Colorado Student Space Weather Experiment (CSSWE) CubeSat: a Success in Education, Engineering, and Science

PL: Xinlin Li, Co-PLs: Scott Palo and Shri Kanekal

LASP Engineers: Rick Kohnert (chief technical mentor), Gail Tate (SW), Vaughn Hoxie (EE) + others

Student Team: involved over 65 graduate and undergraduate students
Lauren Blum (PM), David Gerhardt (SE), Quintin Schiller (CFO and Instrument)
Other current Ph.D. students: Sam Califf and Hong Zhao
Former Ph.D. students: Drew Turner and Weichao Tu

Funded: 1/1/10     Delivered: 1/9/12
Launched: 9/13/12, NRO (Atlas V) under NASA’s ELaNa program
Orbit: ~480 km x 780 km, inclination 65°
CSSWE: Colorado Student Space Weather Experiment

(Spring of 2010)
CSSWE: Colorado Student Space Weather Experiment
(Fall of 2010)
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Relativistic Electron and Proton Telescope integrated little experiment (REPTile)
Characteristics of an electron’s motion:

- Electron loss cone opens up at low altitude
- Low altitude measurements are most useful in determining the electron loss rate
Outer Radiation Belt Electrons Measured by SAMPEX and CSSWE
(launched on 7/03/92: 550km × 675km, 82°, re-entered on 11/13/12)

Color-coded outer radiation belt electron (2-6 MeV) flux

(Li et al., 2013)
Outer Radiation Belt Electrons Measured by SAMPEX and CSSWE
(launched on 7/03/92: 550km × 675km, 82°, re-entered on 11/13/12)

(Li et al., 2013)
GOES measurements of >2 MeV electrons since 1996 show the same trend around \( L=6 \)
Concurrent measurements with NASA/Van Allen Probes
(orbits: 605km x 30410km and 635km x 30540km, inclination: 10°)
A block diagram of the subsystems and interfaces:
CubeSat bus, main subsystems, and the payload

3U: 10x10x30 cm³

- Hysteresis Rod 6x
- Battery
- EPS
- Comm
- C&DH
- REPTile Electronics (behind the housing)
- Magnetic Bar

REPTile: Relativistic Electron Proton Telescope integrated little experiment
FEA Results – Factor of Safety and Displacement

50G Static Load
Results shown for loading along the vertical axis
Simulation-based design of the detector

Table: Estimated worst-case signal-to-noise ratios (SNR)

<table>
<thead>
<tr>
<th></th>
<th>Detector 1</th>
<th>Detector 2</th>
<th>Detector 3</th>
<th>Detector 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e: R_{sn}$</td>
<td>87.9</td>
<td>42.2</td>
<td>28.9</td>
<td>23.8</td>
</tr>
<tr>
<td>proton: $R_{sn}$</td>
<td>13.6</td>
<td>8.5</td>
<td>6.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>

$\gamma_{signal} \approx 0.55 \ Sr \cdot cm^2$

<table>
<thead>
<tr>
<th>$\gamma_{noise}[Sr \cdot cm^2]$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.23</td>
<td>0.18</td>
<td>0.72</td>
<td>11.1</td>
<td>2.1</td>
<td>15.4</td>
</tr>
</tbody>
</table>
REPTile’s Signal Chain

**Step 1:** Signal generated by a detector

**Step 2:** Charge Sensitive Amplifier

**Step 3:** Second Stage Amplifier

**Step 4:** Discriminators

**Step 5:** Programmable Logic Device

**Step 6:** Store data counts

- **Detector**
- **CSA**
- **PSA**
- **D1**, **D2**, **D3**
- **CPLD**
- **μC**

**Signal Voltage**
- 0.25 - 0.33V
- 3.25 - 4.3V
- 20 - 33mV

**Ref. 1**, **Ref. 2**, **Ref. 3**

**10x**

**130x**

**1x**

<table>
<thead>
<tr>
<th><strong>Ref. 1</strong></th>
<th><strong>Ref. 2</strong></th>
<th><strong>Ref. 3</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>p</strong></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td><strong>e</strong></td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Electron**

**Proton**
Passive Magnetic Attitude Control (PMAC)

Low cost & performance, simple, robust

High cost & performance, complex

Bar Magnet & Hysteresis Rods

Magnetic Torque Coils

Momentum Wheels
By the early of 2011, design phase were over for most subsystems → building, integration, and testing

Testing – E2E Test Progress
After pass the End-to-End test on flatsat ➔ fit in check ➔ potting all boards ➔ integrated tests on the flight satellite

Pre-potted flight board

REPTile assembly

Potted flight board

Test-POD fit check
Thorough solar cell and panel testing

Solar cell forward bias testing

System testing and debugging

Solar cell mounting

Integrated testing
Testing in anechoic chamber of FirstRF Corp. to determine the antenna gain pattern

First Plugs-out Test (11/10-11/2011):
Third Plugs-out Test (after T-V test): 12/21/2011

437.345 MHz
Vibe Test at Navy Postgraduate School (11/16/2011):
Colorado Student Space Weather Experiment (CSSWE)

Thermo-Vac Test at LASP: 12/06-14/2011
TVAC cycling temperature. Blue: the average of four thermistors placed on the external shell of the CubeSat; Green: on solar cell; Red portion: when PFT was performed; Red Stars: on/off.
Additional Reviewers: Bill Possel, Bret Lamprecht, Andrew Jones, Beth McGilvray, Heather Reed, Darren Osborne
ASE: Trudy Schwartz, Diane Dimeff
Roof Antenna: Paul deFalco, CU Fac-man
QA and ESD Training: Doug Vincent, Jon Thiede, Dwight Reinhardt
CPLD: Magnus Karlsson
T-Vac and REPTile testing: James Mason, Hong Zhao, David Hall, David James, Matt Carton
Mission Operation & Software: Colin Stewart, Wayne Russell, Samantha Pettus, Tyler Fox, Scott Taylor, Tyler Traver, Mike Dorey, Steve Roughton, Chris Pankratz, Sean Ryan, Jennifer Reiter
EPO and Website: Stephanie Renfrow, Tom Mason, Marisa Lubeck, Ransom Christofferson, Nick Diorio,
http://lasp.colorado.edu/home/csswe/
Business Analysts: Peter Wise, Jason LaClair, Zak Eaton, Nina Davis
Launched on 9/13/12, we received beacon packets during its first over pass

Commissioning phase completed on 10/04/12 and Particle detectors were turned on

The data are clean, exceeding our expectation!

<table>
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<tr>
<th></th>
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<th>Channel 2</th>
<th>Channel 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrons</strong></td>
<td>0.5-1.7 MeV</td>
<td>1.7-3.3 MeV</td>
<td>&gt;3.3 MeV</td>
</tr>
<tr>
<td><strong>Protons</strong></td>
<td>9-18 MeV</td>
<td>18-30 MeV</td>
<td>30-40 MeV</td>
</tr>
</tbody>
</table>
--- Passive Attitude Control
--- No pointing requirement
--- Only the knowledge is needed

Onboard magnetometer + photo sensors + temperature sensors → s/c attitude

Not concerned with the total magnitude, but the ratio of the B-components

The s/c swings <1°/s around the local B

10 min
Sci Singles Count Log (unprocessed raw data)

(0.5-1.7 MeV electron)
(1.7-3.3 MeV electron)

2nd detector turned on

Count [Directional Differential Flux]

Time starting on Oct 04, 2012 (RTC corrected to MDT)

Orbit: ~480 km x 780 km, inclination ~65°
Concurrent measurements with NASA/Van Allen Probes
(orbits: 605km x 30410km and 635km x 30540km, inclination: 10°)

- CSSWE
- Electrons
- Outer Radiation Belt
- Inner Radiation Belt
- BARREL
- Van Allen Probes (x2)
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”
Comparison REPTile and REPT (>1.77 MeV):

(1) Outer belt electrons dynamic with continuous PA scattering, but stayed at L≥3, and no “transit ring”

(2) Inner belt electrons stable, confined to the equatorial region, only detectable by REPTile over SAA
Comparison between REPT and REPTile:

1. Very few energetic protons in the outer belt
2. Inner belt protons stable, confined to the equatorial region

REPTile Proton Measurements
Proton Flux: $E = 18-30$ MeV

REPT-B measurements
21.25 MeV Proton Flux
REPT PI: Dan Baker

21.25 MeV proton flux [n/cm²/s/ster/Mev]
Measurements of electrons & protons from REPTile provide a clear picture of energetic particles (electrons and protons) in the near Earth environment (10/5-25/2012)
Based on where the measurements are made, we can classify the electron populations: **Untrapped (BLC)**, **Quasi-trapped (DLC)**, and **Trapped**

(Suggested by Richard Selesnick, Hong and Quintin made the above figure)
REPTile electron measurements since launch

Daily Averaged Electron Flux for $E = 0.5$-$1.7$ MeV

Through 03/07/2013

Jaynes et al.
Evolution of relativistic outer belt electrons during extended quiescent period

Electron Flux: $E = 0.5-1.7$ MeV

RBSP-A MagEIS, $E=0.6$ MeV, Dec 15, 2012 to Jan 15, 2013

(Jaynes et al. with RBSP/ECT, to be submitted to GRL, 2013)
REPTile electron measurements since launch

10/05/2012

Daily Averaged Electron Flux for $E = 0.5-1.7$ MeV

Through 03/07/2013

Schiller et al.
Enhancement during non-storm time, but with some substorm activity
REPTile electron measurements since launch

10/05/2012

Daily Averaged Electron Flux for E = 0.5-1.7 MeV

Through 03/07/2013

Log (Flux) [#/cm²/s/sr/MeV]

2 2.5 3 3.5 4 4.5

L

Nov 01  Dec 01  Jan 01  Feb 01  Mar 01

Daily Averaged Electron Flux for E = 1.7-3.3 MeV

Blum et al. with BARREL Team

Log (Flux) [#/cm²/s/sr/MeV]

1 1.5 2 2.5 3 3.5 4

L

Nov 01  Dec 01  Jan 01  Feb 01  Mar 01
BARREL-CSSWE Conjunctions – 01/18-19

(BARREL Team/Blum et al., to be submitted to GRL, 2013)

BARREL

CSSWE

E1: 0.5-1.7 MeV
E2: 1.7-3.3 MeV
E3: >3.3 MeV

Flux (#/cm² s sr MeV)

Time (hours UT, 1/18)

Flux (#/cm² s sr MeV)

Time (hours UT, 1/19)
REPTile electron measurements since launch

10/05/2012

Daily Averaged Electron Flux for $E = 0.5-1.7$ MeV

Through 03/07/2013

Log$_{10}$ (Flux) [#/cm$^2$/s/sr/MeV]

Jaynes et al.

Schiller et al.

Li et al., JGR, to be submitted soon

Blum et al. with BARREL Team

Log$_{10}$ (Flux) [#/cm$^2$/s/sr/MeV]
The satellite went silent on 3/08/13.
Data analysis and modeling efforts have been continuing ...

Then on 6/18/13 (Tuesday), 23 beacons were recorded by the automated system, bi-directional communications with the satellite were re-established yesterday ...
Publications


Title: Conducting Science with a CubeSat: The Colorado Student Space Weather Experiment, Scott Palo, Xinlin Li, David Gerhardt, Drew Turner, Rick Kohnert, Vaughn Hoxie and Susan Batiste, *24th Annual AIAA/USU Conference on Small Satellites*

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

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

Title: Passive Magnetic Attitude Control for CubeSat Spacecraft, David T. Gerhardt with advisor Scott Palo, *24th Annual AIAA/USU Conference on Small Satellites*
Conclusions

Our tiny CubeSat has been operating over five months, providing clean measurements of energetic electrons and protons → a success in education, engineering, and science! → A Proof!

Combined measurements with other missions such as Van Allen Probes and THEMIS provide a better characterization of the inner and outer belts (for both \(e^-\) and \(p^+\)):

1. penetration depth is energy dependent
2. energy spectrum is \(L\) dependent
3. inner belt is well confined to the equatorial region
4. quantify the net enhancements measured near the equator
5. refine the spatial and temporal scopes of precipitation

In-depth science results have been harvested ...

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

“The success of the CSSWE mission exemplifies everything we hope to achieve with the NSF CubeSat program. The CSSWE CubeSat has provided unique and highly valuable scientific data for space weather research.

At the same time, the project is an extraordinary demonstration that this can be done successfully with a student-built satellite in an educational setting. This data is an outstanding resource that will be aiding scientific advances for years to come.”

Therese Moretto Jorgensen, PhD
Program Director, Space Weather Research
National Science Foundation