Doing Science with University CubeSats

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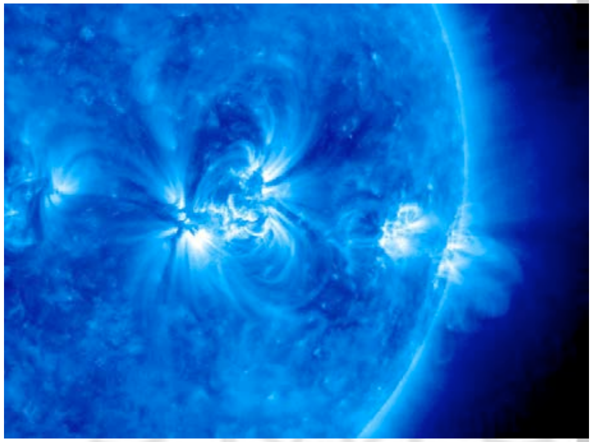
The National Science Foundation

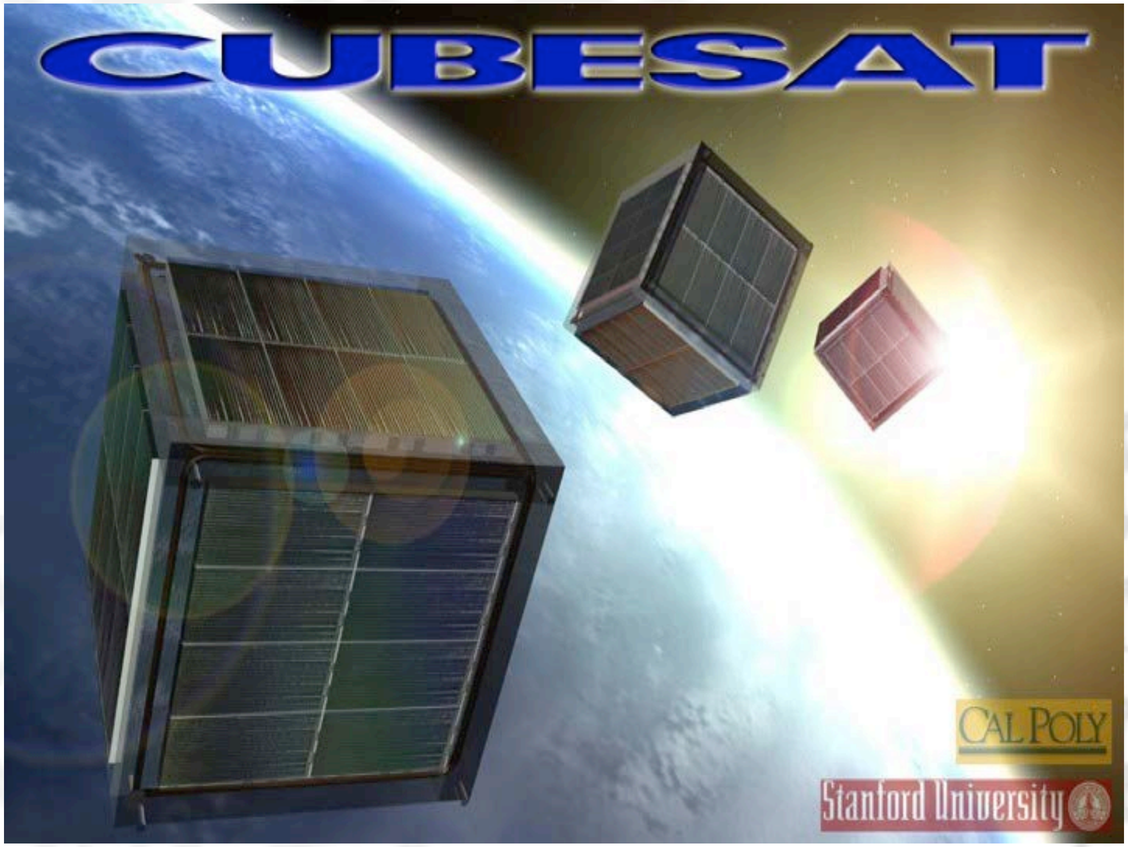
NSF and Space

- **Long tradition of utilizing space observations in research, e.g. in astronomy, astrophysics, space physics, and geosciences**
- **Mostly based on data provided by NASA, NOAA, and DOD.**
- **Recently small ventures into also providing scientific measurements from space**



NSF and CubeSats

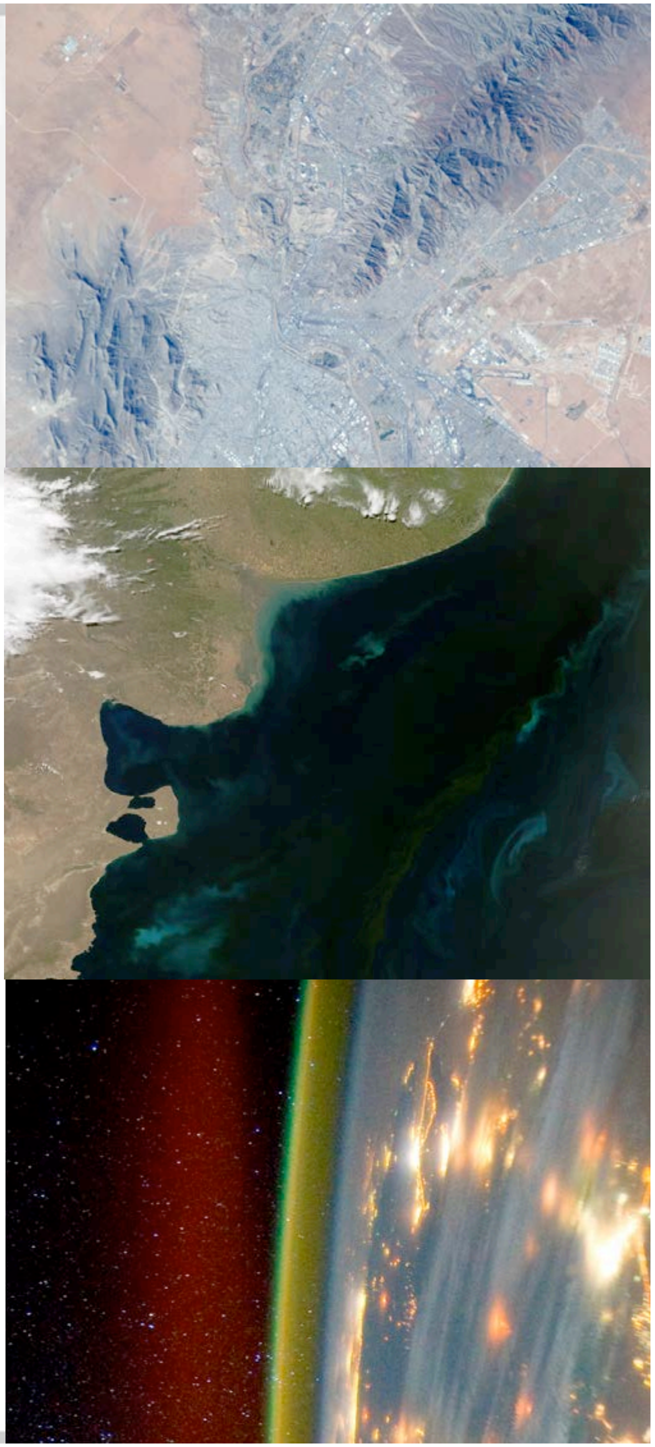
- **Exploring untraditional, creative, and low-cost ways to provide space measurements for scientific research**



Motivation: Science

CubeSat missions do:

- advance research in many science areas
- spur innovation, creativity and technology development
- Bring space missions within the scope of traditional NSF grants
- enhance university participation in space activities



Cubesats: Obvious Limitations

- Physical size (optics, booms, antennas)
- Power, data rate downlink
- Pointing, maneuvering
- Limited control of orbits

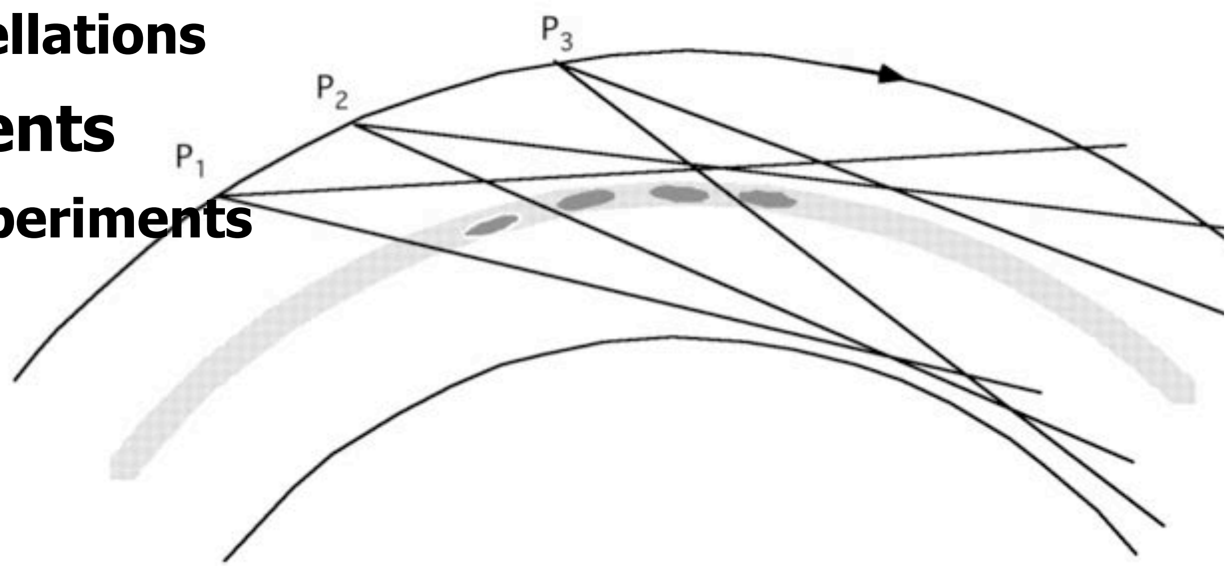
Important Trade-offs

- **Large missions**
  - ❑ **Single satellites**
  - ❑ **Comprehensive measurements – Complex missions**
  - ❑ **Long lead-times**

- **Small missions**
  - ❑ **Multi-point simple measurements**
  - ❑ **Narrowly focused objectives**
  - ❑ **Fast turn-around**
  - ❑ **Experimental approaches**
  - ❑ **Dispensable & replenishable**

Cubesat contributions

- **Fill-in gaps in coverage**
  - **geographic, local time, sky-view, long-time monitoring**
- **Small-scale structure**
  - **Multi-point measurements to avoid space-time aliasing**
- **Interferometry & Tomography**
  - **Satellite constellations**
- **New measurements**
  - **Technology experiments**



Frey, S. et al (2001) *J. Geophys. Res.*, *106*(A10).

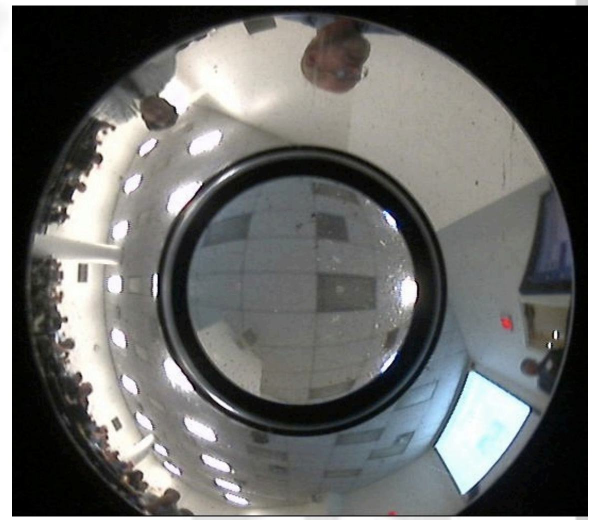
Motivation: Education and Workforce

CubeSat projects do:

- **train the next generation of scientists and engineers in space**
- **offer rare full, end-to-end mission experience**
- **spur new excitement for science & engineering**

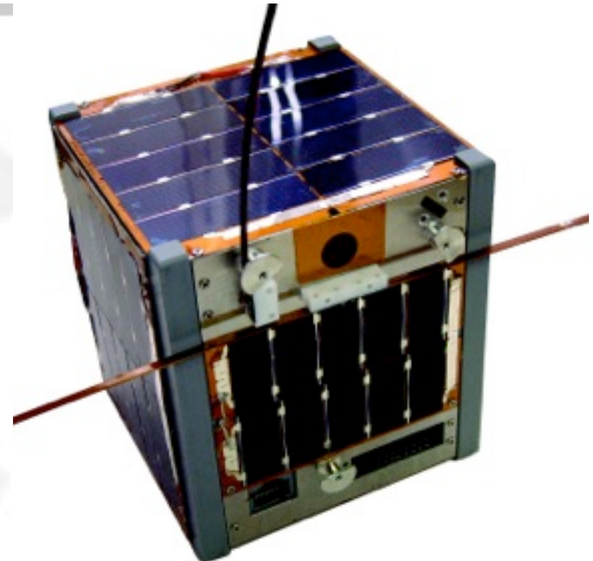
A New NSF Program

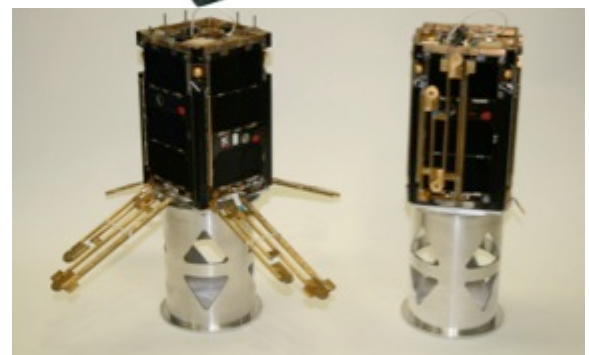
- Program conceived 2007; first solicitation 2008
- Utilize CubeSat and P-POD technology development
- Space weather & atmospheric research and education
- 2 new projects per year

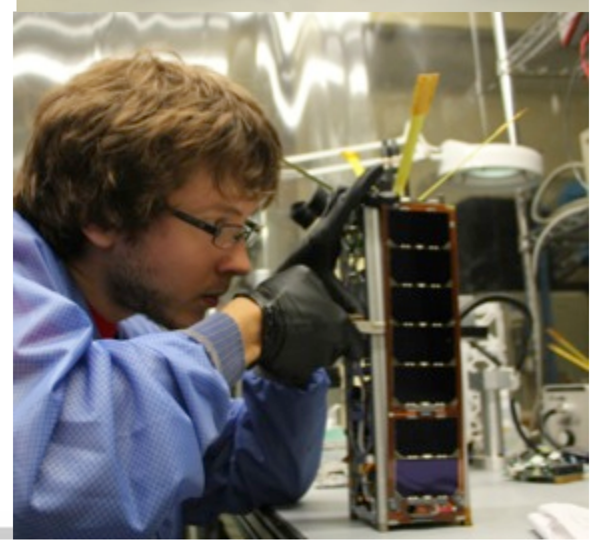


NSF Cubesat Program since 2008

- Geospace & atmospheric science and education
- 5 competitions with >80 unique missions proposed
- 12 (15) projects funded
- Grants $900,000 total cost and 3 year duration







SRI INTERNATIONAL · U MICHIGAN · NSF · ELANA-3 · NPP · NASA · DELTA II · VAFB
RAX 2
Scientia
Ex Cubus

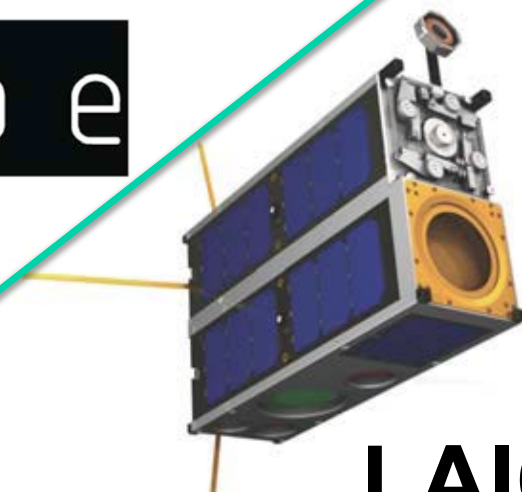
DICE
ASTRA
USU/SDL
Clemson
Embry Riddle

FIREBIRD
Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics
University of New Hampshire • Montana State University • Los Alamos National Laboratory • The Aerospace Corporation
NSF

ExoCube

CSSWE
Colorado Student Space Weather Experiment

CubeSat for Ions Neutrals Electrons and MAgnetic fields
trio cinema 3



LAICE

NATIONAL SCIENCE FOUNDATION · SIENA COLLEGE · NASA/GSFC · USRA · HAWK INSTITUTE FOR SPACE SCIENCES
FIREFLY

CADRE

OPAL

QBUS

Universidad del Turabo
Columbia
University of Colorado
Challenger
Stanford University
Discovery
University of Michigan
Atlantis
Draper
National Science Foundation
QB50

QB50

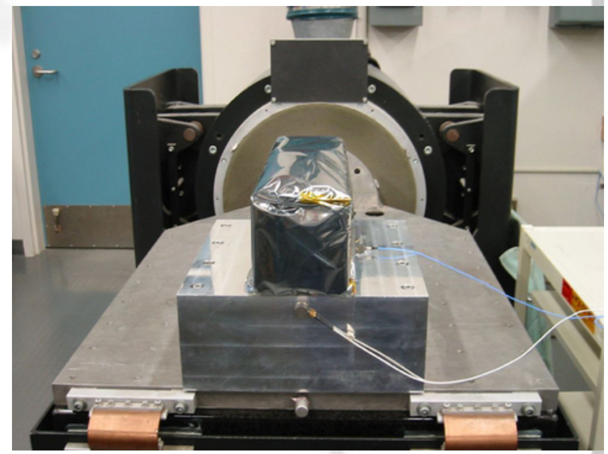
ELFIN

Launch Support

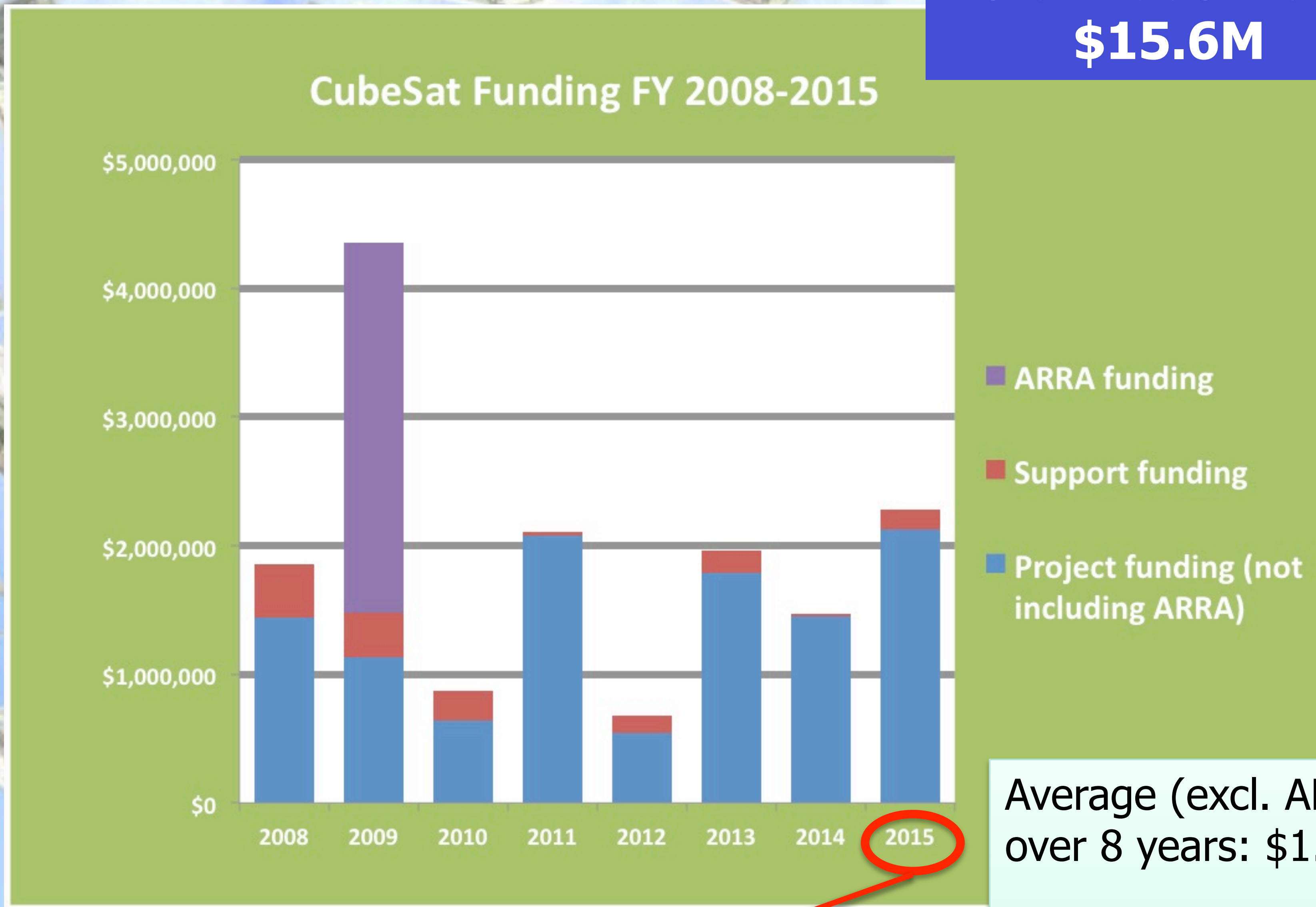
- DOD STP, S26, Nov 2010, Minotaur IV, Kodiak
- NASA ELaNA, NPP, Oct 2011, Delta II, Vandenberg
- NRO/NASA ELaNA NROL-36/ OutSat, Sep 2012, Atlas V, Vandenberg
- ORS, STP-3, Nov 2013, Minotaur-1, Wallops Island
- NRO/NASA ELaNA NROL-39/ GEMSat, Dec 2013, Atlas V, Vandenberg
- NASA ELaNA, SMAP, Jan 2015, Delta II, Vandenberg

Mission Support at NASA Wallops Flight Facility

- Integration, testing, documentation
- Technical POC for satellite developer and launch provider
- Other technical and management support
- UHF and S-Band CubeSat Ground-station support
- As needed & less than 10% of budget



Total 2008-2015: $15.6M



Average (excl. ARRA) over 8 years: $1.6M

ARRA provided 2 satellite projects and a REU site

Note: 2015 numbers are estimated

Total Funding 2008-2015: $15.6M

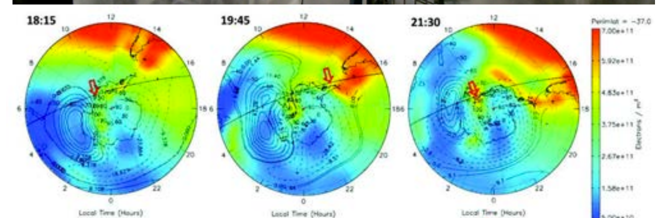
FY	Project funding (not including ARRA)	ARRA funding	Support funding	
2008	$1,441,740	$0	$417,997	
2009	$1,134,773	$2,873,776	$345,657	
2010	$637,457	$0	$234,782	
2011	$2,075,238	$0	$28,871	
2012	$547,234	$0	$135,810	
2013	$1,783,645	$0	$179,970	
2014	$1,447,937	$0	$21,707	
2015	$2,130,296	$0	$150,000	
Total	**$11,198,320**	**$2,873,776**	**$1,514,794**	**$15,586,890**

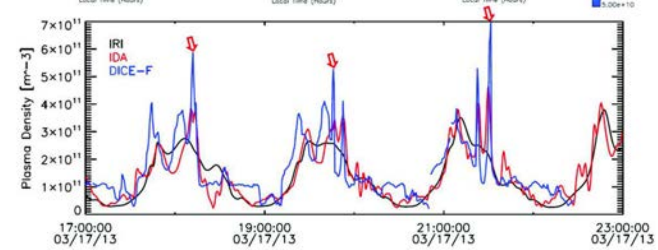
Support funding ~10%
NSF staff ~1/3 FTE

Note: 2015 numbers are estimated

Accomplishments

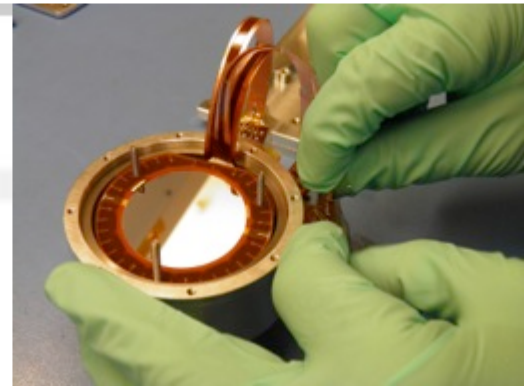
- Scientific value of CubeSat missions confirmed
- Creative mission ideas and successful implementations
- Scientific data & papers
- Big educational impact
- Increased recognition of cubesats as a viable alternative for space

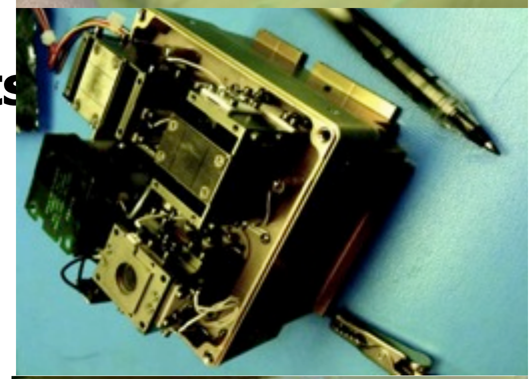


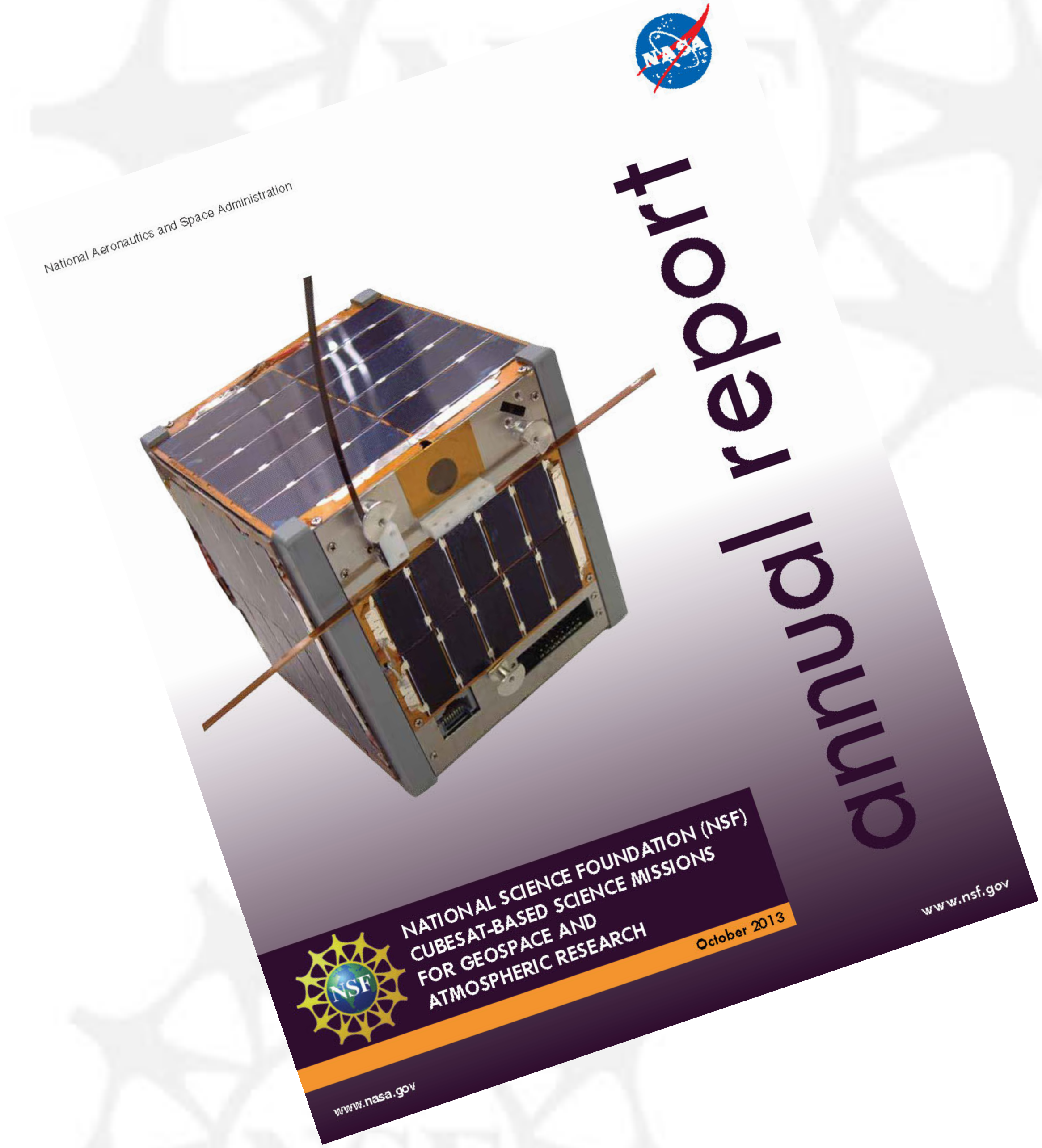


Cubesats in LEO

- **Capability already demonstrated, or will be soon for:**
  - ❑ Electric and magnetic field instruments
  - ❑ Plasma density and temperature instruments
  - ❑ Neutral gas pressure gages and wind instruments
  - ❑ Mass spectrometers
  - ❑ Particle detectors (few keV to several MeV)
  - ❑ Photometers and spectrometers (near-Infrared to extreme Ultraviolet)
  - ❑ Hyper-spectral imagers
  - ❑ Gamma and X ray detectors and spectrometers
  - ❑ Radar and other advanced radio receivers
    - ❑ GNSS receivers for radio occultation
    - ❑ multispectral microwave radiometers







http://www.nsf.gov/geo/ags/uars/cubesat/nsf-nasa-annual-report-cubesat-2013.pdf

Essential Elements

- Strong science and engineering collaborations
- Thorough proposal review and selection as guarantee for success
- Requirements dictated solely by launch acceptance
- Minimal prescriptions for project management (testing, review, and documentation)
- Open inter-team discussions
- Funding for students

Cubesats: Change of mindset

Powerful concepts:

Building to a standard

Containerized launch

New paradigm:

Low cost

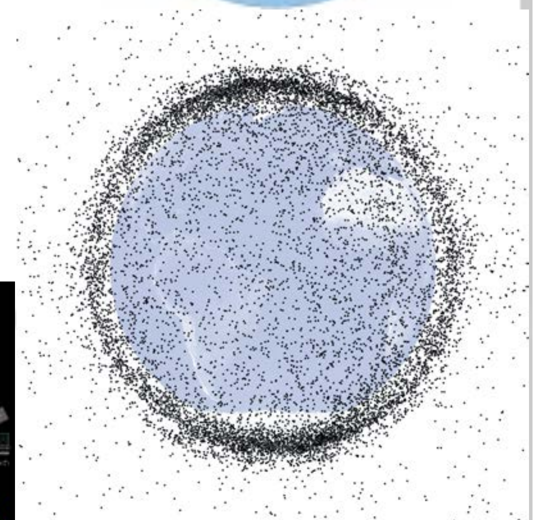
High risk acceptance

Broad participation:

high influx of innovation & widespread expertise

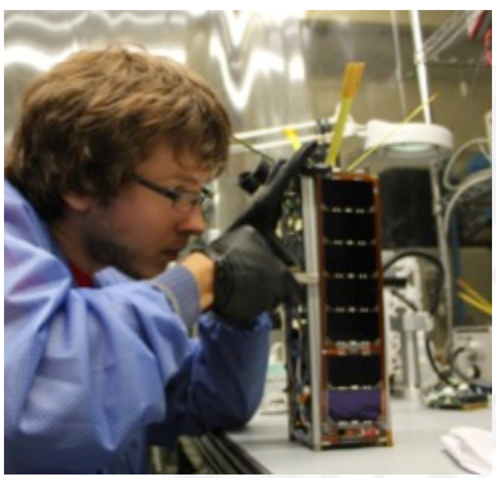
The Future

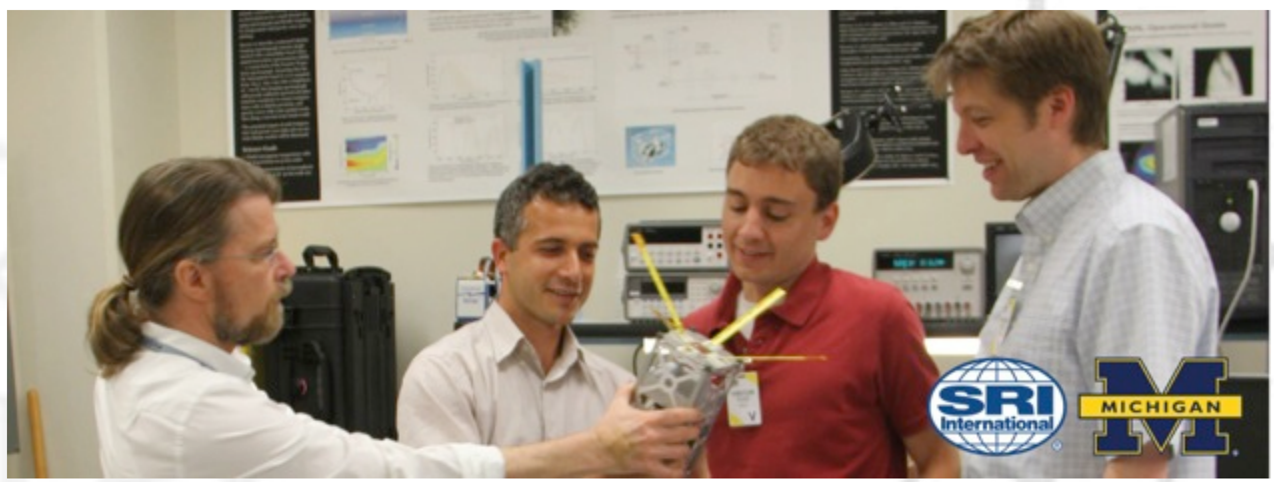
- Secure stable funding line at $2.5 million/ year
- Expansion to other science areas
- Larger constellations (European QB50 project)
- Cubesats everywhere: beyond LEO
- Frequency allocation &

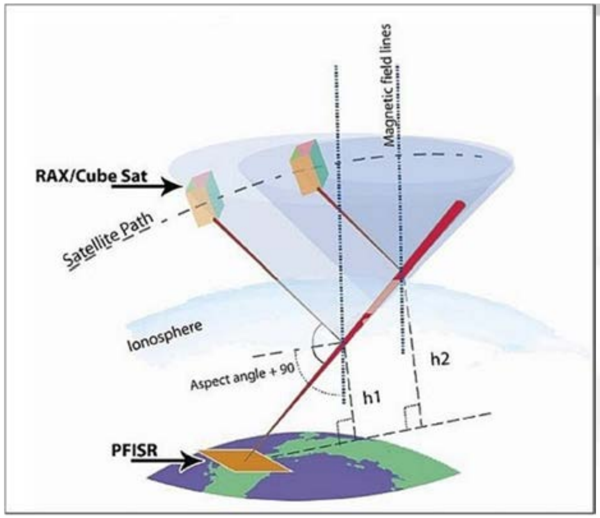


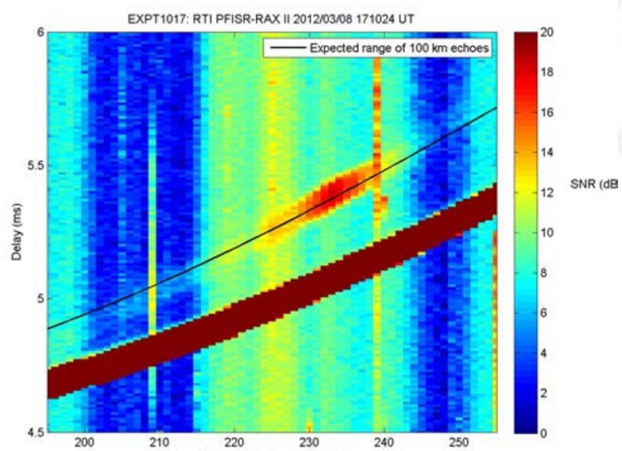
RAX
Radio Aurora Explorer

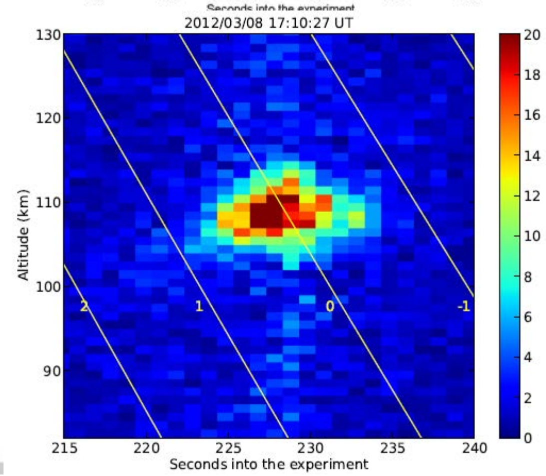
- **SRI International & U. Michigan**
- **Ionospheric Plasma Irregularities**
  - ❑ **3U cubesat**
  - ❑ **UHF Radar Receiver**
- **RAX I Launched Nov 2010**
  - ❑ **A few experiments; Premature power system failure**
- **RAX II Launched Oct 2011**
  - ❑ **Complete mission success**
  - ❑ **Operational nearly 18 months**







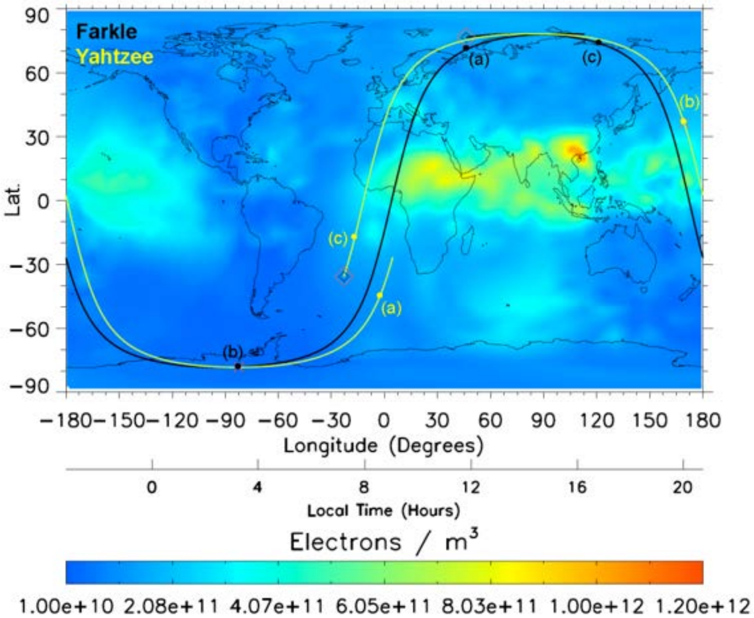


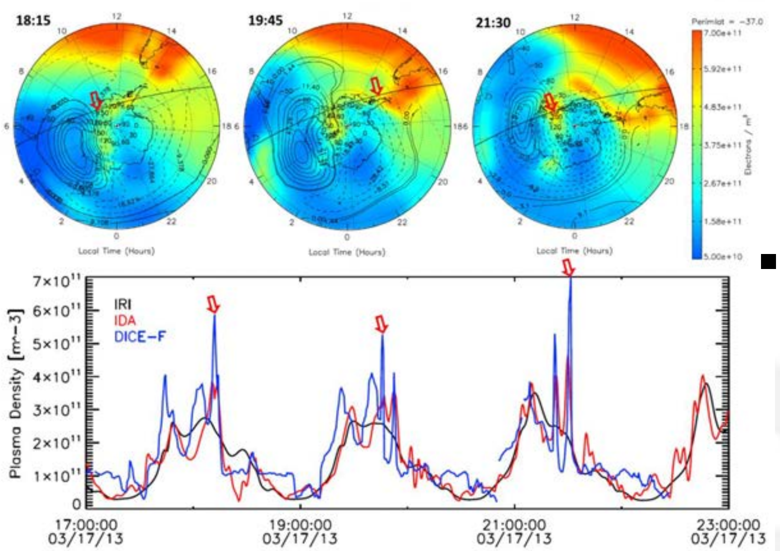


RAX Results

- **New findings on sub-meter scale auroral irregularities**
  - **Conducted a total of 30 experiments; recorded echoes in 4**
  - **Including artificial heating with HAARP**
- **Science outcomes**
  - **More than 10 scientific and engineering publications and more than 15 conference presentations**
  - **Data from experiments available on website**
- **Education outcomes**
  - **36 undergraduate and 3 doctoral students**
  - **Alumni at leading-edge companies and gov. labs, including: Jet Propulsion Laboratory, Applied Physics Laboratory, Orbital Sciences, SpaceX, Space Systems Loral, and Department of Defense research labs**

- **ASTRA, Inc. & Utah St. U.**
- **Ionospheric Storm Enhanced Density structures**
  - **2 identical 1.5U cubesats**
  - **Electron density; B and E fields**
- **Launched Oct 2011**
  - **Part mission success for science (no E-field boom deployment)**
  - **Huge technology success: demonstrated Mbits/s downlink capability**
  - **Operational >18 months**





DICE Results

- New findings on storm enhanced density structures
  - Two-point measurements of electron density and magnetic field
  - Technology demonstration of Mbits/s download capability
- Science outcomes
  - More than 10 scientific and engineering publications and conference presentations
  - Large dataset (> 8 GB) available on website
- Education outcomes
  - 6 undergraduate and 3 graduate students
  - Alumni at leading-edge companies including: L-3 Communications

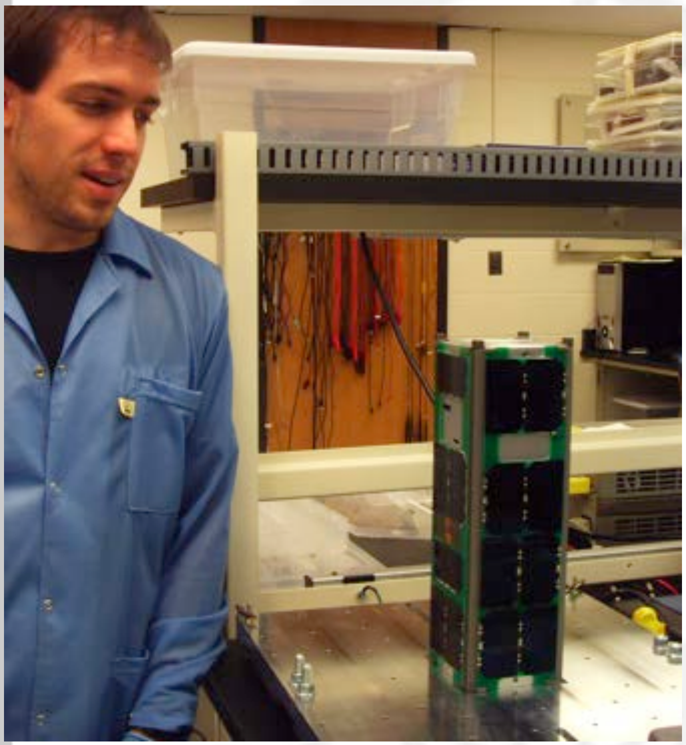
trio cinema

CubeSat for Ions Neutrals Electrons and MAgnetic fields

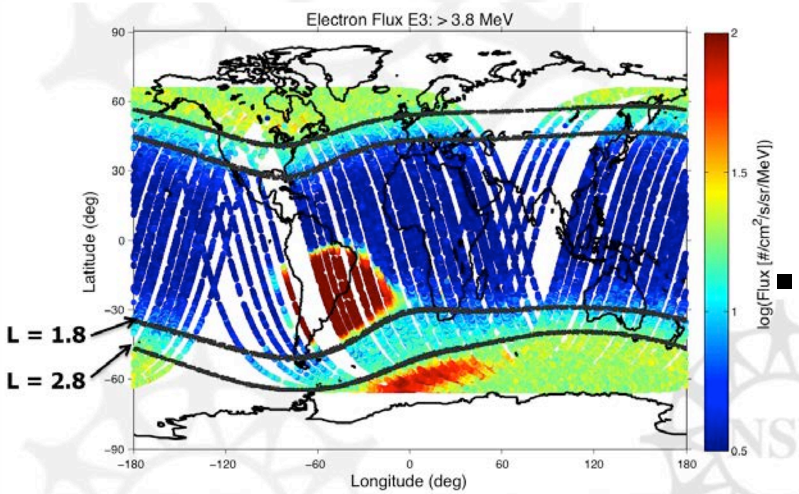
Space Sciences Laboratory, UC Berkeley
Kyung Hee University of South Korea
Imperial College London

- **U. California Berkely & International collaborators**
- **Ring current dynamics**
  - ❑ **3U cubesat**
  - ❑ **Energetic ions, electrons and neutral particles (4-20keV)**
- **Launched Sep 2012**
  - ❑ **Limited mission success; comm problems; some magnetic field data**
  - ❑ **Spacecraft healthy for > 18 months**

CSSWE
Colorado Student Space Weather Experiment



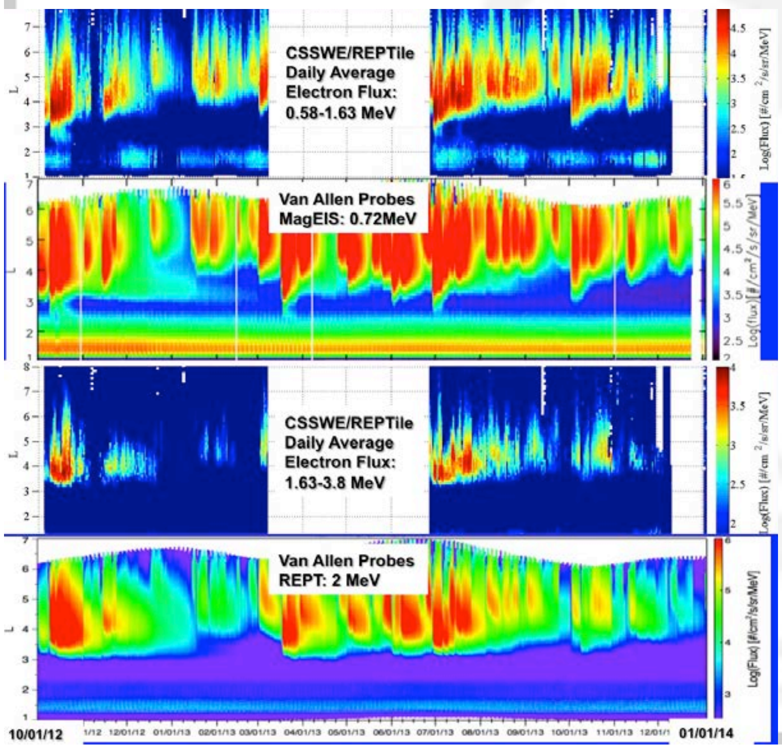
- **U. Colorado, Boulder**
- **Solar Proton Events & Radiation belt dynamics**
  - **3U cubesat**
  - **Energetic electrons (0.5-3MeV) and protons (10-40MeV)**
- **Launched Sep 2012**
  - **Complete mission success**
  - **More than 2 years operation**



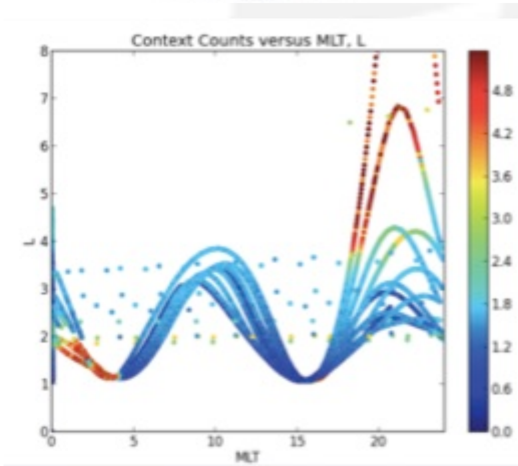
REPTile Data – September 1-23, 2013

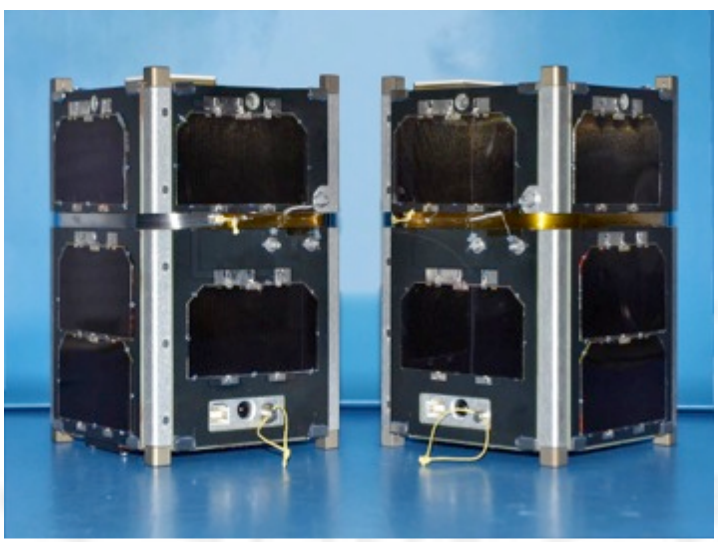
CSSWE Results

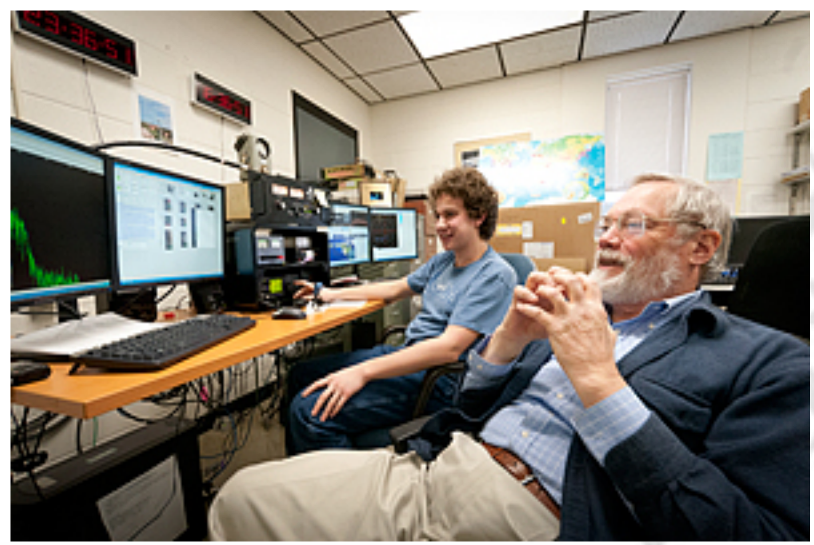
- **New findings on relativistic radiation belt electrons**
  - ❑ **Valuable low-altitude complement to NASA's Van Allen Belt Probes & Barrel balloon campaign.**
- **Science outcomes**
  - ❑ **15 peer-reviewed scientific and engineering publications**
  - ❑ **Full dataset available at NSSDC**
- **Education outcomes**
  - ❑ **>65 students at undergraduate, masters and doctoral level**
  - ❑ **Basis for 4 dissertations and 3 competitive student scholarship awards**



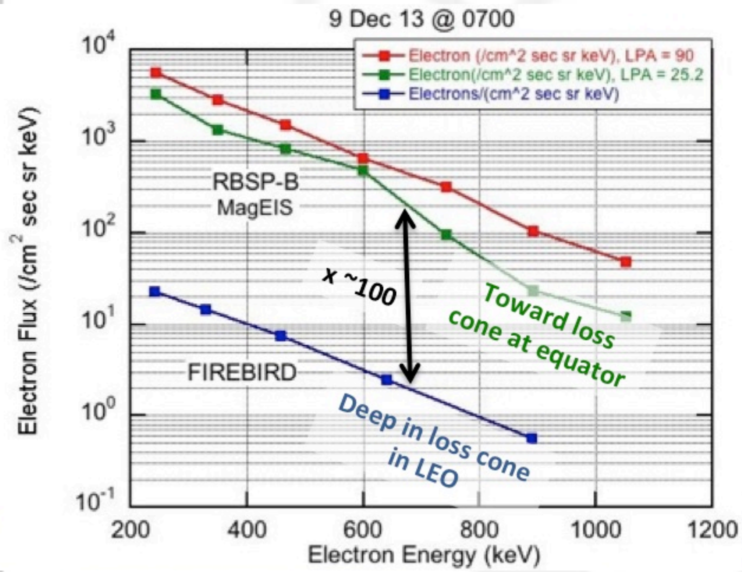
- **U. New Hampshire; Montana St. U & Aerospace Corp.**
- **Relativistic Electron Microbursts**
  - **2 identical 1.5U cubesats**
  - **Energetic electrons (0.3-1MeV) with high time resolution (100ms)**
- **Launched Dec 2013 & Jan 2015**
  - **All satellites fully operational; Second pair simultaneous measurements**
  - **High quality data**

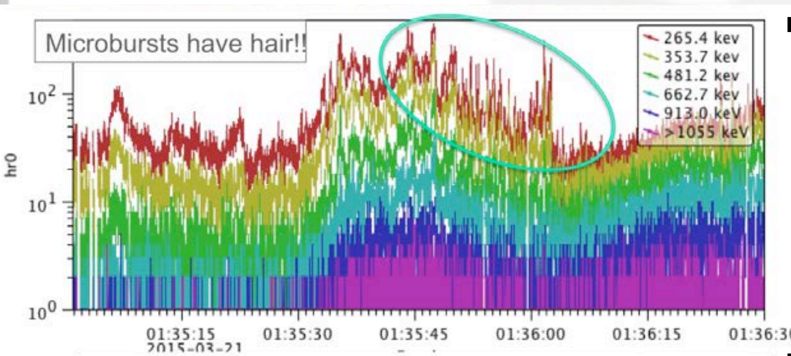


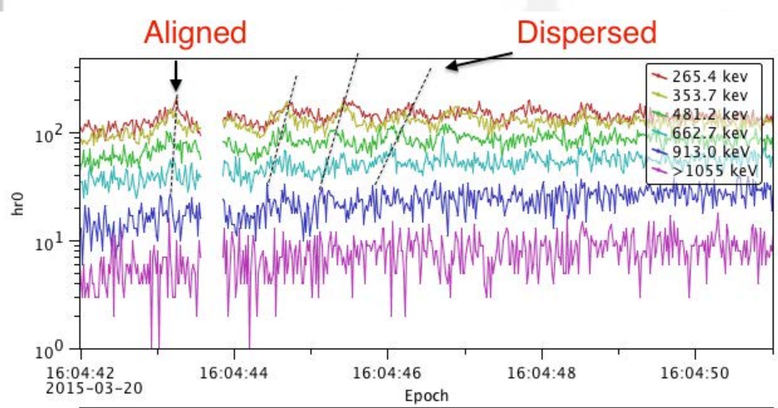




FIREBIRD Results

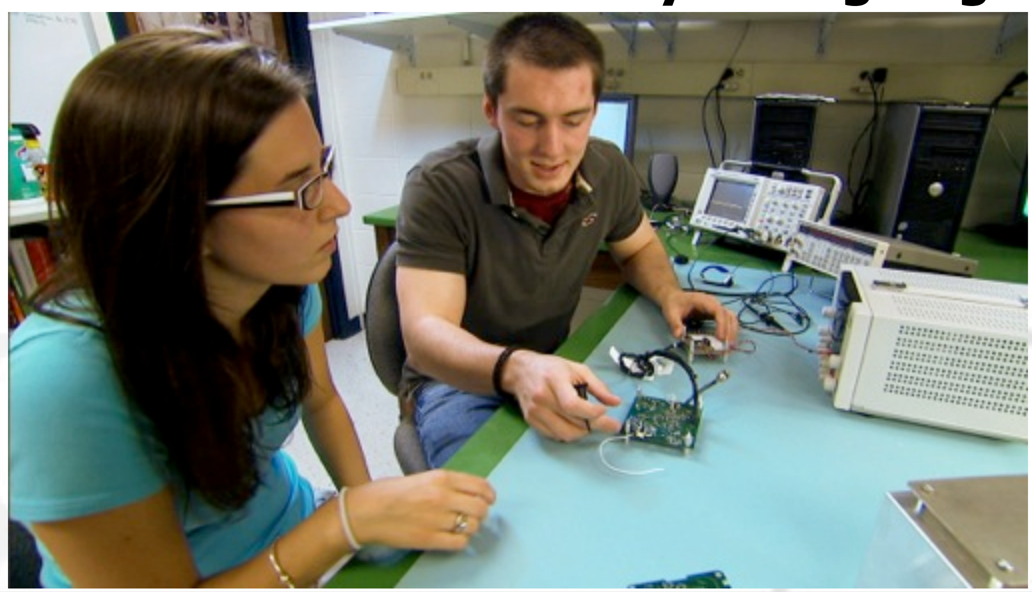


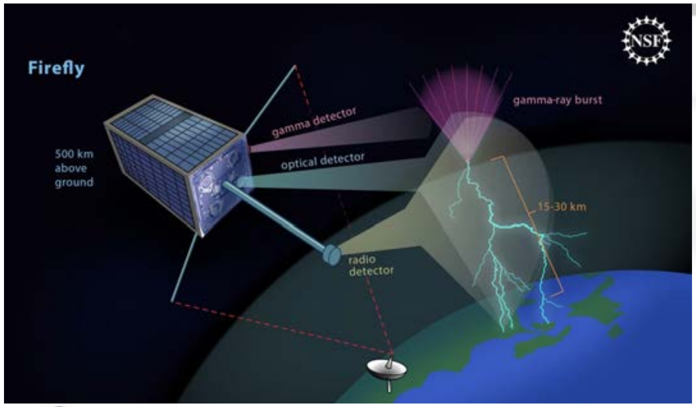


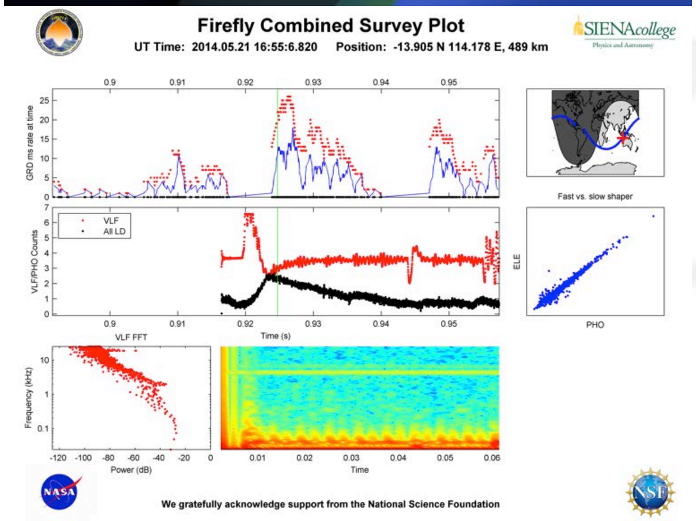


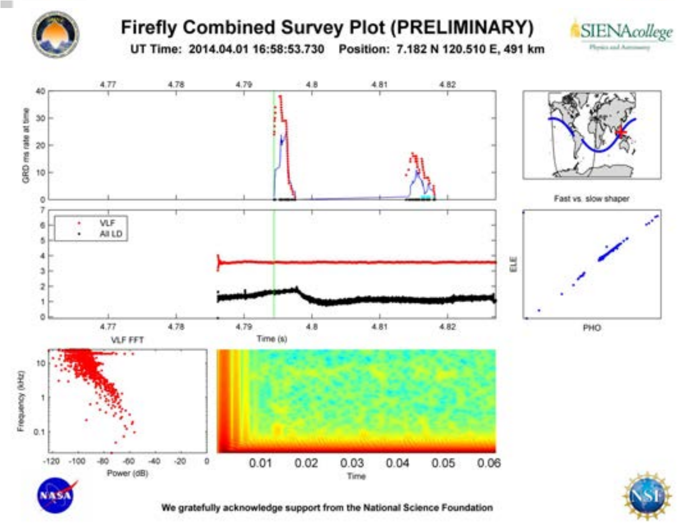
- New findings on relativistic electrons and relativistic electron micro bursts
  - Energy spectrum and spatio-temporal disambiguation of microbursts down to 1.5 seconds (~10km) separation
  - Valuable complement to NASA's Van Allen Belt Probes
- Science outcomes
  - Many scientific and engineering publications and conference presentations in preparation
  - Still collecting data
- Education outcomes
  - More than18 undergraduate and graduate students
  - Alumni at leading-edge companies and institutions including: Northrup Grumman Corp, Tyvak, Aerospace Corp, Stanford Universtiy

- **NASA Goddard Space Flight Center & Siena College**
- **Terrestrial Gamma Ray Flashes and Lightning**
  - **3U cubesat**
  - **Gamma Rays (to 20MeV); VLF radio and optical**
- **Launched Nov 2013**
  - **2 months to first contact**
  - **Data collection and analysis ongoing**





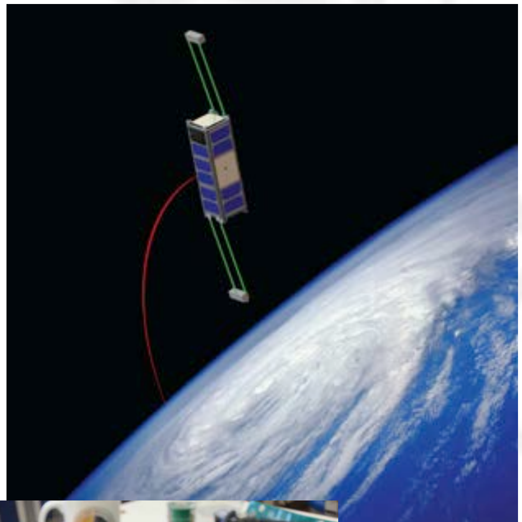




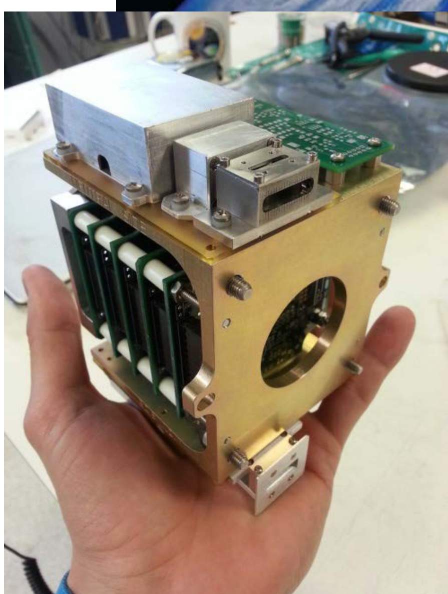
Firefly Results

- **New findings on lightning physics and electron acceleration in Terrestrial Gamma Ray Flashes**
  - ❑ **To date, Firefly has captured over 60 science "snapshots" of high resolution measurements of lightning and gamma ray activity**
- **Science outcomes**
  - ❑ **Validation and analysis of candidate events still ongoing**
  - ❑ **Data collection still ongoing**
  - ❑ **10 scientific and engineering publications and presentations**
- **Education outcomes**
  - ❑ **30 undergraduate and 6 high school students**
  - ❑ **Internships at NASA GSFC**

ExoCube

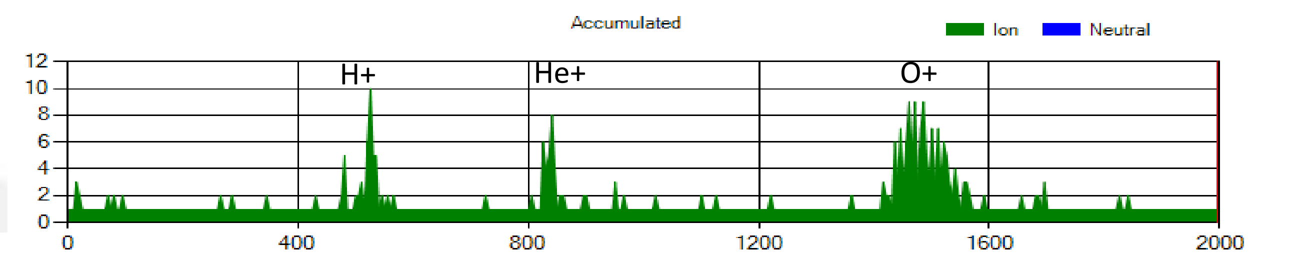


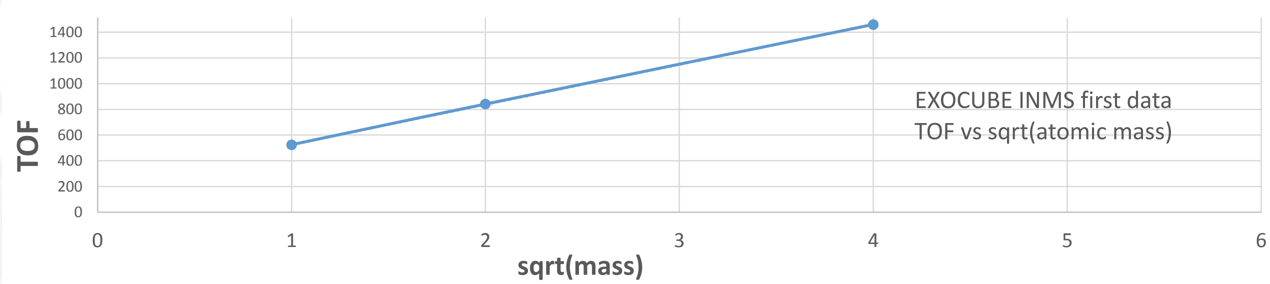
- **Scientific Solutions, Inc; CalPoly; NASA Goddard; U. Wisconsin & U. Illinois**
- **Composition of the upper atmosphere**
  - **3U cubesat**
  - **Miniature mass spectrometer; global density of H, He, and O and ions**
- **Launched Jan 2015**

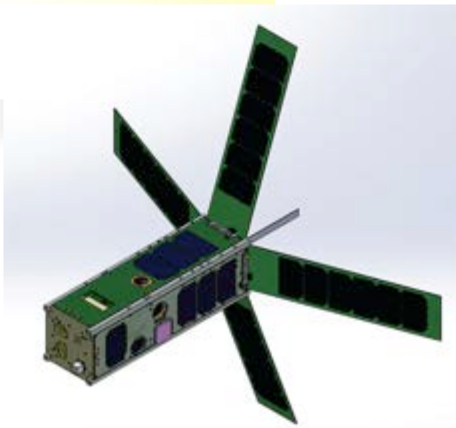


ExoCube Results

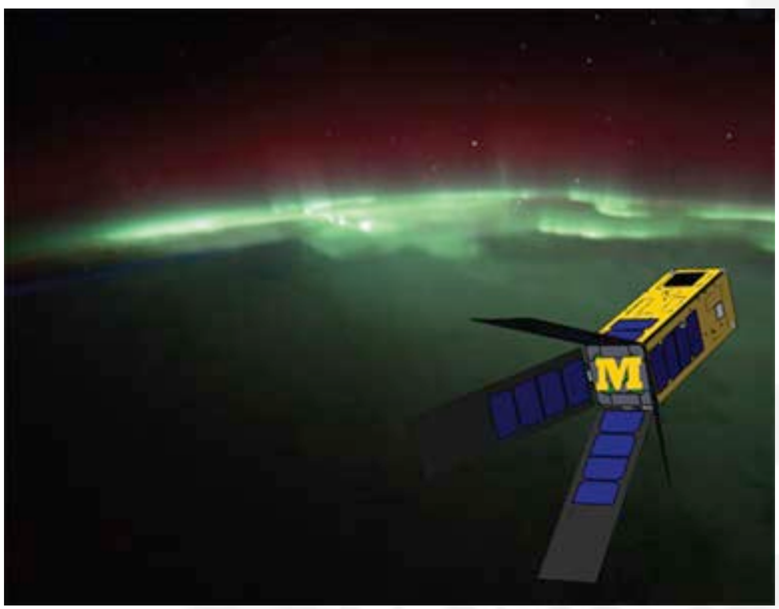
- **Still in commissioning phase**
  - **Weak radio signal: antenna didn't deploy**
  - **Successful comm with 150 foot dish at SRI: solutions at CalPoly and Wallops being worked**
- **Science outcomes**
  - **First-light measurements: Successful demonstration of the mass spectrometer instrument**
- **Education outcomes**
  - **More than 40 undergraduate and graduate students**







- **U. Michigan & Naval Research Lab**
- **Thermosphere dynamics**
  - **3U cubesat**
  - **Miniature mass spectrometer; density, temperature, winds and composition of neutrals and ions**
- **Launch Early 2016**



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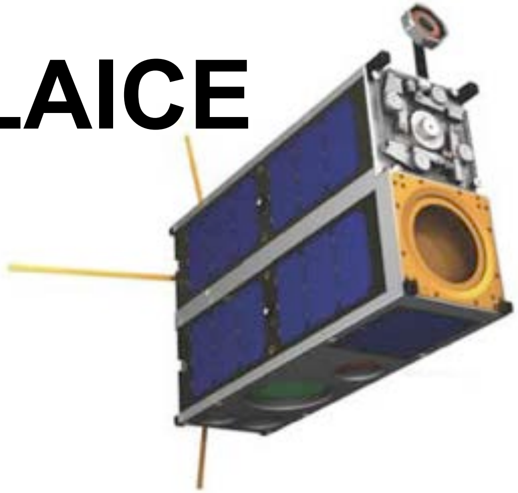
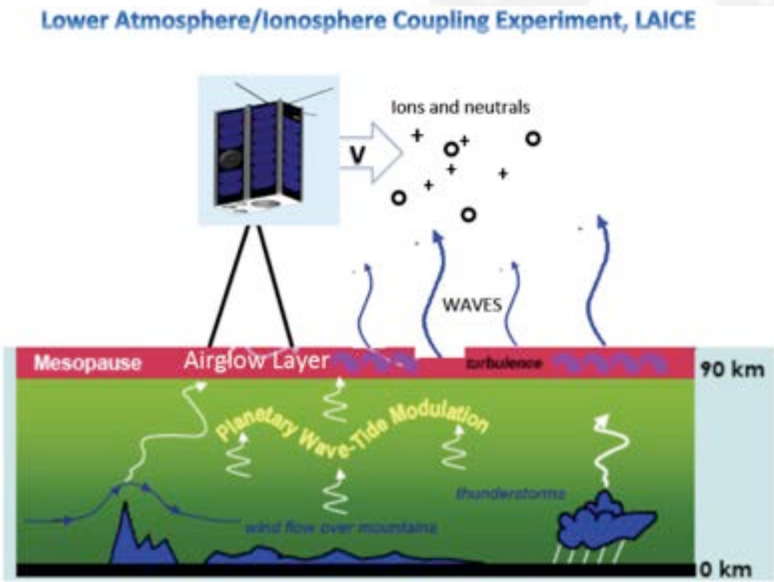
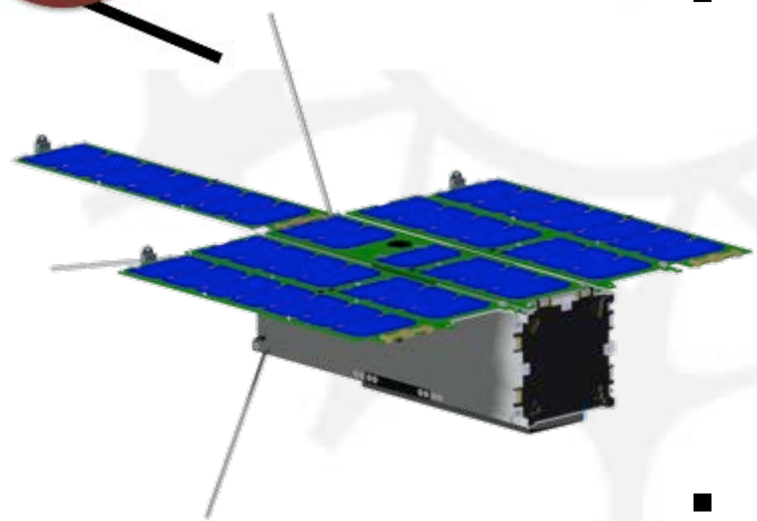


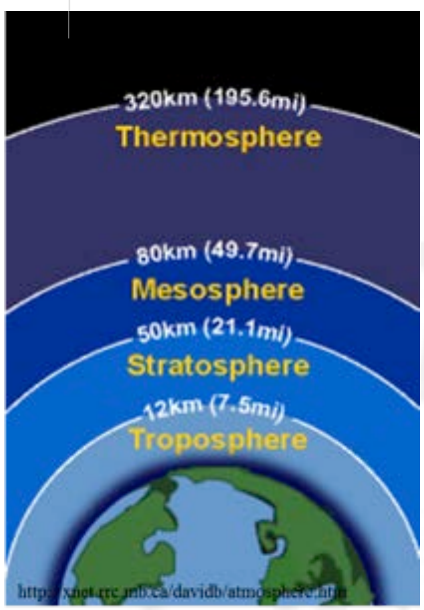


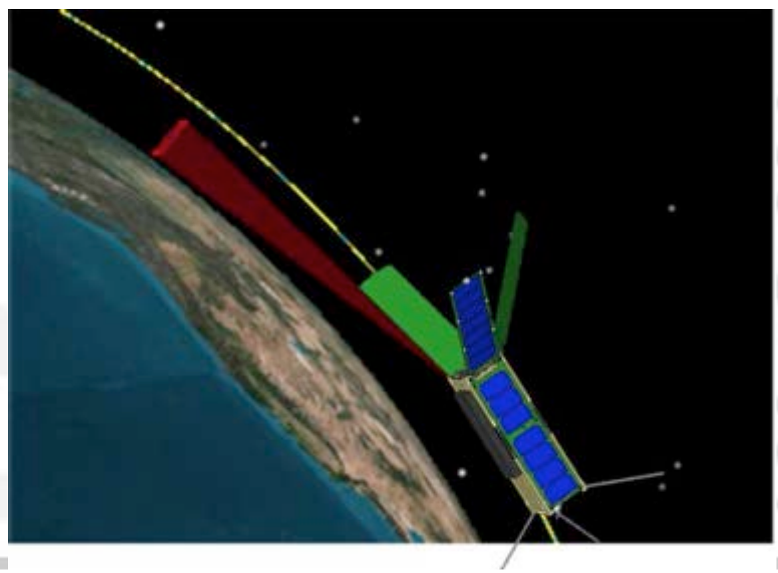
- **Virginia Tech; U. Illinois; Aerospace Corp. & NWRA, Inc.**
- **Atmospheric gravity waves**
  - **6U cubesat**
  - **In-situ and remote sensing; plasma and neutral temperature and density; Airglow ~90km**
- **Project Started May 2013**
  - **Expected launch early 2016**

OPAL

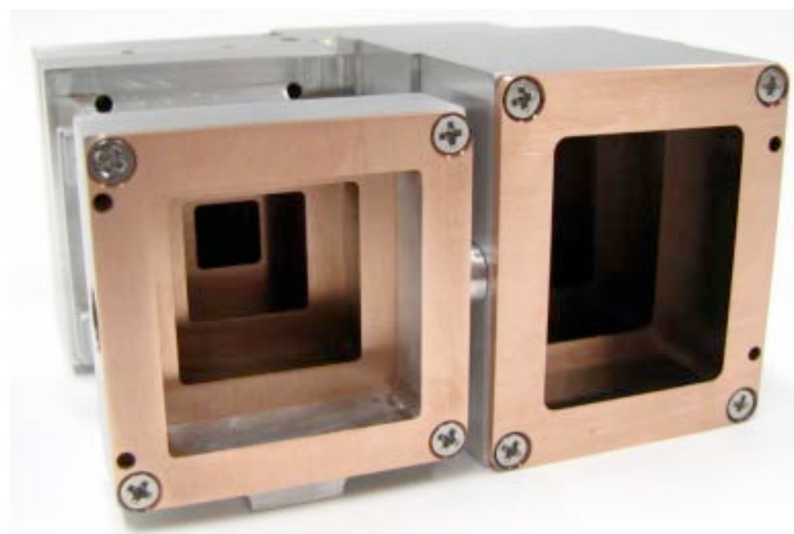


- **Utah St. U. & & HISS (U. Maryland Eastern Shore)**
- **Neutral temperature profiles 90-140km**
  - **3U Boeing Colony cubesat provided by NRO**
  - **High resolution, hyper-spectral imaging spectrometer; Daytime airglow O2 760-770nm**
- **Project Started Sep 2013**





- **UCLA**
- **Pitch angle distribution of relativistic electrons and ions**
  - **3U cubesat; spinning @20rpm**
  - **Full angular distribution of electrons (50keV-5MeV) and ions (50-300keV); Magnetic field**
- **Project Started August 2014**
  - **Jointly funded with NASA**



- **Drapber Lab; U. Michigan; UC Boulder; Stanford U.; U. del Turabo**
- **Providing 4 Cubesats to the European-led QB50 project**
  - ❑ **In-situ measurements of the lower thermosphere 100-320km**
  - ❑ **Atlantis, Columbia, Challenger, Discovery**
  - ❑ **2 Ion-Neutral-Mass-Spectrometers & 2 AO and O2 Sensors (FIPEX)**
  - ❑ **High resolution, hyper-spectral imaging spectrometer; Daytime airglow O2 760-770nm**
- **Project Started July 2014**