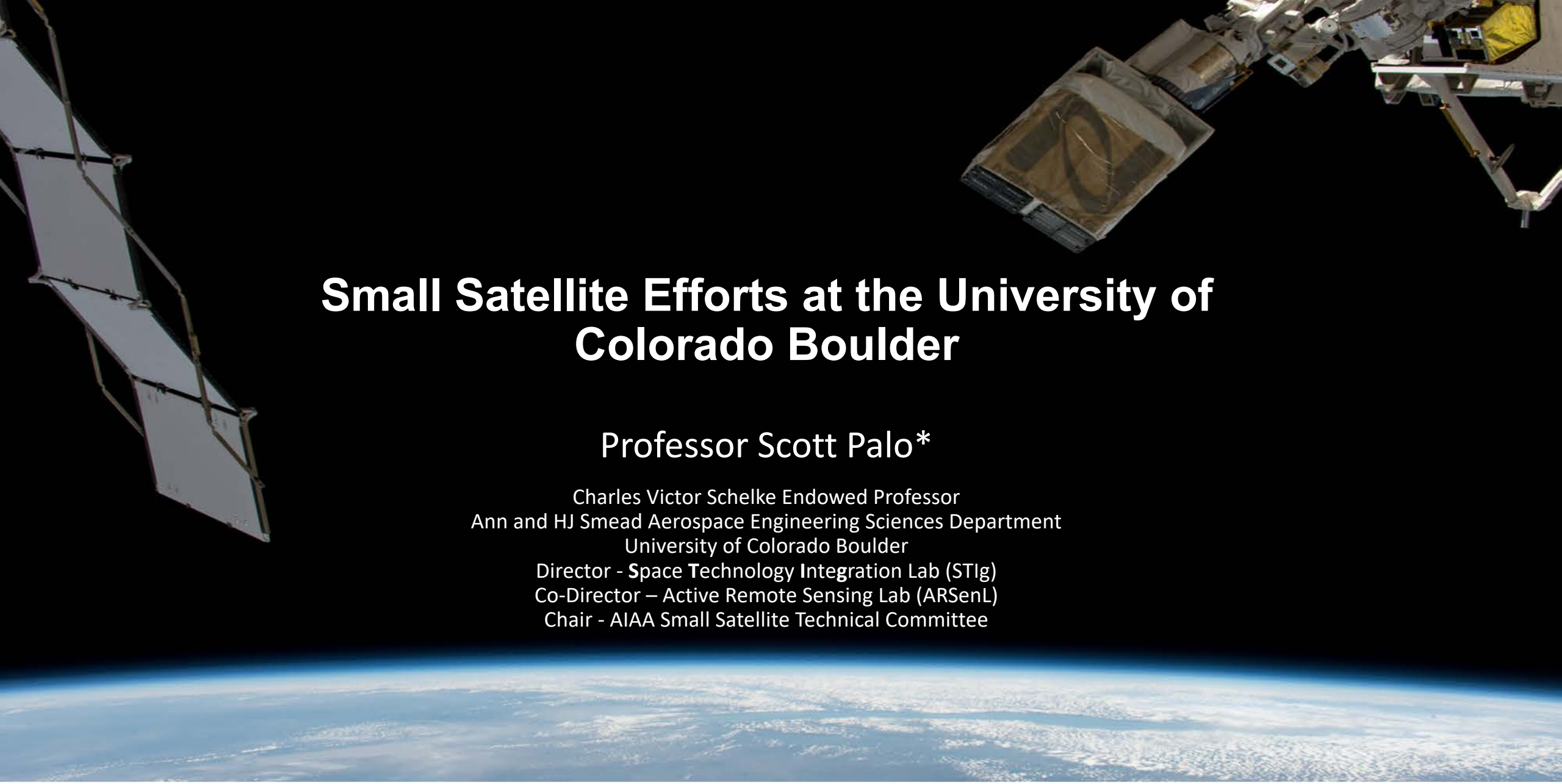


Small Satellite Efforts at the University of Colorado Boulder

Professor Scott Palo*

Charles Victor Schelke Endowed Professor
Ann and HJ Smead Aerospace Engineering Sciences Department
University of Colorado Boulder
Director - **S**pace **T**echnology **I**nte**g**ration Lab (STIg)
Co-Director – Active Remote Sensing Lab (ARSenL)
Chair - AIAA Small Satellite Technical Committee

Smead Aerospace
UNIVERSITY OF COLORADO **BOULDER**

*COI Disclaimer : Scott Palo has a fiduciary relationship with Blue Canyon Technologies and Blue Cubed LLC.

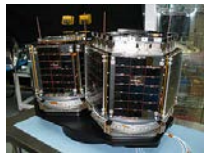
A Brief (incomplete) Small Sat History @ CU

1946 Aerospace Engineering Department Created

1958 NASA Formed

1976-1989 Solar Mesosphere Explorer (SME) operated by CU students has instruments built by LASP on a Ball bus.

1989 COSGC Founded



2001 AES hires first Small Sat Professor (Palo)

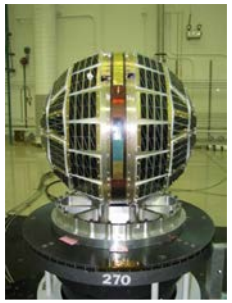
2004 3CS launched (COSGC UNP-1&2)

2005 AES graduates first Small Sat PhD (Shriver)

2011 HERMES CubeSat launched (COSGC)

2014 ALL-STAR CubeSat launched (COSGC/LMCO)

2014 DANDE launched (AES/COSGC UNP-5)



2015 AES hires second Small Sat Professor (Marshall)

2017 QB50 CubeSat launched 2Q (AES)

2018 POLAR Cube CubeSat Launch [4Q17] (COSGC/ECEE UNP-8)

2019 CU-E3 CubeSat SLS Launch [Net 4Q19] (AES NASA CubeQuest Challenge)

2020 MAXWELL CubeSat Launch [NET 2Q20] (AES UNP-9)

1948 Upper Air Lab (LASP) Created

1956 LASP Engineers create new company – becomes Ball Aerospace

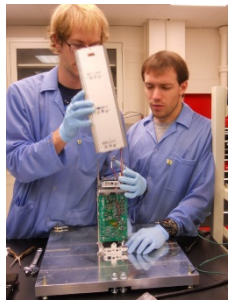
1965-1975 LASP builds instruments for Mariner 5,6,7,8 & 9

1995-2003 Student Nitric Oxide Explorer (SNOE) satellite and instruments built and operated by AES/LASP students and professionals

2006 New Horizons launches to Pluto with CU student built Student Dust Counter

2008 CU AES/LASP students who worked on SNOE start Blue Canyon Technologies

2012 CSSWE CubeSat launched (AES/LASP)



2015 New Horizons arrives at Pluto with CU student built Student Dust Counter

2015 MinXSS-1 CubeSat launched Includes S/N 001 BCT XACT (AES/LASP)

2018 MinXSS-2 launch 3Q18 (AES/LASP CubeSat)

http://lasp.colorado.edu/home/missions-projects/

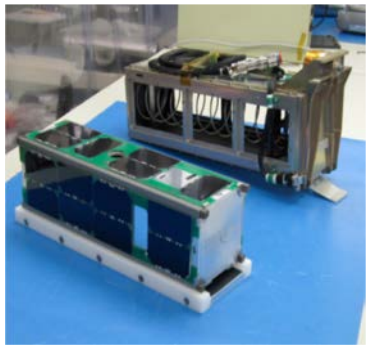
Recent SmallSat work at CU

Heliophysics

Jan 2007 – Mar 2014

DANDE (39267)
Launch Sep 2013
331x1426km 81°
SpaceX Falcon-9 Flight #6

Aug 2009 - Jan 2015

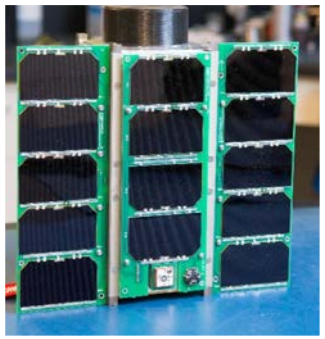


CSSWE (38761)
Launch Sep 2012
442x777km 64.6°
ULA Atlas V [NROL-36]

Aug 2011 – May 2017

MinXSS-1 (41474)
Launch Dec 2015
402x402km 51.2° [ISS]
ULA Atlas V [OA-4]

Jan 2014 - Present



Challenger (42721)
Launch Apr 2017
410x410km 51.2° [ISS]
ULA ATLAS V [OA-7]

Upcoming CU Cubesat Missions

Heliophysics

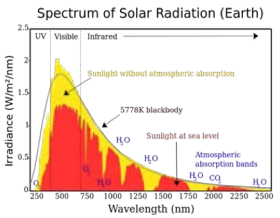
MinXSS CubeSat

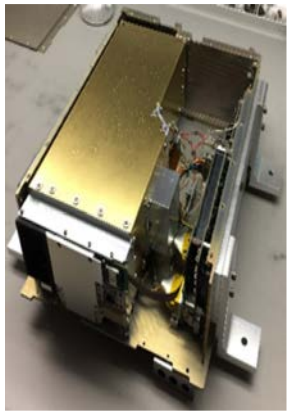
MinXSS-2

Launch 3Q18

SSO 575km

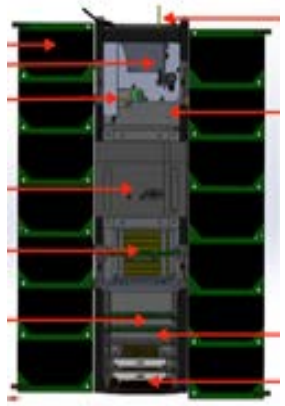
Earth Science





CSIM

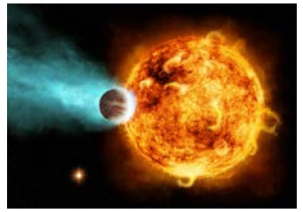
Launch 3Q18

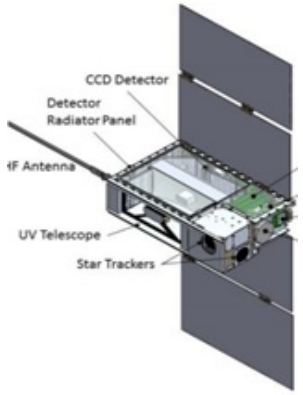


INSIPRE-SAT

Launch 2Q19

Astrophysics





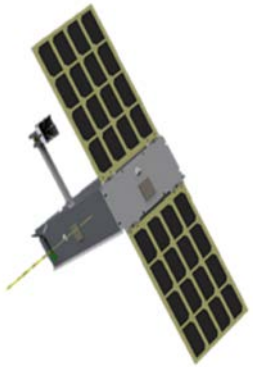
CUTE

Launch 1Q20

Centennial Challenge

CU-E³

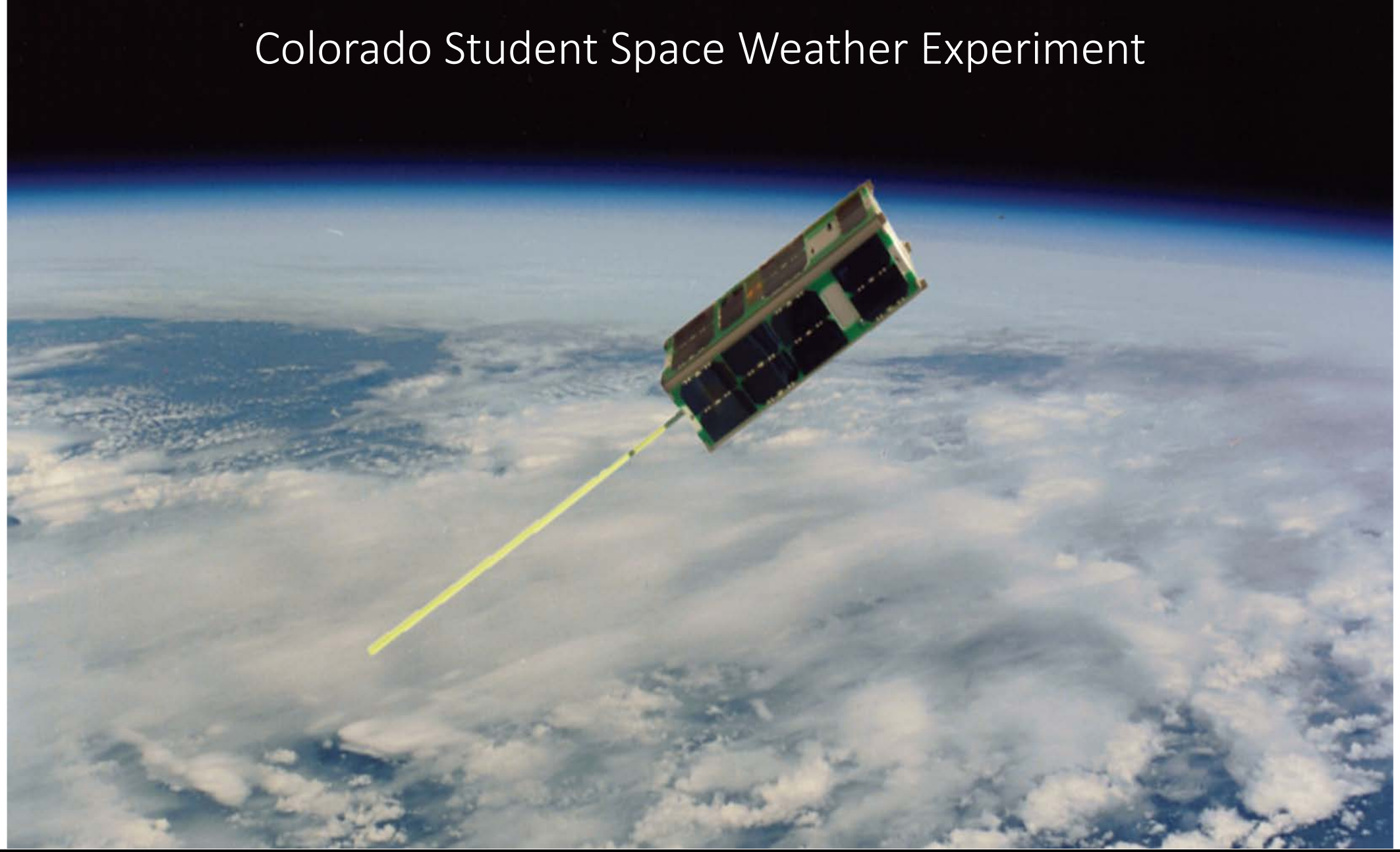
Launch NET 4Q19



MAXWELL

Launch NET 2Q20

Colorado Student Space Weather Experiment



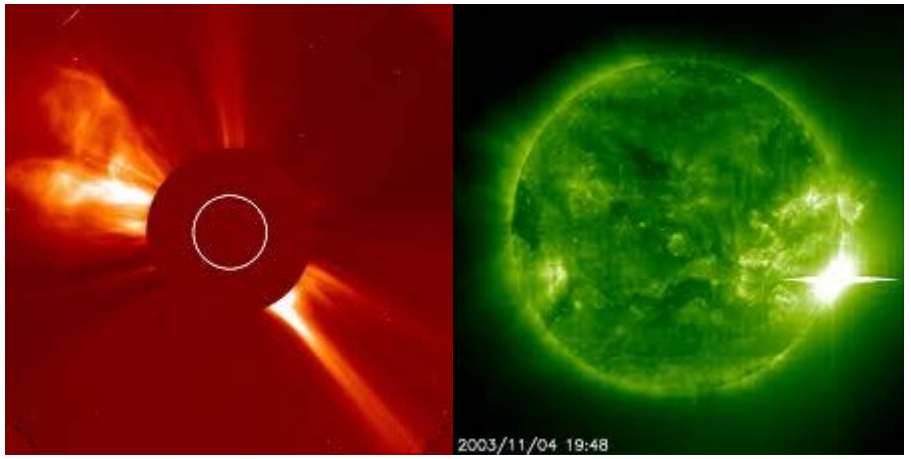
CSSWE Science

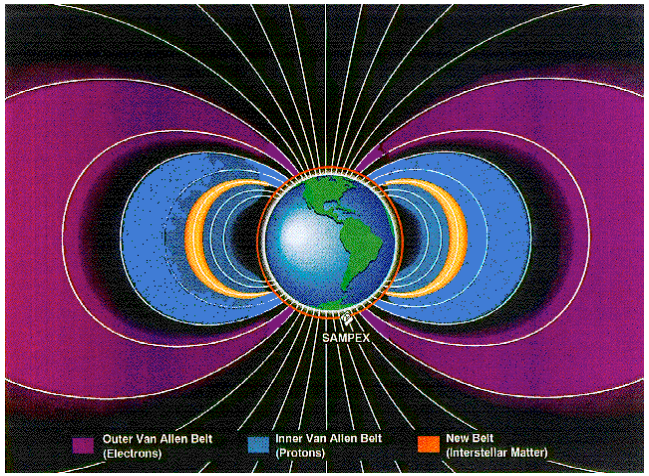
Science Objectives

To understand the relationships between solar energetic particles (SEPs), flares, and coronal mass ejections (CMEs), and to characterize the variations of the Earth's radiation belt electrons.

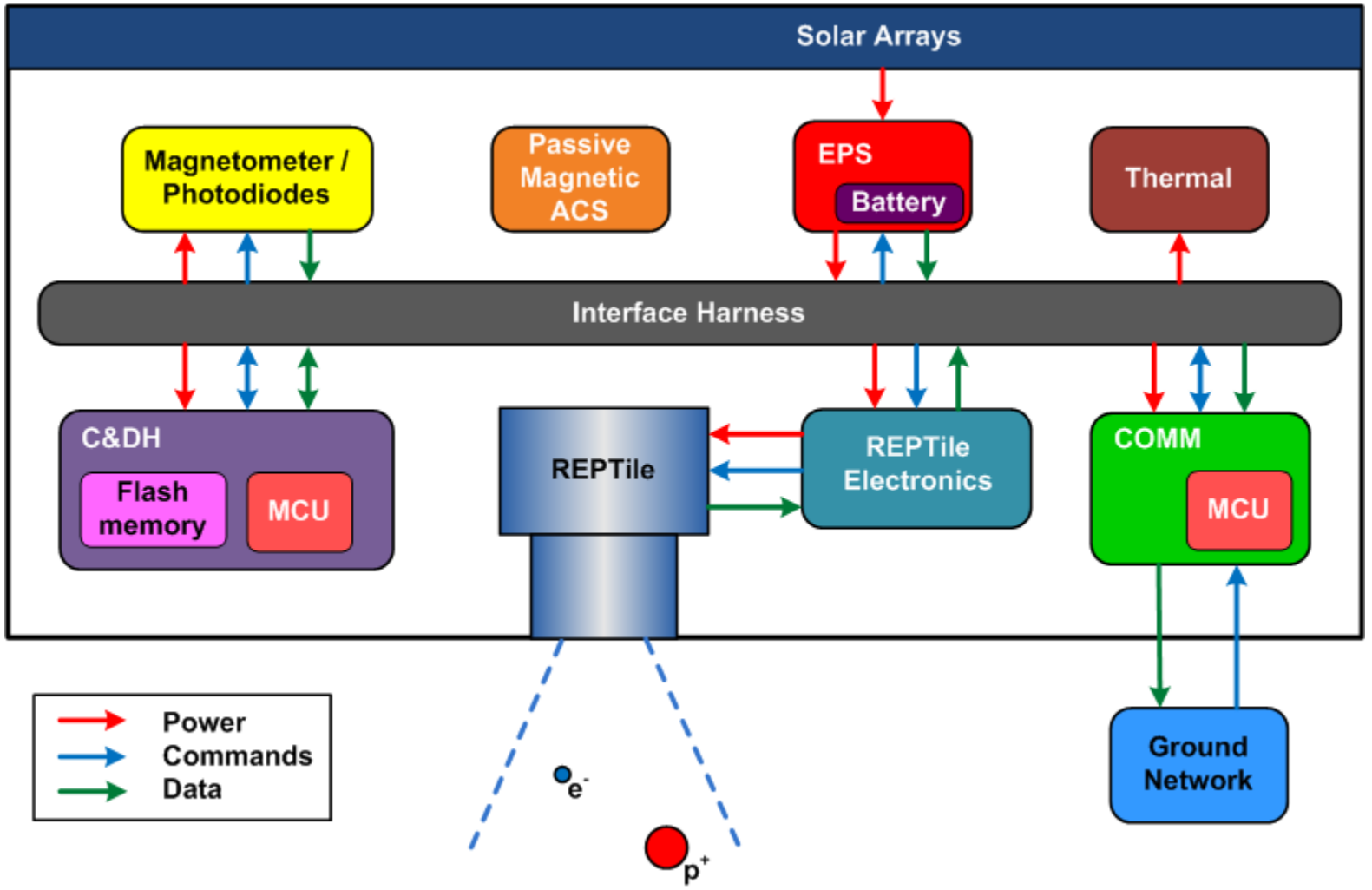
Science Questions:

1. How do the flare location, magnitude, and frequency relate to the timing, duration, and energy spectrum of SEPs reaching Earth?
2. How does the energy spectrum of radiation belt electrons evolve and how does this evolution relate to the acceleration mechanisms?

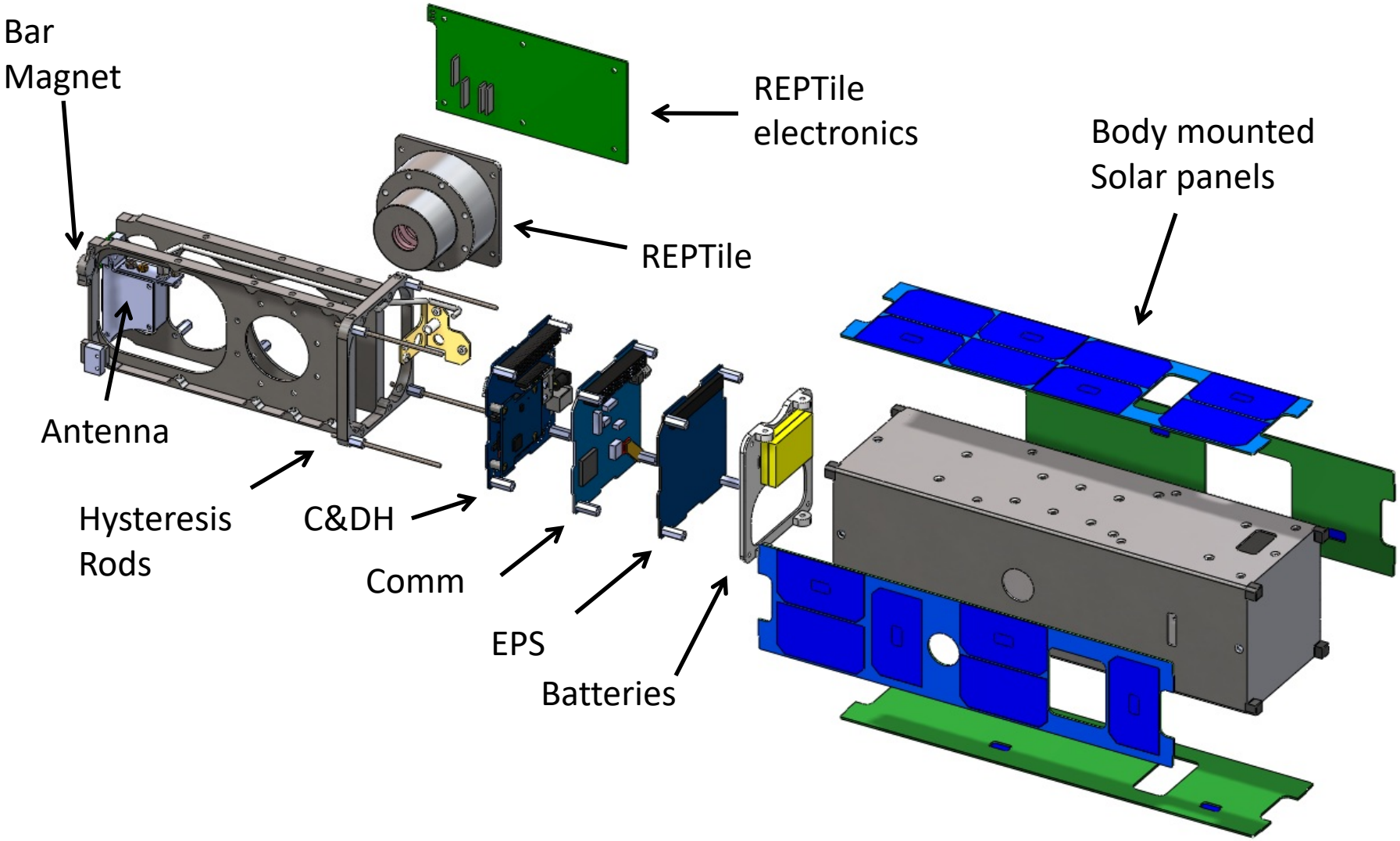




Mission Overview: System

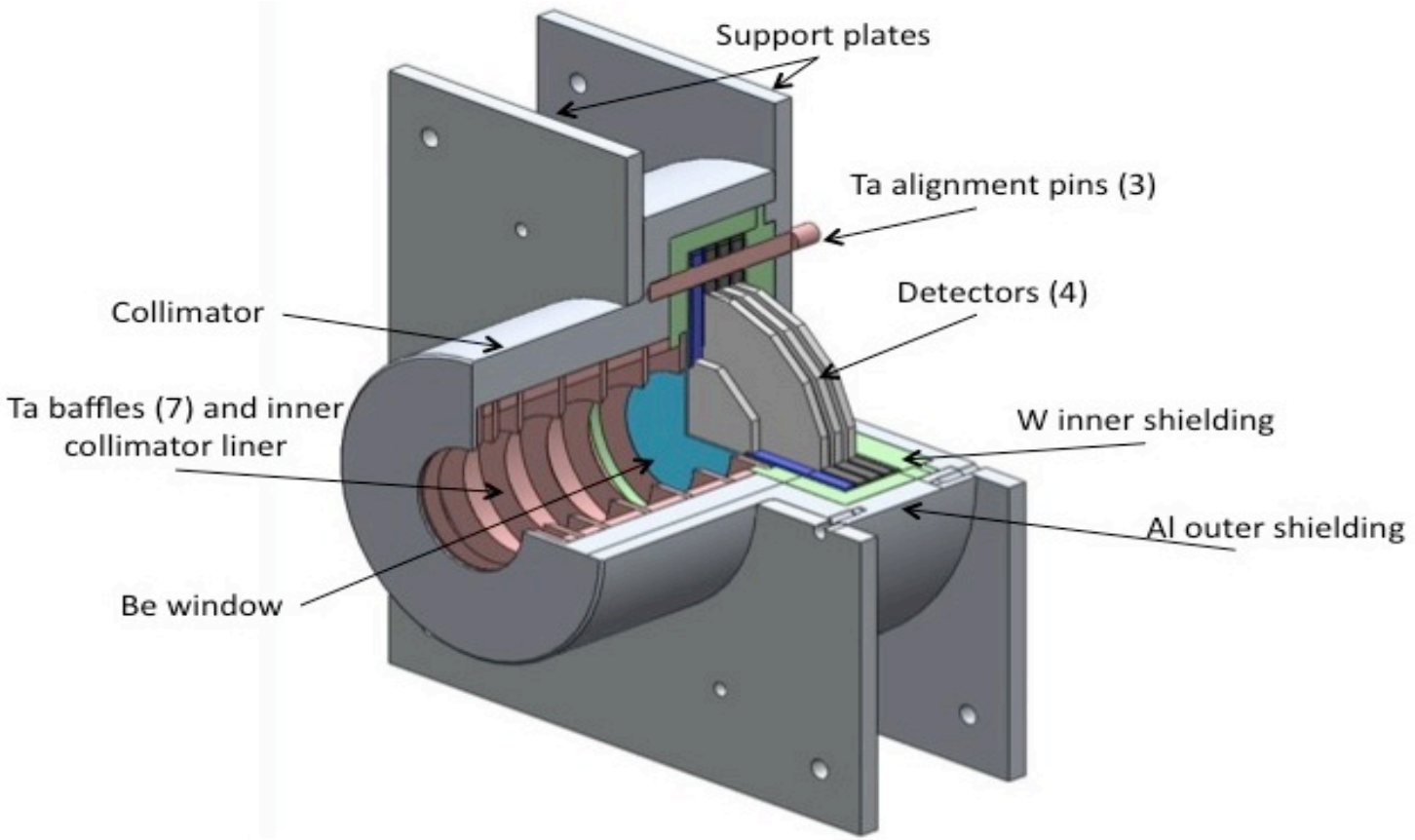


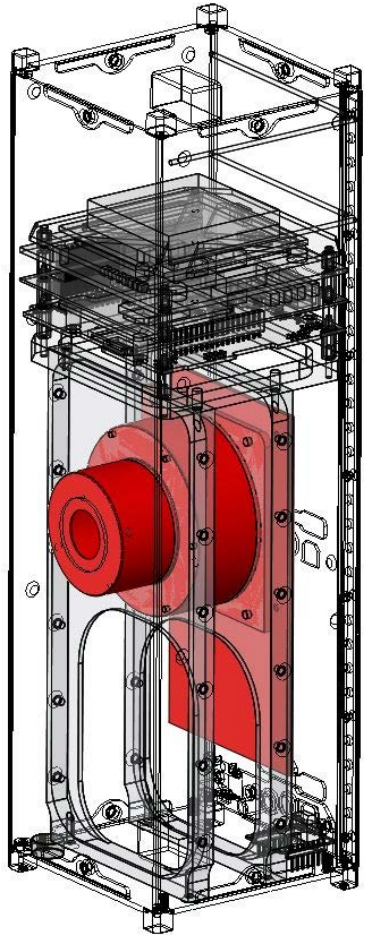
Exploded View



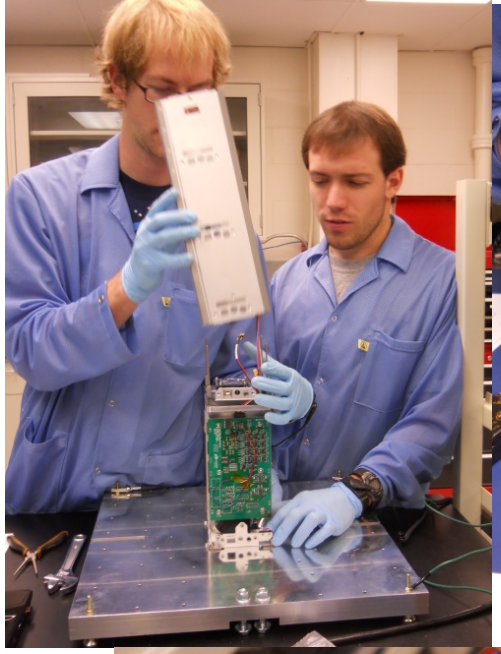
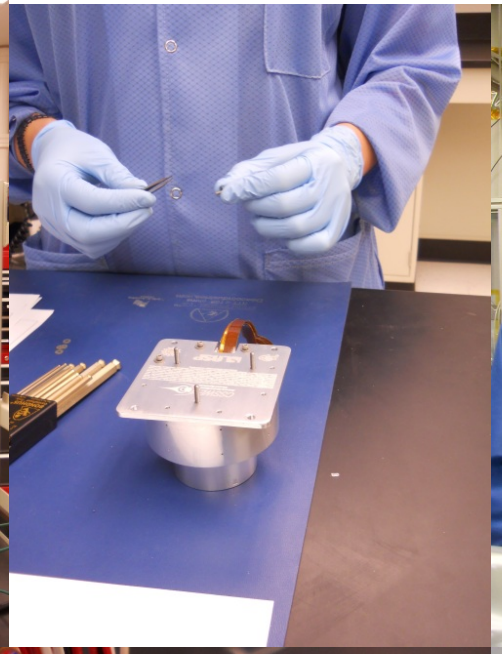
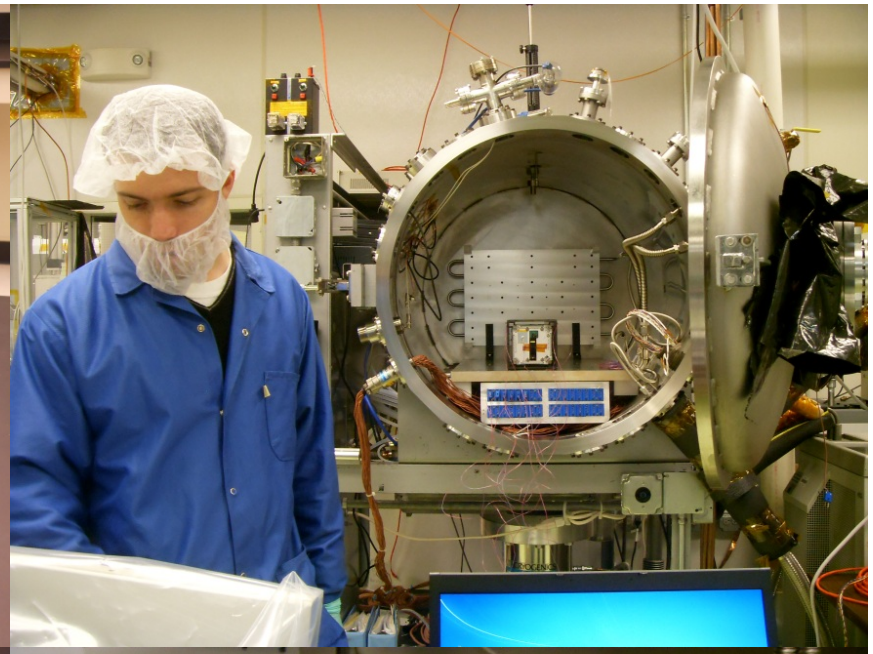
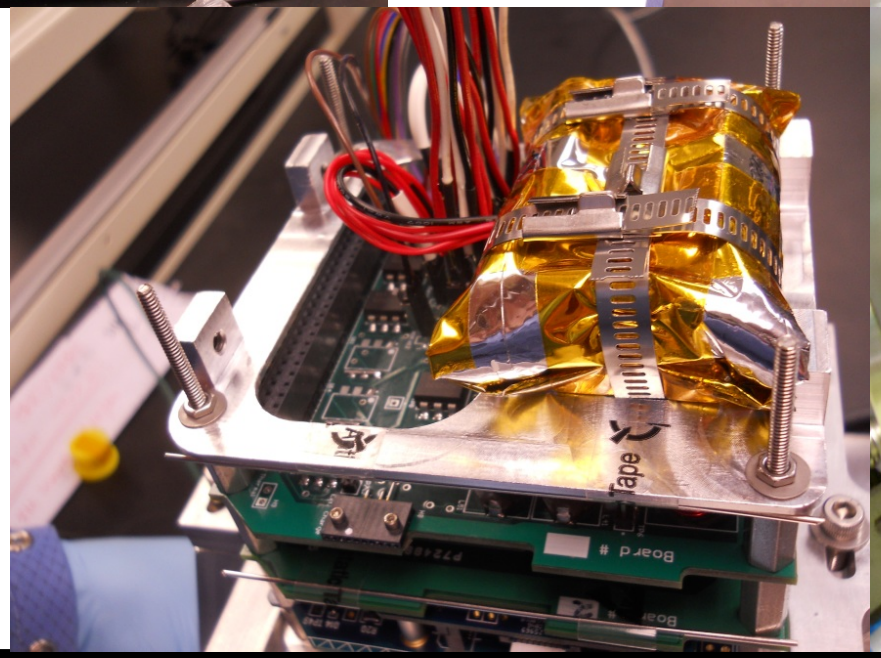
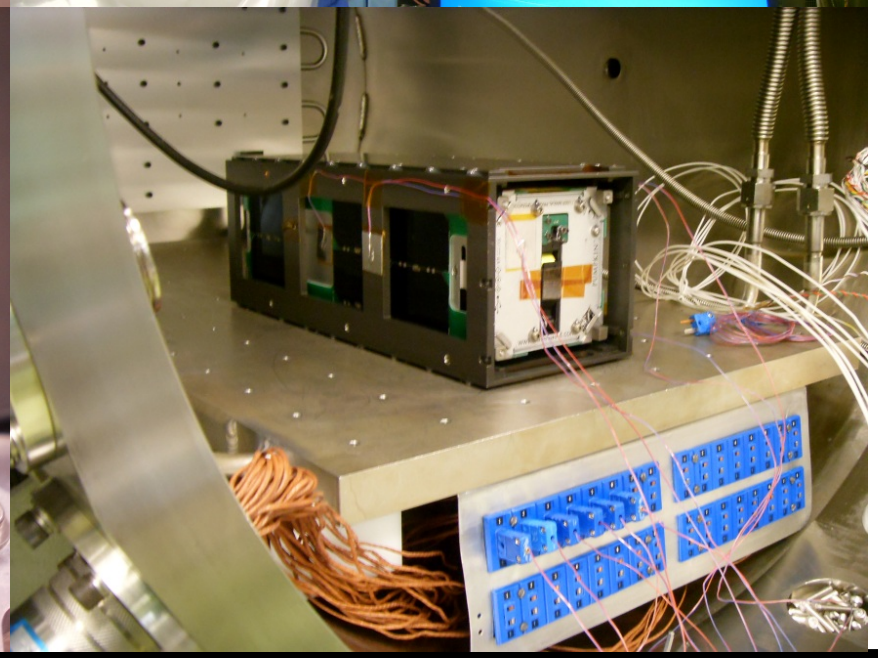
REPTile

Relativistic electron proton integrated little experiment

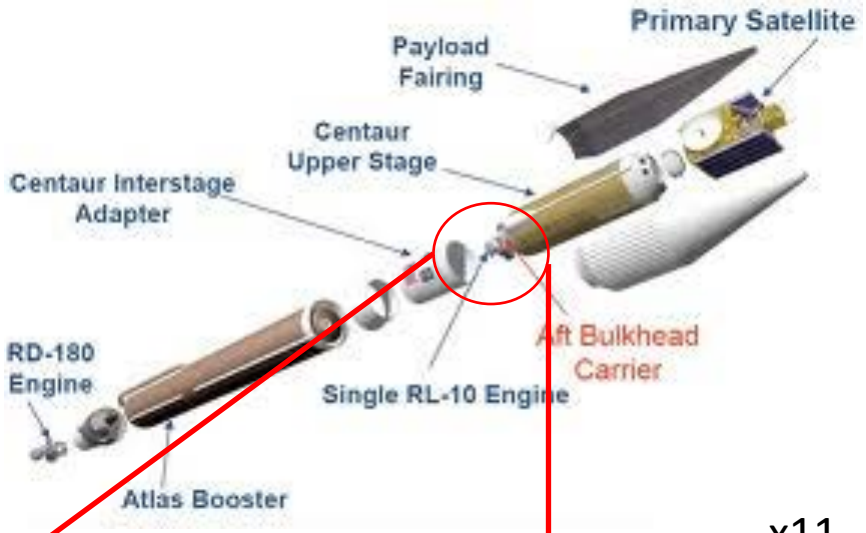


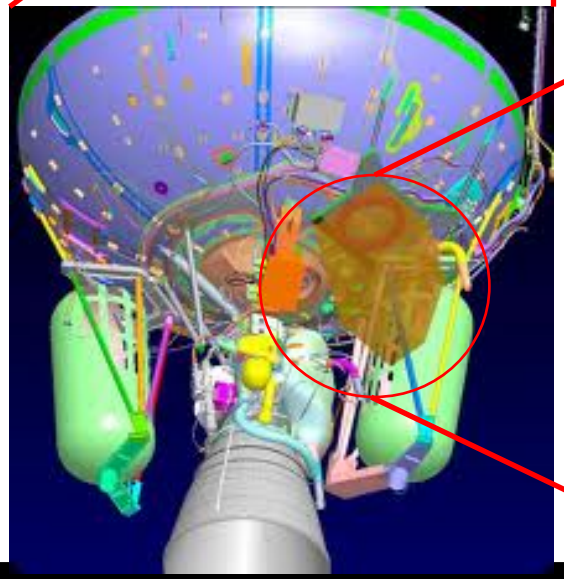


Miniature version of Van Allen probes REPT instrument

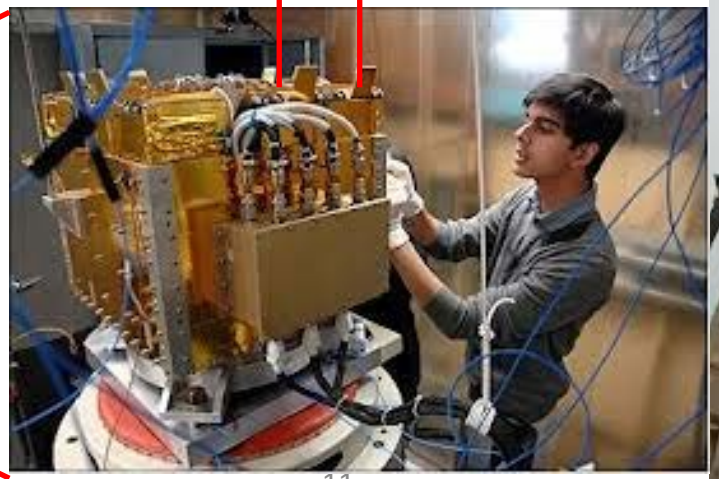






NROL-36 Launch Vandenberg AFB (ATLAS-V)
ELaNa-6 13-SEP-12





x11

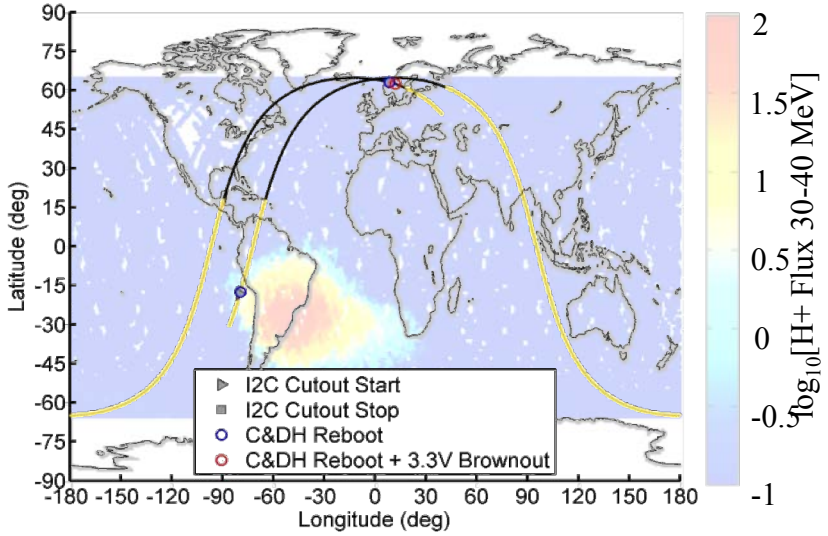


Ground Station

- Built by students
  - Designed for CSSWE and future missions
- UHF cross-Yagi antennas
  - Amateur radio frequency band
- Automated tracking with SatPC32
- Hydra commanding software

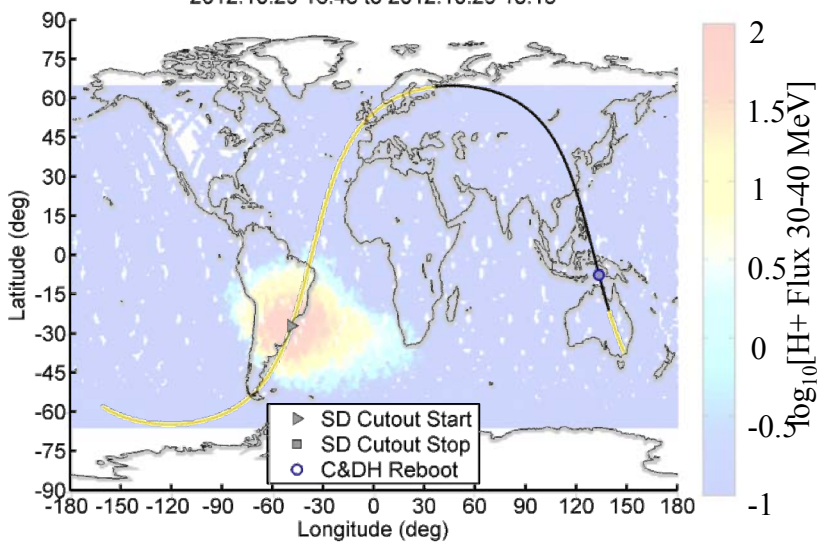
Latch-up (E2)

2012.10.14 23:25 to 2012.10.15 01:45



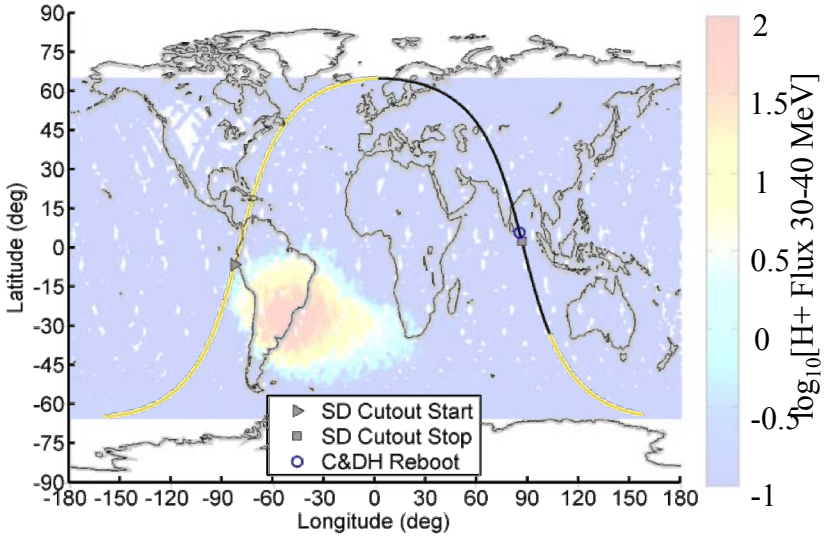
Battery Drain Anomaly #1 (E3)

2012.10.29 16:45 to 2012.10.29 18:15



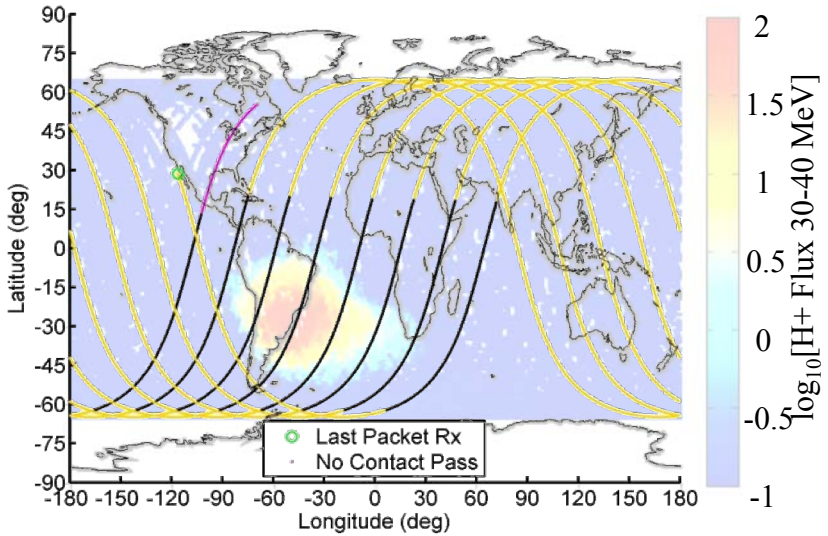
Battery Drain Anomaly #2 (E5)

2013.01.28 19:05 to 2013.01.28 20:40



Loss of Contact (E6)

2013.03.07 22:36 to 2013.03.08 11:12

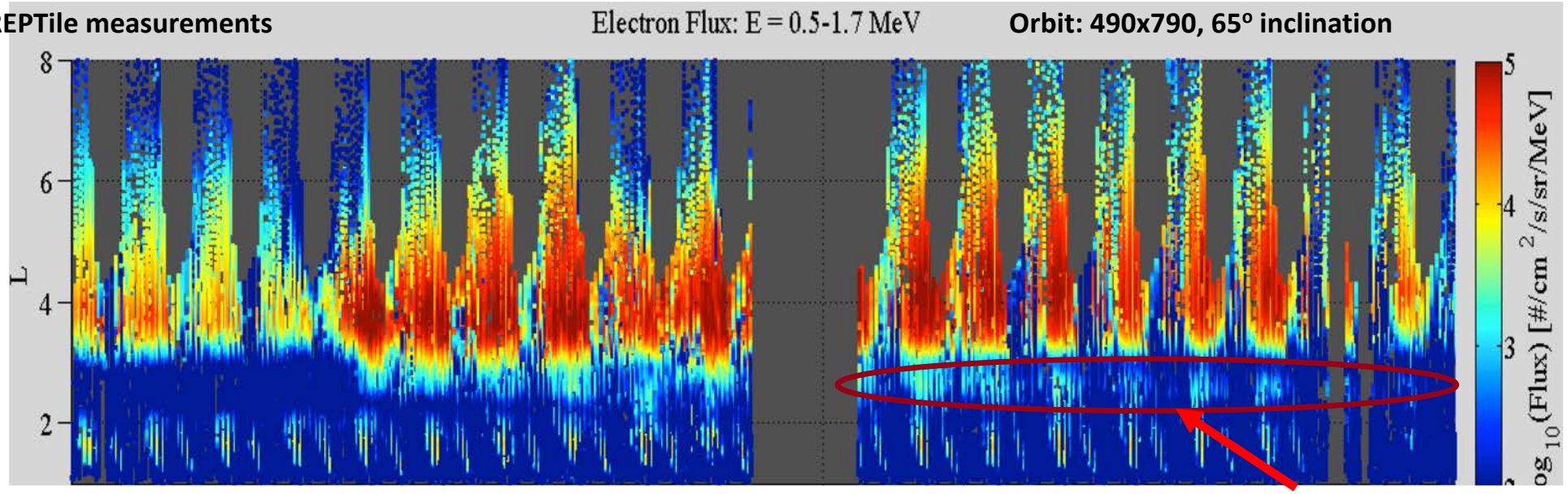


Comparison REPTile and MagEIS (~ 0.5 MeV):

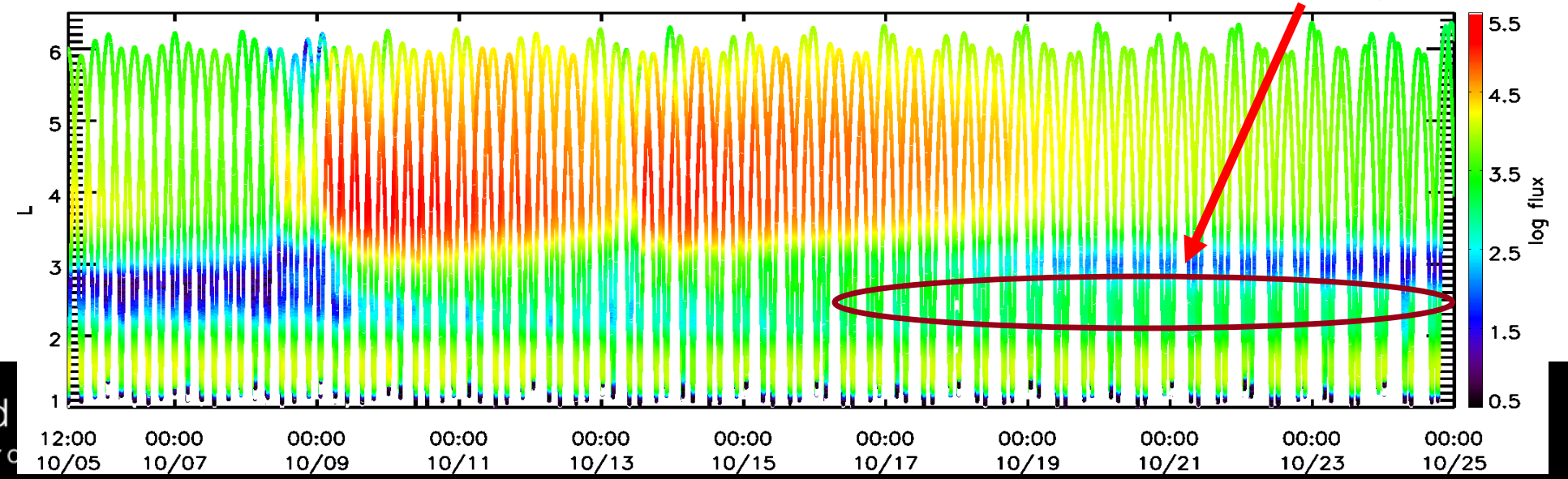
(1) ~ 0.5 MeV electrons go deep, pass slot region and merge with inner belt

(2) Detailed structures: including so called “transient ring”

REPTile measurements



MagEIS measurements (Blake, Fennell et al.)



As of today, 20 peer-reviewed papers published

+ 1 accepted (*Nature*), 1 in preparation

+ 3 Ph.D. Theses completed; 1 in preparation

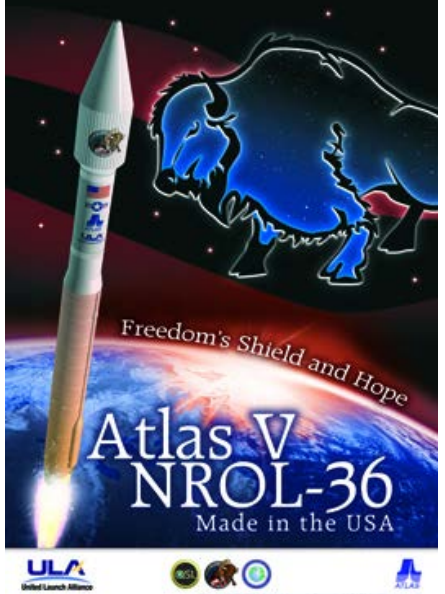
CubeSat Mission Website:
http://lasp.colorado.edu/home/csswe/

Peer-reviewed Publication List Associated with Colorado Student Space Weather Experiment (CSSWE) CubeSat Mission

1) Zhang, K., X. Li, Schiller, D. Gerhardt, H. Zhao, and R. Millan (2017), Detailed characteristics of radiation belt electrons revealed by CSSWE/REPTile measurements: Geomagnetic activity response and precipitation observation, *J. Geophys. Res. Space Physics*, 122, doi:10.1002/2017JA024309.
2) Li, X., D. N. Baker, H. Zhao, K. Zhang, A. N. Jaynes, Q. Schiller, S. G. Kanekal, J. B. Blake, and M. Temerin (2017), Radiation belt electron dynamics at low L (<4): Van Allen Probes era versus previous two solar cycles, *J. Geophys. Res. Space Physics*, 122, doi:10.1002/2017JA023924.
3) Q. Schiller, W. Tu, A. Ali, X. Li, H. Godinez, D. L. Turner, S. K. Morley, M. G. Henderson (2017), Simultaneous event specific estimates of transport, loss, and source rates for relativistic outer radiation belt electrons, *J. Geophys. Res. Space Physics*, 122, doi:10.1002/2016JA023093.
4) Gerhardt, David T., Scott E. Palo (2016), Volume magnetization for system-level testing of magnetic materials within small satellites, *Acta Astronautica 127*, 1-12.
5) Xiang, Zheng et al. (2016), Multi-satellite simultaneous observations of magnetopause and atmospheric losses of radiation belt electrons during an intense solar wind dynamic pressure pulse, Ann. Geophys., 34, 493–509.
6) Li, X., R. S. Selesnick, D. N. Baker, A. N. Jaynes, S. G. Kanekal, Q. Schiller, L. Blum, J. F. Fennell, and J. B. Blake (2015), Upper limit on the inner radiation belt MeV electron intensity, *J. Geophys. Res. Space Physics, 120*, 1215-1228, doi:10.1002/2014JA020777.
7) Baker D. N. et al. (2014), An Impenetrable Barrier to Ultra-Relativistic Electrons in the Van Allen Radiation Belt, *Nature*, doi:10.1038/nature13956.
8) Jaynes, A. N., X. Li, Q. G. Schiller, L. W. Blum, W. Tu, D. L. Turner, B. Ni, J. Bortnik, D. N. Baker, S. G. Kanekal, J. B. Blake, and J. Wygant (2014), Evolution of relativistic outer belt electrons during an extended quiescent period, *J. Geophys. Res. Space Physics, 119*, doi:10.1002/2014JA020125.
9) Gerhardt D Scott E. Palo, Quintin Schiller, Lauren Blum, Xinlin Li, and Rick Kohnert (2014), The Colorado Student Space Weather Experiment (CSSWE) On-Orbit Performance, *J. of Small Satellites*, Vol. 03, No. 01 (Jul 2014) pp. 265-281.
10) Schiller, Q., D. Gerhardt, L. Blum, X. Li, and S. Palo (2014), Design and Scientific Return of a Miniaturized Particle Telescope Onboard the Colorado Student Space Weather Experiment (CSSWE) CubeSat, 35th IEEE Aerospace Conference, 8.1102, doi:10.1109/AERO.2014.6836372.
11) Schiller, Q., X. Li, L. Blum, W. Tu, D. L. Turner, and J. B. Blake (2014), A non-storm time enhancement of relativistic electrons in the outer radiation belt, *Geophys. Res. Lett.*, 41, doi:10.1002/2013GL058485.
12) Blum, L. W., Q. Schiller, X. Li, R. Millan, A. Halford, and L. Woodger (2013), New conjunctive CubeSat and balloon measurements to quantify rapid energetic electron precipitation, *Geophys. Res. Lett., 40*, 1-5, doi:10.1002/2013GL058546.
13) Li, X., et al. (2013a), First results from CSSWE CubeSat: Characteristics of relativistic electrons in the near-Earth environment during the October 2012 magnetic storms, *J. Geophys. Res. Space Physics, 118*, doi:10.1002/2013JA019342.
14) Li, X., S. Palo, R. Kohnert, L. Blum, D. Gerhardt, Q. Schiller, and S. Califf (2013b), Small Mission Accomplished by Students - Big Impact on Space Weather Research, *Space Weather Journal, 11*, doi:10.1002/swe.20025, 2013.
15) 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.
16) 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*
17) 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*
18) Palo, S., Xinlin Li, David Gerhardt, Drew Turner, Rick Kohnert, Vaughn Hoxie and Susan Batiste (2010), Conducting Science with a CubeSat: The Colorado Student Space Weather Experiment, *24th Annual AIAA/USU Conference on Small Satellites.*
19) Schiller, Q., 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.*
20) Gerhardt, D. T. with advisor Scott Palo (2010), Passive Magnetic Attitude Control for CubeSat Spacecraft, *24th Annual AIAA/USU Conference on Small Satellites.*

Student Involvement

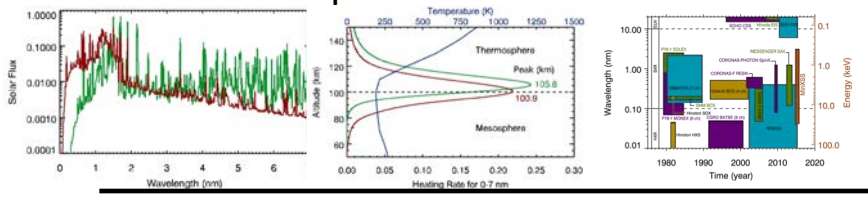
Over 60 students involved in the project

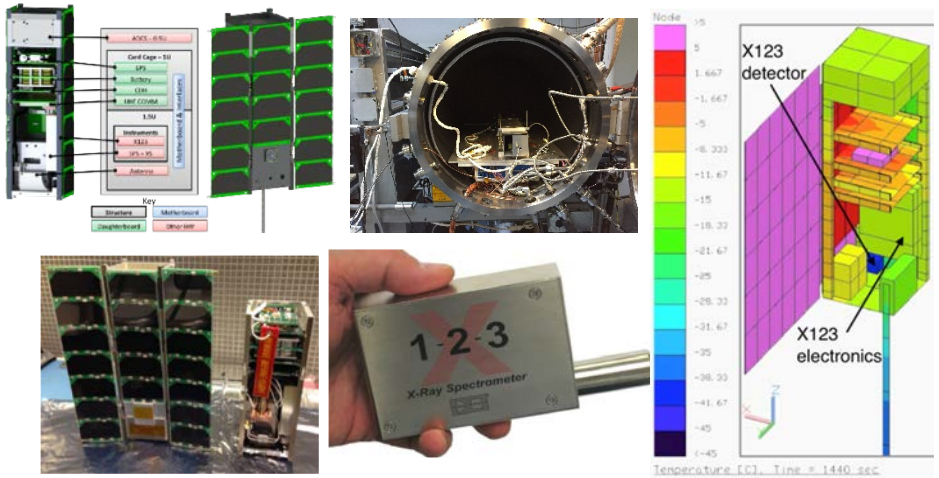


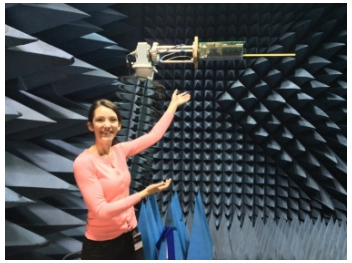
The Miniature X-ray Solar Spectrometer

Objectives

Observe the Sun, specifically the intensity of the soft X-ray spectrum from 0.4 keV (30 Å) to 30 keV (0.4 Å), with a resolution of 0.15 keV. These observations will be used to better understand how soft X-ray flares effect the earth's atmosphere .

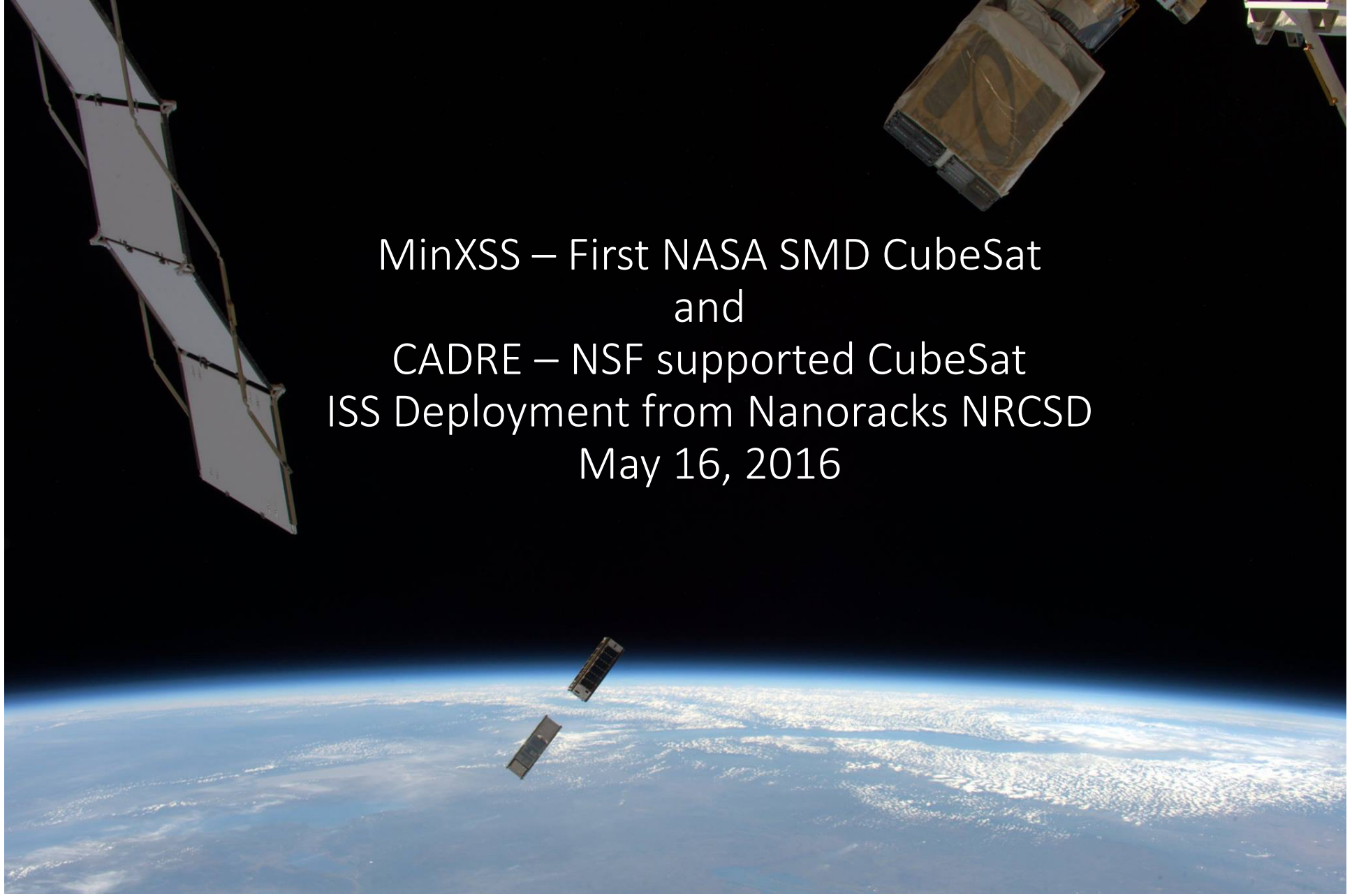






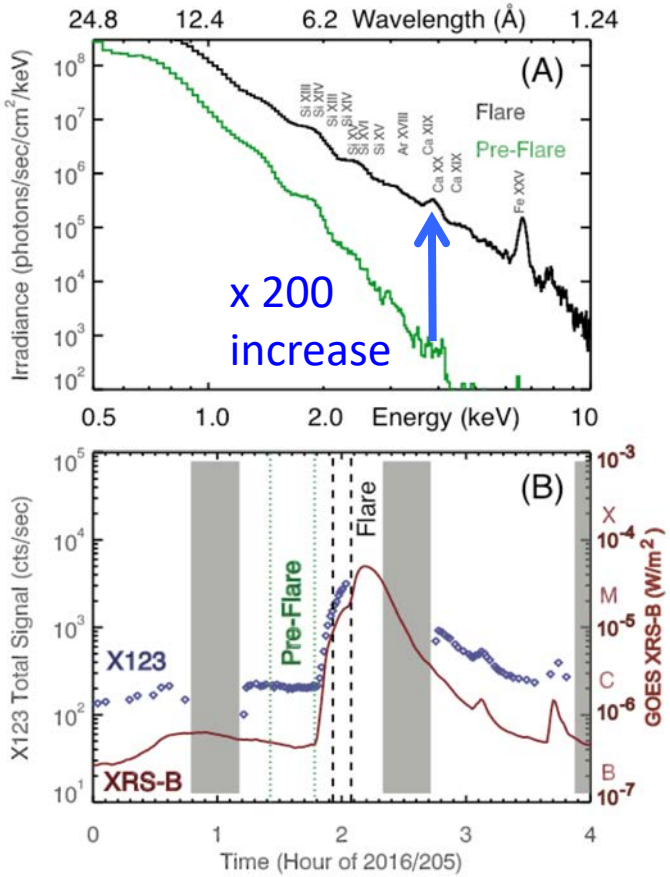
- First NASA SMD CubeSat
- Launched Dec 6, 2015, OA-4 to ISS
- Deployed May 2016
- Achieved full success and deorbited in May 2017
- S/N 001 BCT XACT – Demonstrated ~10 arcsec pointing
- Coordinated in AES projects course
- MinXSS-2 scheduled to launch 2Q18

[MinXSS Website]


MinXSS – First NASA SMD CubeSat
and
CADRE – NSF supported CubeSat
ISS Deployment from Nanoracks NRCSD
May 16, 2016

MinXSS Reveals Flare Plasma Temperature and Brightness

- **M5.0 flare on 23-Jul-2016**
  - SXR irradiance increases during this flare by a factor of 4-200 relative to the pre-flare level.
  - Emission includes Bremsstrahlung continuum along with many hot coronal lines
  - Pre-flare spectrum (green) has plasma temperature of 2-4 MK and abundance (composition) factor of 2.1.
  - **Flare spectrum (black) has plasma temperature of 2-15 MK and abundance (composition) factor of 1.2.**
- MinXSS X123 data have 10-sec cadence but with data gaps during orbit eclipse periods
- MinXSS-1 during its 1-year mission has observed:
  - 8 M-class flares and
  - 100+ C-class flares



Figures from Woods *et al*. (*ApJ*, 2016)


MinXSS wins the
2016 Small Satellite of the Year award !

QBUS

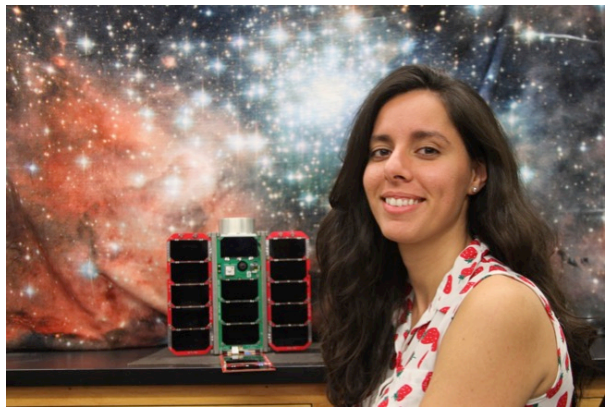
- US QB50 Consortium
  - Four Universities
  - ITM science expertise
  - Prior CubeSat experience
  - Over 100 students involved

University of Colorado Boulder

MICHIGAN

Stanford University

pensar es crear la luz de la vida
1972
UNIVERSIDAD DEL TURABO
Ana G. Méndez University System

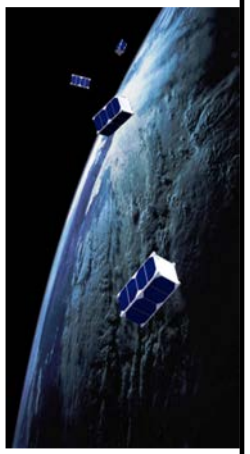


QBUS – University of Colorado

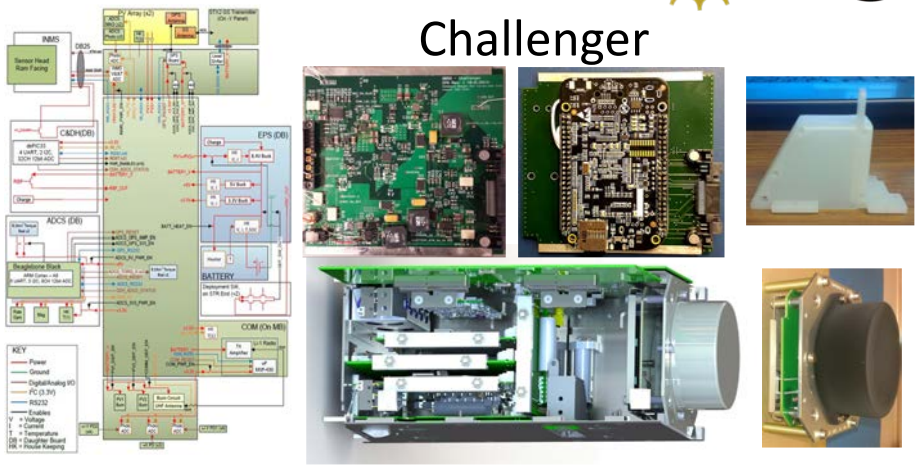
QB50

Objectives

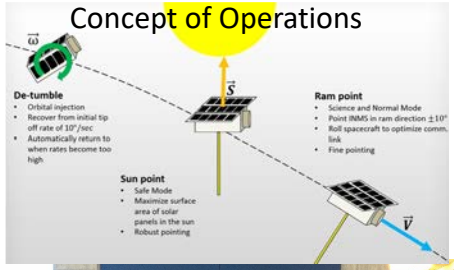
The QB50 project is an initiative born out of the European von Karman Institute that aims to deploy approximately fifty CubeSats into LEO in order to conduct multi-point, in-situ, measurements of the lower thermosphere.



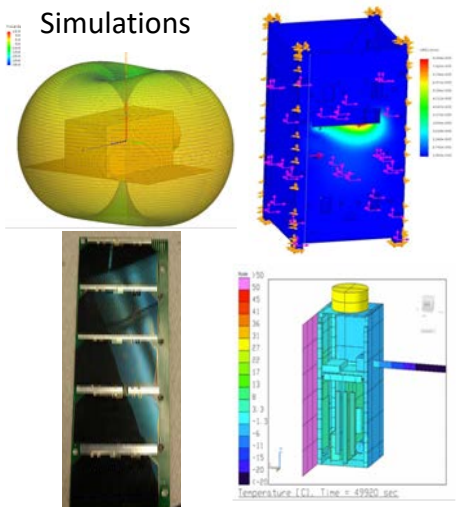
Challenger



Concept of Operations



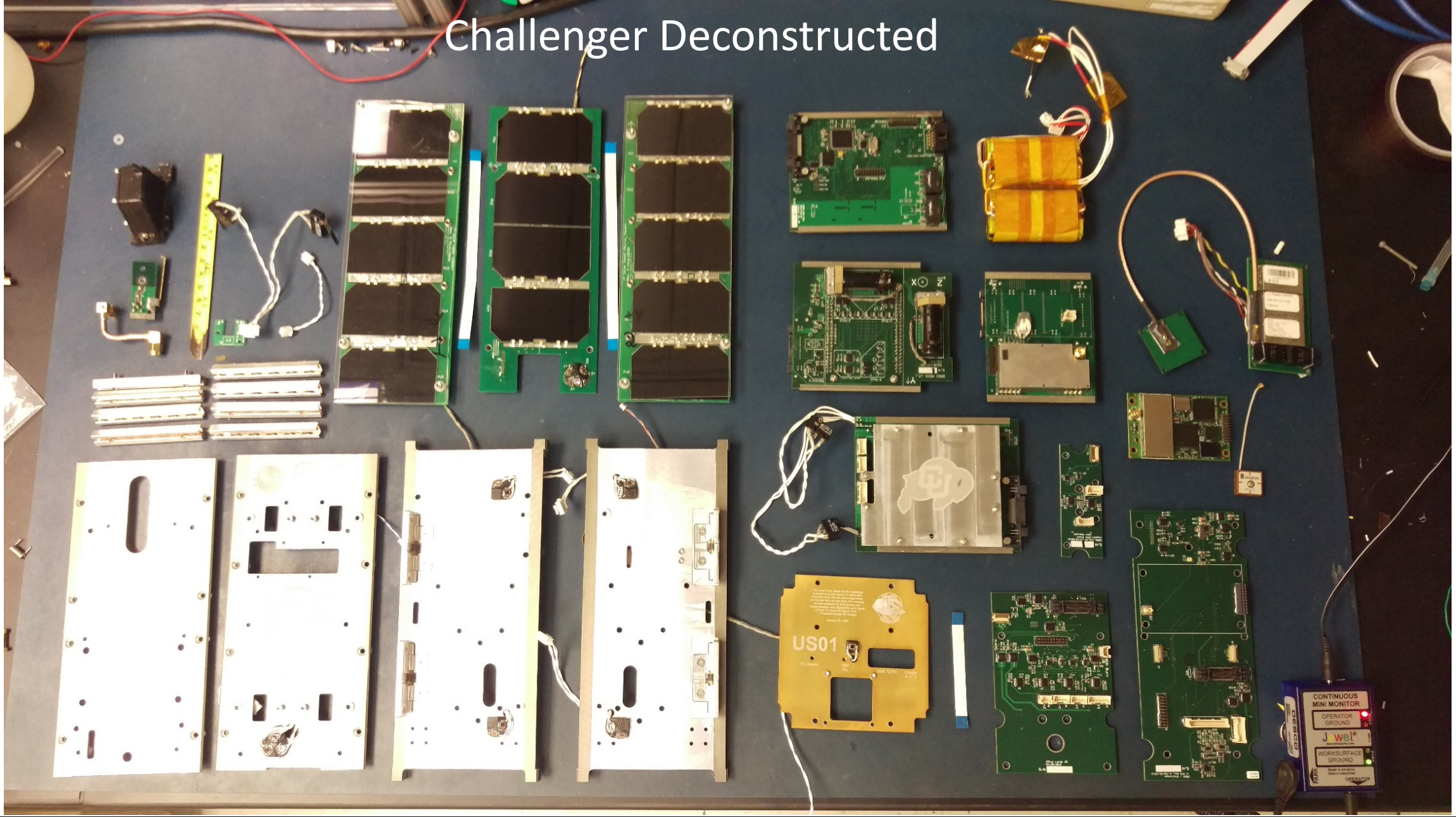
Simulations



- Funded by NSF ($180K)
- 2016-04-18 OA-7 launch
- 2016-05-25 ISS deployment
- 9-12mo orbital lifetime
- Builds on CSSWE and MinXSS Heritage
- New CU constructed ADCS system
- University College London constructed ion neutral mass spectrometer (INMS)
- Coordinated in AES projects course

QB50 Website

Challenger Deconstructed



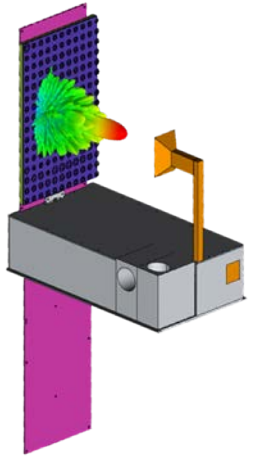

COMMERCIAL RESUPPLY SERVICES
OA-
NASA • ORBITAL ATK
OA-7 Launch
April 18, 2017
@johnkrausphotos
www.johnkrausphotos.com

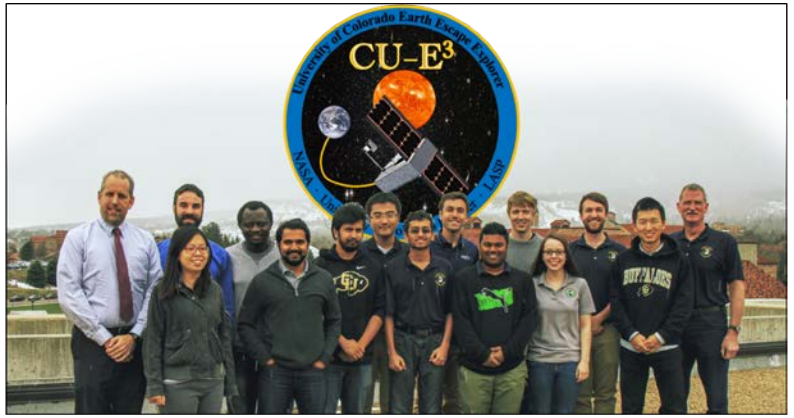
CU-E3
Colorado Earth Escape Explorer

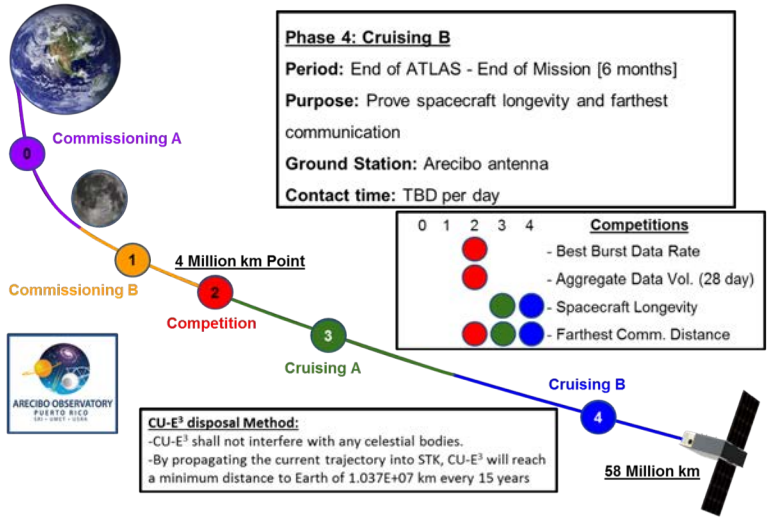
Part of the NASA CubeQuest Challenge
Demonstrate Deep Space CubeSat Com
Placed 4th in ground tournament #2
Placed 3rd in ground tournament #3
Placed 2rd in ground tournament #4
Selected for launch on EM-1

Enabled through AES graduate projects curriculum
Builds on prior hardware development – X-band radio
Prototyping novel X-band reflectarray
Leverage partnerships
- BCT – XB1 small satellite bus with XACT ADCS
- ATLAS ground station resources

Scheduled delivery, 2Q17







2nd Place & SLS Launch Opportunity

Summary

- The University of Colorado has had a robust cubesat program for more than 10 years
- Students have been an integral part of the program
- The focus has been on space weather science
- We are excited about the opportunities to operate in deep space
- We are always open for discussion about potential collaborations