitude, at an inclination near 45 degrees. This orbit will allow the system to:

1. Systematically observe gravity waves with large vertical wavelengths at lower F-region heights, and correlate on a global scale remotely-sensed wave-induced airglow perturbations in the upper mesosphere with in-situ measurements of ion and neutral density fluctuations at higher altitudes;



Retarding Potential Analyzer for the LAICE system.

2. Produce global maps of active gravity wave regions in the mid- and low-latitude ionosphere over multiple seasons at all local times, so that global patterns and climatological variations can be quantitatively compared to and correlated with terrestrial weather systems via ray-trace modeling.

The LAICE project was funded early in the summer of 2013, so to date the team has carried out design work on the instrumentation and flight software. Some hardware has been fabricated (see the Retarding Potential Analyzer (RPA) figure), and schematics have been generated for the instrumentation systems. Testing of the flight software has begun using simulated data streams. The UI and VT teams hold weekly telecoms to foster collaborative design efforts between the groups.

The LAICE in orbit figure shows a cartoon view of the LAICE system to provide a better understanding of the overall configuration.

Planned Technology

This is the first 6 U CubeSat funded by NSF, and it includes 3 distinct instruments. One of the instruments (Space Pressure Sensor) comprises a technology demonstration component utilizing cold field emitters as a space-based ionization source. The bus for the LAICE satellite includes the ILLINI-2 bus which includes magnetic torque for attitude control using coils imbedded in flex circuits. A mechanical structure using a rail assembly provides a simplified assembly and expands to various CubeSat dimensions. The solar panel substrates are a carbon epoxy for low mass considerations. Both a Cadet Radio (460-470 MHz) which was well tested on the two DICE spacecraft and an amateur band radio (437 MHz) are planned for communication. The amateur band radio includes a unique modem using a Digital Signal Processing (DSP) microprocessor.

Planned Education

From the educational standpoint, VT does not have a specific course built around the LAICE project, but elements of the LAICE design will be accomplished through a senior design course. In addition to this, various elements of the LAICE project are forming the basis for graduate thesis and project work (M. Engineering degree). Five VT graduate students are utilizing LAICE design efforts to satisfy their research/design degree requirements, and three undergraduates are assisting in these efforts.

The planned educational elements at UI include the direct involvement of Electrical and Aero Engineering students in a Senior Design class named 'Cubesat'. The LAICE satellite development activities in the class laboratory will involve the LAICE satellite development and testing. It is estimated that 15 students will be in the class. A 5-6 experience student team will continue software development for the bus (3 students) and 2-3 others will work hardware and testing.

Cubesat for Ions, Neutrals, Electrons and MAgnetic fields (CINEMA)

Project Description

The Cubesat for Ions, Neutrals, Electrons and MAgnetic fields, or CINEMA, is a 3U spacecraft built by students at the Space Sciences Laboratory (SSL) at the University of California Berkeley (UCB). CINEMA has one operating spacecraft and is scheduled to become a four satellite constellation mission with the ultimate goal of imaging the Earth's dynamic ring current through remote sensing of Energetic Neutral Atoms (ENAs). ENAs represent a unique way to remote sense energetic plasma populations and CINEMA pushes the instrumentation to study these particles from 4keV to hundreds of keV into remarkably small packages. CINEMA-2 and -3 are slated to be launched by collaborating institutions in Fall, 2013 and the 4th copy is planned for launch in mid-2014. These additional copies of the CubeSat have solved numerous operational issues found in the first CINEMA and expectations for good science return are high.

Planned Scientific Accomplishments

CINEMA hopes to become the first CubeSat mission with four operating 3U CubeSats imaging the Earth's ring current from multiple perspectives. The constellation of satellites will make coordinated measurements and will complement nicely with the in situ measurements being made by larger satellites, such as the two satellite Van Allen Probes, and the multi satellite THEMIS mission. CINEMA's sensitive STEIN instrument with multiple viewing angles has the capability to make the highest time resolution images of injections into the earth's ring current and study the early time profile of ring current growth across all local times. Software to integrate the multiple viewing angles into improved spatial information is under development and should provide a tool for additional future ring current ENA observations.

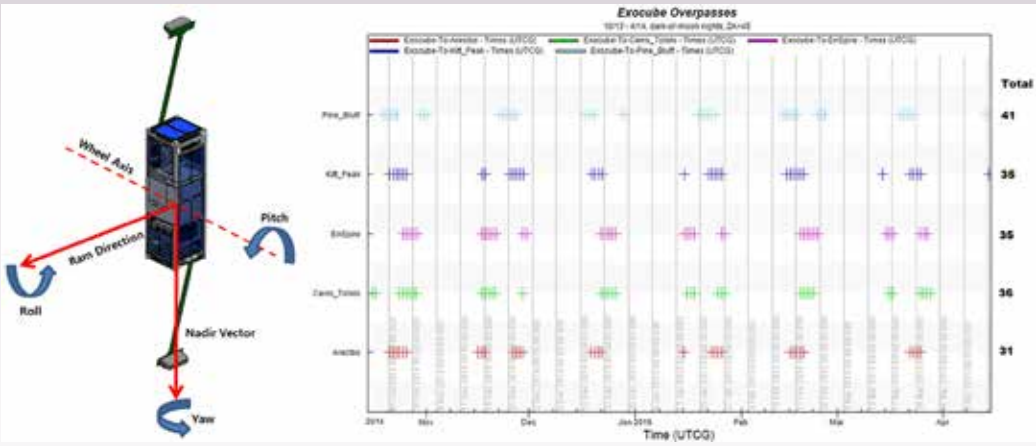
Planned Technology

Lessons learned from CINEMA 1 are being incorporated into CINEMA 2, 3 and 4 spacecraft will be shared with other teams through the monthly NSF Principal Investigator (PI) teleconferences.

Composition Variations in the Exosphere, Thermosphere, and Topside Ionosphere (EXOCUBE)

Project Description

The ExoCube satellite is being developed by Scientific Solutions, NASA Goddard, California Polytechnic State University, University of Wisconsin and University of Illinois. The primary mission of the satellite is to measure [O], [H], [He], [O+], [H+], [He+] over the poles and over incoherent scatter radar (ISR) ground stations. Data from the satellite and the ISR stations will be compared.



Left: ExoCube orientation on-orbit. Right: With updated orbital parameters, ExoCube's observatory overpasses can be predicted for timing coincident ground based airglow observations.

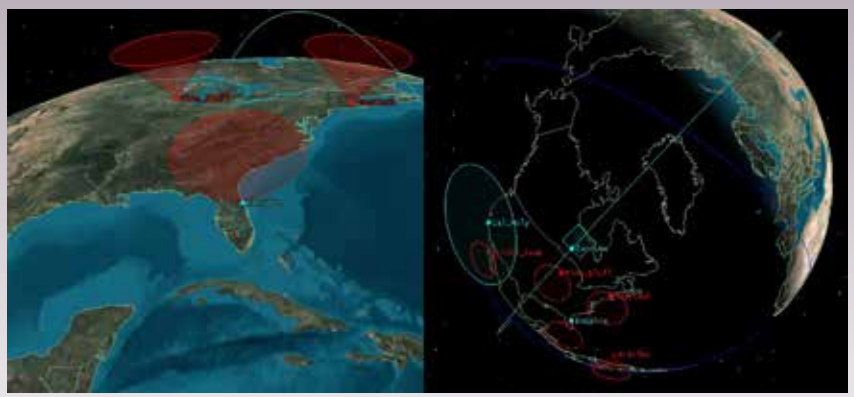
ExoCube is on ELaNa-X SMAP, –scheduled for launch in October 2014. The orbit will be approximately 400 x 670 km altitude and 98° inclination with an expected orbital lifetime of eight years. Expected minimum mission life will be six months. The figures below show ExoCube and its orientation in orbit and the expected overpasses of ground based observing sites.

Planned Scientific Accomplishments

The ExoCube mission is designed to acquire global knowledge of the in-situ densities of [O], [H], [He], [O+], [H+], [He+] in the upper ionosphere and lower exosphere, using a gated time-of-flight spectrometer. Atomic oxygen and helium have not been measured in situ since the early 1980s during the era of the Dynamics Explorer and then only for 18 months. Atomic hydrogen has never been directly measured in situ in this region. By providing benchmark measurements over Arecibo, Wisconsin, Kitt Peak, and Cerro Tololo, ExoCube aids in the validation and inter-comparison of ground-based observations from these sites using passive optical interferometry and photometry of neutral airglow emissions as well as active ISR to characterize the local ionosphere.

ExoCube density measurements will be used to characterize the climatology of the upper ionospheric and lower exospheric composition. The combination of orbital inclination and precession will enable a robust assessment of diurnal density and composition variations, while the expected minimum six-month mission lifetime will facilitate comparisons between equinox and solstice conditions. Key scientific objectives include investigation of upper atmospheric global, diurnal, and seasonal variability, charge exchange processes, atmospheric response to geomagnetic storms, and validation of empirical and climatological atmospheric models (e.g. MSIS, TIE-GCM). ExoCube measurements of in-situ neutral hydrogen also help constrain retrievals of

aeronomical parameters of interest from airglow observations and forward radiative transfer modeling.



LEFT: an STK model of ExoCube orbits passing over ground based sites. RIGHT: a view of ExoCube passing over ground based observatories; the red circles are the field-of-view of the ground based instruments at the nominal orbital altitude.

A ground-based remote sensing observation of the fluorescent Balmer α column emission from atomic hydrogen is one of the primary methods for studying the hydrogen distribution in the upper thermosphere and exosphere. These measurements are sensitive not only to thermospheric and exospheric atomic hydrogen density, but also to the solar excitation flux and radiative transfer, including multiple scattering of the solar Lyman β excitation radiation below the Earth's shadow. Geophysical quantities are retrieved by reconciling these observations with forward model predictions based on specification of a model hydrogen distribution function and calculation of radiation transport (RT) to account for the significant multiple scattering in the geocorona. ExoCube measurements of in-situ hydrogen densities with near coincident ground-based Balmer α will provide an independent constraint to these retrievals of the hydrogen density profile and flux.

Charge exchange processes involving H, O, H+, and O+, are important for sustaining nighttime F-region ionospheric density as well as for governing thermal equilibrium and non-equilibrium atmospheric escape processes. The equations governing such processes (the proton continuity equation and the O+ momentum and energy balance equations) require accurate specification of relevant species densities in order to isolate key charge exchange collisional cross sections as the only free parameters. Since these rate coefficients are not well characterized by laboratory measurements, the ExoCube constraints will thus enable more accurate determination of the rate coefficients and hence retrieval of the both O and H density from past and future ground-based observations.

ExoCube in-situ observations will provide a data set that can be used for validation of both empirical and climate models. Thermospheric hydrogen densities in the empirical NRLMSISE-00 model are derived from charge exchange equilibrium analyses of Atmospheric Explorer satellite simultaneous observations of H+, O+, and O. Comparisons of ground-based hydrogen emission observations with MSIS indicate discrepancies. ExoCube in-situ measurements [H], [O], and [He] will be compared with MSIS at different latitudes and during different diurnal and seasonal conditions. Similarly ExoCube in-situ measurements of neutral densities will provide a resource for validation of climate models such as the Thermosphere-Ionosphere-Mesosphere-Energetics Global-Circulation-Model (TIME-GCM) and the thermospheric extension of the Whole Atmosphere Community Climate Model (WACCM). In situ measurements of hydrogen will also help validate the upper boundary conditions for hydrogen chemistry and composition included in these models.

Planned Technology

Environmental Chamber

The Environmental Chamber is the housing for the two scientific instruments, a miniaturized mass spectrometer and an ion sensor. It is designed to secure the instruments and provide the necessary conditions for accurate data collection. The chamber incorporates the following features:

- Shape Memory Alloy Wire Actuators
    - Allow for the controlled release of hatches covering inlet ports
- Adjustable Check Valve
    - Used to fill the chamber with Sulfur Hexaflouride (SF6)
    - Provides unidirectional flow
- Umbrella Valves
    - Seal the chamber until specified pressure differential is reached
    - Serve as exhaust ports for the Sulfur Hexaflouride
- Silicone O-Ring Gaskets
    - Maintain positive pressure in the chamber
    - Provide a low-outgassing seal

Attitude Determination Control System (ADCS)

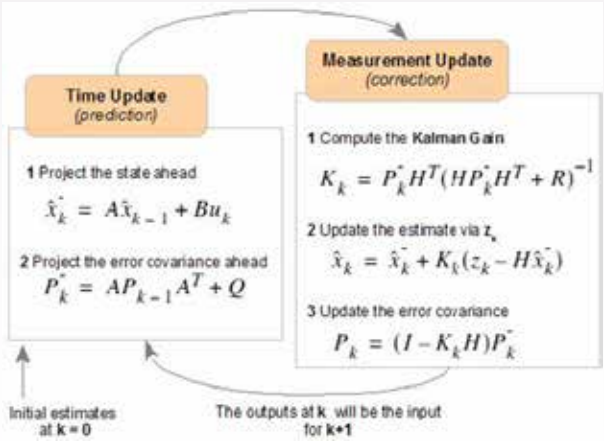
To achieve accurate measurements, there are pointing and orientation requirements for the mission. The satellite must maintain a Nadir pointing of +/- 10 degrees and a ram knowledge of +/- 5 degrees. To maintain these requirements, an attitude determination control system (ADCS) was developed by PolySat and integrated on the satellite. The control system has the following components:

- Gravity Gradient system with deployable booms
    - o Provides passive control of the system with no power
    - o Helps maintain pointing and rate of change of the satellite with ADCS turned off
    - o Provides stability during momentum wheel spin up
    - o Booms developed in-house
- Sinclair Momentum Wheel
    - o 10-mNm momentum wheel
    - o Orientated on pitch axis to provide rigidity and stability of pointing
    - o Couples roll and yaw axes together to provide gyroscopic stability
- Kalman Filter
    - o Calculates orientation based on SGP4 propagator, solar array measurements, and magnetometers
    - o Filters out noise from sensors, actuators, and other system disturbances to achieve accurate orientation
    - o Acquire initial orientation using TRIAD algorithm
    - o Stays on for duration of mission
    - o Works for eccentricities < .1 and rates < 10 degrees/second
- PD controller
    - o PD control law developed by Bong Wie for a gravity gradient ADCS
    - o Chosen for simplicity and power efficiency
    - o Proven global stability by Bong Wie

- Sensors and Actuators
    - o Magnetometers for reading magnetic field
    - o Solar array sensors for calculating orientation in reference to the sun
    - o Magnetorquers, designed by PolySat, for torqueing and controlling the satellite
    - o Gyroscope for verification of rates
- Z-panel camera
    - o Omnivision 3 Megapixel camera with 25 degree field of view
    - o On both z-panels
    - o Used for verification of boom deployment
    - o Can calculate rates and orientation of satellite with several successive pictures
    - o Derivative imaging scales the images down to make download from satellite quicker and easier
    - o Cameras were tested on CP8 balloon launch and are on CP8 which is scheduled for launch at the end of 2013

Planned Education

A new remote sensing instrument (Spatial Heterodyne Spectrometer) for Balmer-alpha airglow measurements (coincident with in-situ ExoCube density measurements) has very recently been installed at Pine Bluff Observatory and is currently being field tested. SHS intensity and sensitivity calibrations are being conducted now by UW Madison graduate student Derek Gardner as part of his Ph.D. dissertation work. This SHS is expected to be fully operational by next summer and will be one of several optical instruments contributing to the coordinated ground based campaign observation efforts of the ExoCube mission.



Proposed Kalman filter for ExoCube.

Senior Projects

- Kyle Teixeira and Melody Golobic (Submitted), Polysat ExoCube Environmental Chamber Design and Testing.

- Brian Gilbert Tubb (2012), Radio Link Analysis and Characterization of Past and Future Cal Poly CubeSats.
  http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1195&context=eesp

- Blake Simon (2013), ExoCube Structure.

- Dominic Burtillino (2013), Implementing a MATLAB Based Attitude Determination Algorithm in C within the PolySat Software Architecture.
  http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1080&context=cpesp

- Matt Zimmerer (2013), Leo Nano-Satellite Clock Synchronization Software.
  http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1107&context=cpesp

Master Thesis

- Ryan Sellers (2012), A Gravity Gradient, Momentum-Biased Attitude Control System for a CubeSat.
  http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=2057&context=theses

- Arash Mehrparvar (In Progress), Kalman Filter Design and Attitude Design.

- Austin Williams (In Progress), Compact, Reconfigurable UHF Communication System for use with PolySat's Embedded Linux Platform.

- Sean Fitzsimmons (2012), Reliable Software Updates for On-orbit CubeSat Satellites.
  http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1849&context=theses

High School Balloon Launches

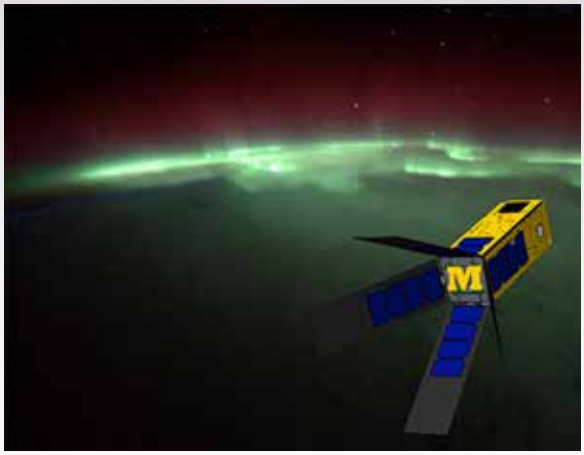
CalPoly has been doing an outreach program with local high schools for the last three years. The high school students participate in the program over summer on the college campus. The students brainstorm project ideas and mission goals for a payload on a high altitude balloon. The CalPoly students teach the process for a typical mission from proposal to flight. The high school students then follow a similar process for their payload as the CalPoly students assist. Payloads typically include a camera controlled by a micro controller along with environmental sensors. CalPoly facilities are used by the students to help create their payload. The balloon is tracked with amateur radio equipment and a GPS transmitting to APRS stations for live tracking. The students and the CalPoly team then track the balloon as it ascends and descends with a parachute. *See http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=3945&context=pao_pr.*

The CalPoly ExoCube team!

Cubesat investigating Atmospheric Density Response to Extreme driving (CADRE)

Project Description

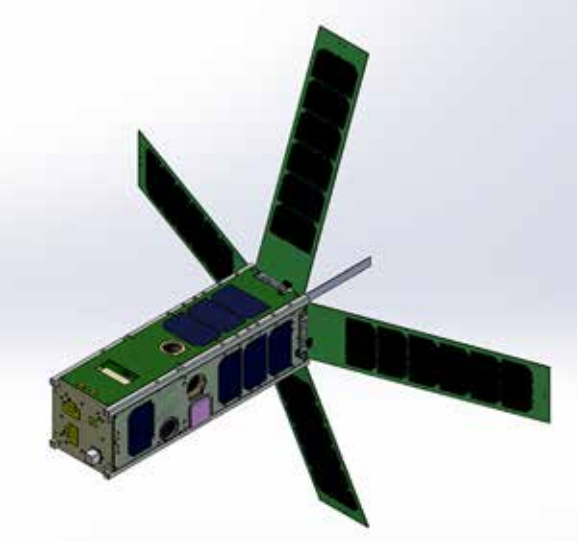
The Cubesat investigating Atmospheric Density Response to Extreme driving (CADRE) is a 3U CubeSat designed and built by undergraduate and Master's-levels students at the University of Michigan (UM). The scientific goal of CADRE is to study how the aurora deposits energy into the upper atmosphere and how the atmosphere responds to that energy in terms of waves, winds and compositional changes. CADRE will be launched in late 2014 on an Atlas V through the NASA Educational Launch of Nanosatellites (ELaNa) program into a high inclination orbit so that it can view the aurora on most orbits. The science payload of CADRE is the Wind Ion Neutral Composition Suite (WINCS), which will measure the thermospheric and ionospheric density, temperature, winds and composition using four electrostatic analyzers (ESAs) and two mass spectrometers.



CADRE Exploring the Ionosphere.

Planned Scientific Accomplishments

CADRE is aiming for a one-year science mission. The ESAs will be mounted in pairs, with one pair mounted perpendicular to the other pair. This will allow WINCS to measure the horizontal and vertical cross-track winds. The ESA will measure the bulk energy of the flow, which will allow the third component (the in-track wind) to be derived. One of each pair will measure the ion flows while the other will measure the neutral flows. In order to get the measurements required for the winds, CADRE will have to have three-axis stability to one degree of control and 0.1 degree of knowledge. This means that three reaction wheels will fly, a star tracker and two fine sun sensors.



CADRE Spacecraft Deployed.

The University of Michigan has launched three CubeSats into orbit - RAX, RAX-2 and M-Cubed. RAX and M-Cubed were somewhat different designs, with the M-Cubed students being essentially independent of any real faculty advise for the design phase of the mission, while the RAX students were being led by James Cutler. The team has recently delivered M-Cubed-2, which is a hybrid design between RAX and M-Cubed. CADRE is using significant technology that has been created for M-Cubed-2's avionics package.

Planned Technology

M-Cubed-2 was delivered in July, 2013. CADRE will use M-Cubed-2's Command and Data Handling board, which is based on a microprocessor running Linux. The Electric and Power

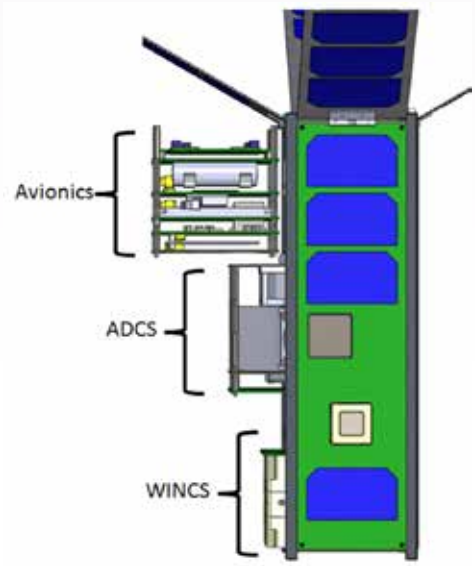
System (EPS) from M-Cubed-2 worked pretty well, but it was quite noisy, so the team is investigating a hybrid between the M-Cubed-2 and RAX EPS. This should only take a month or two to create. The basic design of the structure is completed, with the deployable panel and hinge designs nearly complete. The team has created mass models for each of the most expensive parts to allow us to shake the structure to limits of the launch vehicle. The UHF beacon is completed and will be mounted on the CDH board. The WINCS payload is being manufactured; with the WINCS interface board being delivered to UM in September, 2013.

The team has been working on many technological innovations for CADRE. For example, the S-Band radio is new. There are very few S-Band radios in a CubeSat form factor that can reach speeds of 1Mbps (Mega-bit-per-second). The team is developing one because it was felt that buying an existing one would require almost as much work as building one (interfacing, modulation, etc.). For the attitude determination and control system, CADRE is mostly using off-the-shelf parts, but assembling the entire unit with custom software. A Ph.D. student has been working on the algorithms for this, and it was felt that purchasing a complete package would not allow the flexibility of software that building one would offer.

CADRE 3-U Housing and Preliminary Design.

Planned Education

The two largest subsystems that need work are the S-Band radio, which is being built almost exclusively by the students. An experienced student did most of the design work on the radio over the last year, but graduated in April. He is continuing to help with the radio, but remotely. The students who are working on it now are learning as fast as they can and are debugging problems that arise. The Attitude Determination and Control System (ADCS) is made up of sensors (star tracker, fine sun sensors, rate gyros and a magnetometer) as well as actuators (reaction wheels and magnetic torque rods).



CADRE Main Components.

There is a group of students who are working on each of the different components. Two of the students are creating an electrical design of the entire system and are close to bread-boarding it up. They have flown some of the sensors (magnetometer and gyros) on balloon flights. The wheels have been ordered and delivered. A student has verified that they can get the wheels to spin. Software drivers have been written for many of the devices. In addition, a Kalman filter has been written to determine the orientation of the satellite given the sensor inputs. Further, a control algorithm has been implemented to drive the actuators. This combination of orientation and control software work together and have been tested on various platforms using synthetic data. The team is working on porting this over to a platform that will be consistent with the ADCS processor.

CADRE is being designed, built and tested by students at the undergraduate and Master's level at the University of Michigan. Over 50 students at these levels are working on CADRE

through different class projects (Aerospace senior design, and various Atmospheric, Oceanic and Space Sciences - AOSS - design classes) and during the summer through paid "internships". The vast majority of the students are Aerospace engineering students, but there are also many Mechanical and Electrical Engineering students. The Master's students are all Master's in Space Systems Engineering AOSS students.

CADRE Team.

There have been two Ph.D. students who have worked on CADRE, namely working on the design of the ADCS algorithms and determining the number of solar cells on the body and deployed panels. We have a new Ph.D. student who has just started in September 2013.

Publications

J.T. Hwang, D.Y. Lee, J.W. Cutler, and J.R.R.A. Martins, "Large-Scale MDO of a Small Satellite using a Novel Framework for the Solution of Coupled Systems and their Derivatives", Proceedings of the 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, MA, April 2013.

D.Y. Lee and J.W. Cutler, "Design optimization of a Solar Panel Angle and its Application to CubeSat 'CADRE'." In 2013 CubeSat Developers' Workshop, April 2013.

James Cutler, Aaron Ridley and Andrew Nicholas, Cubesat Investigating Atmospheric Density Response to Extreme Driving, 25th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2011 (SSC11-IV-7).

Presentations

Aaron Ridley and James Cutler, Using Constellations of Small Satellites to Address Large Problems, CEDAR, Boulder, CO, June 24-28, 2013.

Aaron Ridley and James Cutler, UM CubeSat Activities, CEDAR, Boulder, CO, June 24-28, 2013.

Aaron Ridley, James Cutler and Andrew Nicholas, Cubesat Investigating Atmospheric Density Response to Extreme Driving, CEDAR, Santa Fe, NM, June 25-29, 2012.

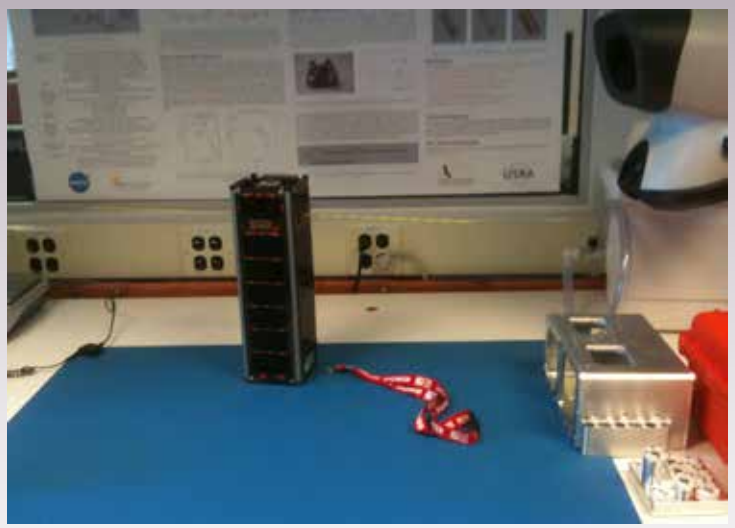
Aaron Ridley, James Cutler and Andrew Nicholas, Cubesat Investigating Atmospheric Density Response to Extreme Driving, CNSF, Washington DC, May 15, 2012.

Aaron Ridley, James Cutler and Andrew Nicholas, Mission Assurance Versus Cost - Thinking in a Smaller Box, AGU Fall Meeting, San Francisco, CA, December 5-9, 2011.

Aaron Ridley and many others, Armada - A Nanosat Constellation Mission to Study the Thermospheric Reaction to Energy Input Across All Scales, QB50 Meeting, Brussels, Belgium, May 2011.

Firefly and FireStation

Project Description



Firefly, assembled and ready for delivery for launch.

Lightning discharges represent the release of enormous amounts of energy and are associated with familiar and powerful manifestations near the Earth's surface: thunder, a bright flash, and powerful currents that can shatter trees and turn sand to glass. Lightning gives rise to x-ray and gamma-ray bursts, and unlike the well-known flashes of light and claps of thunder, these energetic rays are channeled upward and can be detected only from space. A CubeSat mission, called Firefly, sponsored by the National Science Foundation, will explore the relationship between lightning and these bursts of radiation called Terrestrial Gamma Ray Flashes (TGFs). Firefly demonstrates the capability of small missions such as CubeSats to do important, focused science, with abundant student involvement, and with a minimal budget and available resources. The Figure shows the Firefly CubeSat assembled and ready for launch.

Planned Science Accomplishments

Firefly and Firestation will soon answer the following science questions. What causes a TGF's high-energy flashes? Does it trigger lightning--or does lightning trigger it? Could it be responsible for some of the high-energy particles in the Van Allen radiation belts, which can damage satellites? See http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=124901. The Firefly CubeSat and Firefly ISS payload will return the first simultaneous measurements of TGFs and lightning. "Firefly (and Firestation) will provide the first direct evidence for a relationship between lightning and TGFs," says Weatherwax. "Identifying the source of terrestrial gamma-ray flashes will be a huge step toward understanding the physics of lightning and its effect on Earth's atmosphere."

Firestation covers a wider measurement range. It will take advantage of a camera, also onboard the ISS pallet, to snap photos of lightning flashes so that researchers can precisely locate where they are occurring. Furthermore, Firestation will enjoy a data rate that is about 3,000 times larger than Firefly's, which means the team will be able to sample every lightning stroke, instead of Firefly's carefully selected sample. See *http://www.nasa.gov/mission_pages/sunearth/news/firestation-rowland.html*.

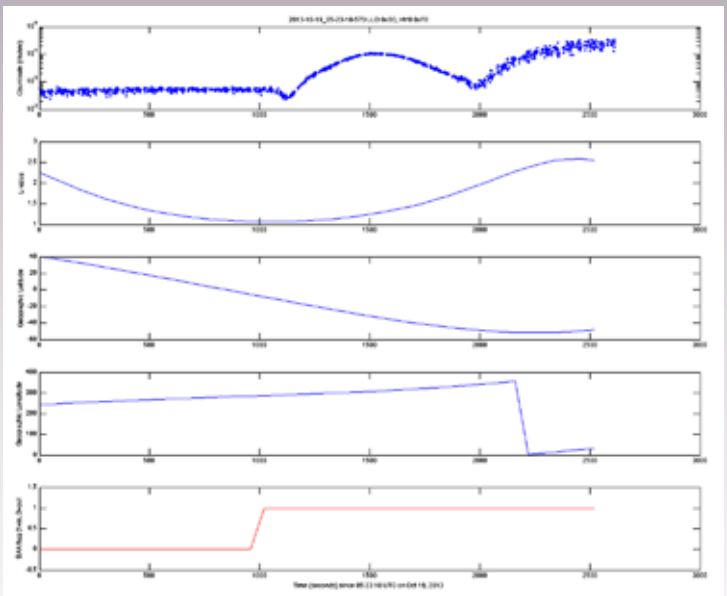
Firestation will also operate in orbit longer than Firefly providing an order of magnitude better coverage. During the first 1100 seconds or so of this partial orbit shown in the figure, there is a nice clean low-background interval (a few hundred counts per second). Typical TGFs will be 10-100 counts in one millisecond, and so will stand out nicely. The higher count rate background regions are in the South Atlantic Anomaly (SAA) and higher latitude regions (primarily SAA).

Planned Technology

Lessons learned from the operation of both Firefly and Firestation will be shared with other teams through the monthly NSF Principal Investigator (PI) teleconferences.

Planned Education

Undergraduate students at Siena College have been involved in all aspects of the project, from design and development, through fabrication and test, to mission operations and data analysis. These students received a very rare opportunity for hands-on, end-to-end experience on a real-life space project. In the future, they will also get a chance to travel to national meetings to talk about their work on FireStation and Firefly, and to learn from other scientists and engineers.



Second averaged count rates in the Firestation detector, as well as four other panels showing geolocation of the ISS (L-value, latitude, longitude, and whether in the South Atlantic Anomaly).

Local high school students and interns will also have access to the FireStation data and educational materials. The FireStation project will also involve the operation of two World Wide Lightning Location Network VLF ground stations, one at Siena and another at the Universidad Privada Boliviana (Dr. Augusta Abrahamse), providing student access to a tool that can be used for many data analysis projects, and that will be a permanent addition to the educational infrastructure at these institutions.

The Siena undergraduate team will further support the development of a website, with continuous updates on the development of the instrument and spacecraft, and on-orbit mission status, open access to the data and science results.

Focused Investigations of Relativistic Electron Burst, Intensity, Range, and Dynamics (FIREBIRD)

Project Description

The mission a targeted, goal-directed, space weather Cubesat mission to resolve the spatial scale size and energy dependence of electron microbursts in the Van Allen radiation belts. Relativistic electron microbursts appear as short durations of intense electron precipitation measured by particle detectors on low altitude spacecraft, seen when their orbits cross magnetic field lines which thread the outer radiation belt. Previous spacecraft missions (e.g., SAMPEX) have quantified important aspects of microburst properties (e.g., occurrence probabilities), however, some crucial properties (i.e., spatial scale) remain elusive owing to the space-time ambiguity inherent to single spacecraft missions. While microbursts are thought to be a significant loss mechanism for relativistic electrons, they remain poorly understood, thus rendering space weather models of Earth's radiation belts incomplete.

Planned Scientific Accomplishments

FIREBIRD's unique two-point, focused observations at low altitudes, that fully exploit the capabilities of the Cubesat platform, will answer three fundamental scientific questions with space weather implications:

- What is the spatial scale size of an individual microburst?
- What is the energy dependence of an individual microburst?
- How much total electron loss from the radiation belts do microbursts produce globally?

FIREBIRD Logo.

See *https://ssel.montana.edu/firbird-cubesat-constellation-in-production/*.

Planned Technology

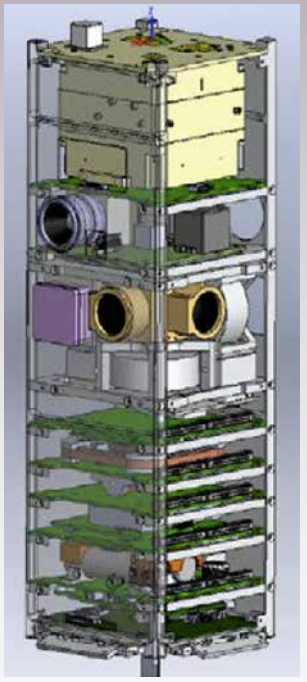
Firebird 2 continues to be improved. Lessons learned from Firebird 1 will be incorporated into Firebird 2 and shared with other teams through the monthly NSF Principal Investigator (PI) teleconferences.

Planned Publications

Space Weather Journal, AGU, "Space Weather and Science Motivations of the Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD) NSF CubeSat Mission."

THE FUTURE

The amazing results that have been achieved over the first five years of the program point towards an exciting and prolific future. Recently, the 2012 Solar and Space Physics Decadal Survey from the National Research Council included a strong recommendation targeting the development of very small satellite flight opportunities as a key growth area for both NASA and NSF. Our plans for 2014 already include a number of specific activities that will further push the boundaries for CubeSat technology, and for the program.



CubeSat investigating Atmopsheric Density Response to Extreme driving (CADRE).

Two new projects have just been started that each represents another first in the program: the first 6U CubeSat (the LAICE mission), which is also the first project carrying an imaging instrument, and the first hyper-spectral imaging project (the OPAL mission). The coming year will also see the start of the QBUS project, the objective of which is to provide four CubeSats to the European-led QB50 project. Aiming to launch approximately 40 CubeSats carrying sets of identical scientific instruments a main goal of the project is to investigate the lower thermosphere, a largely unexplored region of the Earth's atmosphere between 90 and 320km. This constitutes the first NSF participation in a major CubeSat constellation mission.

More generally, evidence from the program so far strongly suggests that the future of scientific CubeSat projects is only limited by the imagination. Crucial measurements from space are needed not only to address many unsolved science problems but also to solve critical societal problems, such as climate change; land use and resource management; pollution and disaster monitoring; communication; and space weather. Exploring and creating new and expanded possibilities for CubeSats to provide these remains a main goal of the program.

Firefly CubeSat in Poly Picosatellite Orbital Deployer (P-POD) on Vibration Table at NASA GSFC WFF.

The capabilities of CubeSat systems are growing at an ever-increasing rate as technological advances are made. Opportunities are many to accelerate this technology through engineering research in an array of fields, including materials research, 3-D printing, sensor miniaturization, micro-electro-mechanical systems, systems engineering, radio science, communication algorithms, and networks. Private firms and other government agencies are also starting to adopt the CubeSat concept as a low-cost way of flying payloads in space while creating important educational opportunities for future leaders of industry.

This offers new and expanded opportunities for partnerships and collaborations. Specifically, a variety of additional CubeSat-based initiatives are currently emerging also at the DOD and NASA. Unique to the NSF program, however, is the focus on pursuing scientific discovery while also providing visionary and inspiring training and education opportunities and targeting mainly the academic community. Consequently, the program will continue to play a key role in the overall national small satellite agenda in the future.

Cubesat projects stimulate widespread excitement and involve a unique set of skills and interests. Therefore, they appeal to a broader range of participants than more traditional science and engineering projects. This makes them a perfect tool for addressing widespread diversity and broadening participation goals in Science Technology Engineering Math (STEM) research and education.

NSF is pioneering exciting CubeSat-based science missions for Geospace and atmospheric research

annual report

NATIONAL SCIENCE FOUNDATION (NSF) CUBESAT-BASED SCIENCE MISSIONS FOR GEOSPACE AND ATMOSPHERIC RESEARCH

NP-2013-12-097-GSFC