REPTile: A Miniaturized Detector for a Cubesat Mission to Measure Relativistic Particles in Near-Earth Space

Quintin Schiller and Abhishek Mahendrakumar
Advisor: Prof. Xinlin Li
University of Colorado at Boulder
Department of Aerospace Engineering Sciences

August 11, 2010
The Radiation Belts

Dynamic system - potentially fatal to spacecraft and astronauts

April 5, 2010 - Intelsat Galaxy 15 “ZombieSat” fails due to unexpected particle flux increase ~$300M loss

Unanswered Questions: Source, Loss, Transport Mechanisms
Conjunctive Science

In-situ measurements: Radiation Belt Storm Probes (RBSP) via the Relativistic Electron and Proton Telescope (REPT)
Conjunctive Science

Colorado Student Space Weather Experiment (CSSWE)
Conjunctive Science

Concurrent particle measurements

INNER RADIATION BELT

OUTER RADIATION BELT

CSSWE

Electrons + Protons

RBSP
REPTile

Relativistic Electron and Proton Telescope integrated little experiment
REPTile

Relativistic Electron and Proton Telescope integrated little experiment
Connecting the Dots

1. Cost
2. Mass
3. Signal
4. Noise
5. Electrical Noise
6. Count Rate
7. Simulations
8. Results which satisfy mission requirements
Connecting the Dots

- Noise
- Signal
- Cost
- Mass
- Simulations
- Results which satisfy mission requirements
- Electrical Noise
- Count Rate

Note: The diagram illustrates a logical flow from noise and signal to cost and electrical noise, leading to simulations and results that meet mission requirements.
Simulating Science Environment

Electronics

To Storage
Simulating Science Environment

9 MeV electron beam
Simulating Science Environment

40MeV proton beam
Simulating Signal
Simulating Signal

Binning Efficiency of Electrons

- Detector 1%
- Detector 2%
- Detector 3%
- Detector 4%

Particle Energy (MeV)

Particles that Hit
Particles that Get Binned
Simulating Science Environment

9 MeV electron beam
Instrument Performance

CSSWE Science Objectives

<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>Electrons</td>
<td>0.5-1.5 MeV</td>
<td>1.5-2.2 MeV</td>
<td>2.2-2.9 MeV</td>
<td>&gt;2.9 MeV</td>
</tr>
</tbody>
</table>

Electron Bin Counts

Proton Bin Counts
Electronics Saturation

- $e^- \quad E < 0.3 \text{ MeV}$
- $H^+ \quad E < 7 \text{ MeV}$

Beryllium Window

Count Rate

Power Consumed

Electronics

Storage

8/11/2010
Effects of Noise

- False data
- Saturation of electronics

Electronics Noise

Detector Output Voltage

- 33mV
- 20mV

Electrical Noise

False Data
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

Electron
Proton

Signal Voltage

Ref. 1
Ref. 2
Ref. 3

3.25 - 4.3V
0.25 - 0.33V
20 - 33mV

130x
10x
1x

Noise
p^+
_e^-

0
0
1
1
1
1

0.25 - 0.33V
20 - 33mV
3.25 - 4.3V

20 - 33mV
0.25 - 0.33V
3.25 - 4.3V

1x
10x
130x

Signal Voltage Graph
## Conclusions

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass and Volume Constraints</td>
<td>Rigorous Design Analysis</td>
</tr>
<tr>
<td>Particle Behavior</td>
<td>Detailed Performance Simulations</td>
</tr>
<tr>
<td>Low Amplitude Signal</td>
<td>Novel Electronics Board Design</td>
</tr>
<tr>
<td>Operational Speed</td>
<td>Detailed Count Rate Analyses</td>
</tr>
</tbody>
</table>

### Acknowledgements

Past and present CSSWE team
LASP engineers
THANK YOU

QUESTIONS

quintin.schiller@colorado.edu
mahendra@colorado.edu

REPTile Engineering Model
Backups
Simulating Noise

Balance Shielding and Noise
Minimize Mass
Maximize Signal
Maintain Signal/Noise > 2

Light Outer Shielding
Aluminum

Heavy Inner Shielding
Tungsten
Balance b/w Mass and Signal

Light Shielding
- High Noise
- Low Mass
- Low Cost

REPTile
- Cubesat Mass ≤4.0 kg
- REPTile Mass ~1.2 kg
- CSSWE Cost <$1M

Heavy Shielding
- Low Noise
- High Mass
- High Cost

Signal to Noise Ratio

<table>
<thead>
<tr>
<th></th>
<th>Det. 1</th>
<th>Det. 2</th>
<th>Det. 3</th>
<th>Det. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻</td>
<td>87.9</td>
<td>42.2</td>
<td>28.9</td>
<td>23.8</td>
</tr>
<tr>
<td>H⁺</td>
<td>13.6</td>
<td>8.5</td>
<td>6.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>
## Binning Logic

<table>
<thead>
<tr>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>bin1:</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>bin2:</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>bin3:</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>bin4:</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Example: bin3 particle**

<table>
<thead>
<tr>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>bin3:</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Example: bin3 electron**

<table>
<thead>
<tr>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>bin3:</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

**Example: bin3 proton**

<table>
<thead>
<tr>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>bin3:</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
</tbody>
</table>
Simulating Science Environment

Electronics

SEP observations
(Mewaldt et al. 2005)

AE8 Max Model

Electron Incidence Flux

Proton Incidence Flux

8/11/2010
Saturation

Electronics

Electron Incidence Flux

Proton Incidence Flux
25 MeV Proton Beam

Energy vs. Position

% Particle Impacts vs. Particle Energy (MeV)


Position: D1, D2, D3, D4
25 MeV Proton Beam

Position vs. Energy

Energy:
- 25 MeV
- 21 MeV
- 11 MeV
- 1 MeV

% Particle Impacts

Particle Energy (MeV)

D1 D2 D3 D4
25 MeV Proton Beam

If ΔE > 4.5 MeV
Then proton

If ΔE > 4.5 MeV
Then proton

% Particle Impacts

Particle Energy (MeV)
25 MeV Proton Beam

If $\Delta E > 4.5$ MeV
Then no bin

% Particle Impacts

Particle Energy (MeV)
REPTile

8 cm

8 cm

8/11/10
REPTile Assembly
Electronics Top-level Requirements

**Science**
- Read detector outputs
- Classify the type of particle
- Estimate particle incident energy
- Bin Data
- Communicate with C&DH

**Housekeeping**
- Enable/disable detectors
- House REPTile sensors
Electronics

Challenges:
- Detector signal - Very low amplitude
- Sensitive to noise
- Difficult to distinguish signal from noise
Simulating Count Rates

GEANT4 – A Statistical Toolkit
Worldwide collaboration spearheaded by physicists at CERN

All aspects of particle simulation included

Applications include any field where particles interact with matter; high energy physics, space science, radiation physics, nuclear medicine\(^1\)

LHC experiments such as ATLAS

The Space Energetic Particle Transport and Interaction Modeling for ESA Science Studies (SEPTIMESS) project

\(^1\)geant4.web.cern.ch
Simulating Count Rates

C = Count Rate [#/s]
I = Environmental Particle Flux
γ = Geometric Factor
α = Detector Efficiency
E = Incident Particle Energy
i = Detector Index

Geant4
Simulating Count Rates

E = Incident Particle Energy
I = Environmental Particle Flux
γ = Geometric Factor
α = Detector Efficiency

Detector Efficiency

**Binning Efficiency of Protons**

- **Ch 1**
- **Ch 2**
- **Ch 3**
- **Ch 4**

**Binning Efficiency of Electrons**

- **Ch 1**
- **Ch 2**
- **Ch 3**
- **Ch 4**

Detector Efficiency vs. Particle Energy (MeV)
Signal vs. Noise

250 MeV protons

Deposited Energy:
- Det 1 ~ 2.1 MeV
- Det 2 ~ 1.9 MeV
- Det 3 ~ 2.4 MeV
- Det 4 ~ 2.3 MeV

Logic:
- P-type = proton
- Energy = bin4

Signal to noise ratio

<table>
<thead>
<tr>
<th>Det. 1</th>
<th>Det. 2</th>
<th>Det. 3</th>
<th>Det. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>87.9</td>
<td>42.2</td>
<td>28.9</td>
</tr>
<tr>
<td>Protons</td>
<td>13.6</td>
<td>8.5</td>
<td>6.4</td>
</tr>
</tbody>
</table>

b) Shield penetrating protons
Testing Plan:
Detectors
Testing Detectors

Detector tray needed for storage and testing
  Radioactive electron sources
  Radioactive alpha sources
  Cosmic rays
  Vacuum tests
  Thermal tests
REPTile Assembly
Simulating Count Rates

\[ E = \text{Incident Particle Energy} \]
\[ I = \text{Environmental Particle Flux} \]
\[ \gamma = \text{Geometric Factor} \]
\[ \alpha = \text{Detector Efficiency} \]

Environmental Flux

SEP observations (Mewaldt et al. 2005)
Simulating Count Rates

\[ E = \text{Incident Particle Energy} \]
\[ I = \text{Environmental Particle Flux} \]
\[ \gamma = \text{Geometric Factor} \]
\[ \alpha = \text{Detector Efficiency} \]

**Geometric Factor**
Derived from the Howell's Radiation Transfer Configuration Factors

www.me.utexas.edu/~howell/index.html
Signal vs. Noise

- **250 MeV protons (5)**
  - Deposited Energy:
    - Det1 ~ 2.1 MeV
    - Det2 ~ 1.9 MeV
    - Det3 ~ 2.4 MeV
    - Det4 ~ 2.3 MeV
  - Logic:
    - P-type = proton
    - Energy = bin4

- **40 MeV protons (4)**
  - Deposited Energy:
    - Det1 ~ 4.5 MeV
    - Det2 ~ 4.8 MeV
    - Det3 ~ 5.4 MeV
    - Det4 ~ 6.8 MeV
  - Logic:
    - P-type = proton
    - Energy = bin4

- **9 MeV electrons (5)**
  - Deposited Energy:
    - Det1 ~ 0.43-1.2 MeV
    - Det2 ~ 0.46-1.7 MeV
    - Det3 ~ 0.45-1.3 MeV
    - Det4 ~ 0.46-2.5 MeV
  - Logic:
    - P-type = electron
    - Energy = bin4

a) Signal protons
b) Shield penetrating protons
c) Signal electrons
d) Collimator demonstration
ACS Analysis

Electron Trajectories

- 100 keV

Proton Trajectories

- 10 MeV
Testing Electronics

Test electronics module by module
Test interface between modules
Progress from digital end towards analog end
Interface the electronics with the detector