On-orbit Calibration with Penetrating Proton and Helium

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Calibration on the ISS orbit

• For continuous high performance of the detector, on-orbit calibration considering detector condition is required.

• We use the measured response to MIP (Minimum Ionizing Particle) for the calibration. Applicability of the basic method has been confirmed in beam tests using muons.

• There are few muons in space, so we use protons and helium nuclei for on-orbit calibration.

We should confirm following points:

• number of penetrating events obtained during 1 orbit
• efficiency and accuracy of off-line event selection
• expected calibration error
1. Number of penetrating events obtained on orbit

1.1. Calculation of proton & Helium spectra on ISS orbit

- As interstellar spectra:
  use AMS-01 data (June 1998, altitude: 320-390 km)

- Solar modulation:
  calculate based on Force Field approximation
  assuming modulation factor $\Phi = 0.4$ GV

- Effect of geomagnetic field & interaction with atmosphere:
  calculate using ATMNC3
1. Number of penetrating events obtained on orbit

1.1. Rate of triggered events

- interaction in the detector:
calculate using EPICS (EPICS version: 9.161, detector config.: CAD rev.21)
- trigger mode: Single
- average trigger rate: 170 Hz
  proton: $7.8 \times 10^5$ events/orbit
  He nuclei: $1.3 \times 10^5$ events/orbit (when $\Phi = 0.4$ GV)

<table>
<thead>
<tr>
<th></th>
<th>High Energy Shower</th>
<th>Low Energy Shower</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHD each lay.</td>
<td>-</td>
<td>$&gt; 0.7$ MIP</td>
<td>$&gt; 0.7$ MIP</td>
</tr>
<tr>
<td>IMC 1-6th lay.</td>
<td>-</td>
<td>$&gt; 0.7$ MIP</td>
<td>$&gt; 0.7$ MIP</td>
</tr>
<tr>
<td>IMC 7-8th lay.</td>
<td>$&gt; 7.5$ MIP</td>
<td>$&gt; 2.5$ MIP</td>
<td>$&gt; 0.7$ MIP</td>
</tr>
<tr>
<td>TASC 1st lay.</td>
<td>$&gt; 55$ MIP</td>
<td>$&gt; 7$ MIP</td>
<td>$&gt; 0.7$ MIP</td>
</tr>
</tbody>
</table>
1. Number of penetrating events obtained on orbit

1.1. Rate of single penetrating events

According to EPICS calculation...

- 20\% of triggered events pass through the detector from the top to the bottom without escaping through the side ... (A)
- 96\% of (A) reach to the bottom without stopping inside the detector ... (B)
- \(19\% (p)\) of (B) penetrate the detector without creating shower particles ... (C)
- \(11\% (\text{He})\)

\[\Rightarrow (C) / \text{triggered events}\]
\[= 0.2 \times 0.96 \times \left\{ 0.19 (p) \right\} = 3.6\% (p)\]
\[\left\{ 0.11 (\text{He}) \right\} = 2.1\% (\text{He})\]

\(\ast\) exact rate depends on latitude

average penetrating event rate: 6.5 Hz
proton: 2000 events /orbit /log
He nuclei: 150 events /orbit /log
(when \(\Phi = 0.4 \text{ GV}\))
2. Off-line analysis for event selection

Without any event selection...

(when $S/N = 3$)

Basic idea of selection

1. reject events which escape through the side and identify the hit PWO by track reconstruction

2. reject events which create shower particles using total deposited energy in TASC

3. reject events which stop inside the detector using likelihood parameter
2. Off-line analysis for event selection

2.1 Track reconstruction

least-squares fit of the most luminous fiber in each IMC layer

hit PWO in the TASC bottom layer can be correctly identified for almost 77% of single penetrating protons -> Fig. A

The other events are affected by
- reconstruction errors (3%) -> Fig. B
- elastic scattering (20%) -> Fig. C

Signal distribution of 1 PWO log (bottom layer) after the selection
2. Off-line analysis for event selection

2.2 Selection using total deposited energy in TASC

Shower events which make a large energy deposition (Fig. A) can easily be cut by the distribution below. More than 70% of shower events can be rejected.

※ Shower events which fade out before reaching the bottom layer (Fig. B) are rejected in the next step.
2. Off-line analysis for event selection

2.3 Selection using likelihood parameter

Template signal distribution of penetrating particles: $F(s)$
Likelihood of penetrating a layer as a single particle: $p(s) = F(s)/ \int F(s) \, ds$
Likelihood of penetrating the TASC as a single particle: $P(s_1,s_2,\ldots,s_{12}) = \prod_{i=1}^{12} p(s_i)$

We can use $P$ as a selection parameter.

93% of shower events and 98% of stopping particles can be rejected.
2. Off-line analysis for event selection

2.4 Efficiency and purity in the final state

Efficiency \(\equiv \frac{N_{\text{select (single)}}}{N_{\text{trig (single)}}}\)

Purity \(\equiv \frac{N_{\text{select (single)}}}{N_{\text{select}}}\)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Efficiency [%]</th>
<th>Purity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77.3</td>
<td>87.9</td>
</tr>
<tr>
<td>2</td>
<td>76.2</td>
<td>86.4</td>
</tr>
<tr>
<td>3</td>
<td>75.7</td>
<td>85.8</td>
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<tr>
<td>4</td>
<td>75.5</td>
<td>85.4</td>
</tr>
<tr>
<td>5</td>
<td>74.8</td>
<td>84.6</td>
</tr>
<tr>
<td>6</td>
<td>74.3</td>
<td>84.0</td>
</tr>
<tr>
<td>7</td>
<td>73.3</td>
<td>82.9</td>
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<tr>
<td>8</td>
<td>72.6</td>
<td>82.0</td>
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<tr>
<td>9</td>
<td>71.4</td>
<td>80.6</td>
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<td>10</td>
<td>70.2</td>
<td>79.4</td>
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<tr>
<td>11</td>
<td>68.6</td>
<td>77.7</td>
</tr>
<tr>
<td>12</td>
<td>67.1</td>
<td>76.4</td>
</tr>
</tbody>
</table>

\(N_{\text{trig (single)}}\): all triggered single events
\(N_{\text{select (single)}}\): all selected single events
\(N_{\text{select}}\): all selected events
3. Expected calibration error

Fitting function: Landau Function convoluted with a Gaussian

Fitting error of the most probable value of the function:

- proton (1 orbit) : 2.0%
- Helium (1 orbit) : 2.1% (when $\Phi=0.4$ GV)

Error becomes smaller with higher statistics (1% in 4 orbital periods)
Conclusions

We carried out Monte Carlo simulations and confirmed that we can calibrate the CALET detector on the ISS orbit using cosmic ray protons and helium nuclei with high accuracy within a reasonable amount of time.

Expected trigger rate:

- 170 Hz on average (Φ=0.4 GV) ※ depending on solar modulation

Expected number of single penetrating events:

- proton: 2000 events/orbit/log
- He nuclei: 150 events/orbit/log (Φ=0.4 GV) ※ depending on solar modulation

Expected calibration error:

- 2-3% within one orbit (90 min)
- This can be reduced to below 1% within several orbital periods.

In this way, the energy resolution for high energy electrons is kept under a few %. Therefore, we can expect a precise measurement of GeV-TeV electrons with the CALET observation starting in 2015.
End
Correction of incident energy

Energy deposition vary with particle energy.

→ We can use the function (right figure) as a correction factor when we combine the data obtained at different geomagnetic latitudes.
**Expected Event Rate**

modulation factor: 0.6 GV

<table>
<thead>
<tr>
<th>Latitude [deg]</th>
<th>proton [/s]</th>
<th>proton [/s] &gt; 800MeV</th>
<th>He [/s]</th>
<th>He [/s] &gt; 800MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>per layer</td>
<td>per log (average)</td>
<td>per log (average)</td>
<td>per layer</td>
</tr>
<tr>
<td>0.00-5.16</td>
<td>1.17</td>
<td>0.073</td>
<td>1.13</td>
<td>0.071</td>
</tr>
<tr>
<td>5.16-10.32</td>
<td>1.21</td>
<td>0.076</td>
<td>1.18</td>
<td>0.084</td>
</tr>
<tr>
<td>10.32-15.48</td>
<td>1.28</td>
<td>0.080</td>
<td>1.25</td>
<td>0.078</td>
</tr>
<tr>
<td>15.48-20.64</td>
<td>1.44</td>
<td>0.090</td>
<td>1.42</td>
<td>0.089</td>
</tr>
<tr>
<td>20.64-25.80</td>
<td>1.82</td>
<td>0.11</td>
<td>1.80</td>
<td>0.11</td>
</tr>
<tr>
<td>25.80-30.96</td>
<td>2.51</td>
<td>0.16</td>
<td>2.50</td>
<td>0.16</td>
</tr>
<tr>
<td>30.96-36.12</td>
<td>3.69</td>
<td>0.23</td>
<td>3.68</td>
<td>0.23</td>
</tr>
<tr>
<td>36.12-41.28</td>
<td>5.36</td>
<td>0.34</td>
<td>5.35</td>
<td>0.33</td>
</tr>
<tr>
<td>41.28-46.44</td>
<td>7.67</td>
<td>0.48</td>
<td>7.56</td>
<td>0.47</td>
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<tr>
<td>46.44-51.60</td>
<td>10.1</td>
<td>0.63</td>
<td>0.67</td>
<td>0.60</td>
</tr>
<tr>
<td>Counts / period</td>
<td>2666</td>
<td>1667</td>
<td>25962</td>
<td>1623</td>
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</table>
## Expected Event Rate

modulation factor: 0.2 GV

<table>
<thead>
<tr>
<th>Latitude [deg]</th>
<th>proton [/s]</th>
<th>proton [/s] &gt; 800MeV</th>
<th>He [/s]</th>
<th>He [/s] &gt; 800MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>per layer</td>
<td>per log (average)</td>
<td>per layer</td>
<td>per log (average)</td>
</tr>
<tr>
<td>0.00-5.16</td>
<td>1.29</td>
<td>0.080</td>
<td>1.24</td>
<td>0.078</td>
</tr>
<tr>
<td>5.16-10.32</td>
<td>1.34</td>
<td>0.084</td>
<td>1.31</td>
<td>0.082</td>
</tr>
<tr>
<td>10.32-15.48</td>
<td>1.42</td>
<td>0.089</td>
<td>1.39</td>
<td>0.087</td>
</tr>
<tr>
<td>15.48-20.64</td>
<td>1.62</td>
<td>0.10</td>
<td>1.61</td>
<td>0.10</td>
</tr>
<tr>
<td>20.64-25.80</td>
<td>2.10</td>
<td>0.13</td>
<td>2.08</td>
<td>0.13</td>
</tr>
<tr>
<td>25.80-30.96</td>
<td>3.01</td>
<td>0.19</td>
<td>3.00</td>
<td>0.19</td>
</tr>
<tr>
<td>30.96-36.12</td>
<td>4.68</td>
<td>0.29</td>
<td>4.67</td>
<td>0.29</td>
</tr>
<tr>
<td>36.12-41.28</td>
<td>7.38</td>
<td>0.46</td>
<td>7.37</td>
<td>0.46</td>
</tr>
<tr>
<td>41.28-46.44</td>
<td>11.9</td>
<td>0.74</td>
<td>11.5</td>
<td>0.72</td>
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<tr>
<td>46.44-51.60</td>
<td>17.1</td>
<td>1.07</td>
<td>15.5</td>
<td>0.97</td>
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<tr>
<td>Counts / period</td>
<td>4071.6</td>
<td>2545</td>
<td>38326</td>
<td>2395</td>
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</table>
### Expected Event Rate

modulation factor: 1.2 GV

<table>
<thead>
<tr>
<th>Latitude [deg]</th>
<th>proton [s] per layer</th>
<th>proton [s] per log (average)</th>
<th>proton [s] &gt; 800MeV per layer</th>
<th>proton [s] &gt; 800MeV per log (average)</th>
<th>He [s] per layer</th>
<th>He [s] per log (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00-5.16</td>
<td>1.02</td>
<td>0.064</td>
<td>0.98</td>
<td>0.061</td>
<td>0.087</td>
<td>0.0054</td>
</tr>
<tr>
<td>5.16-10.32</td>
<td>1.05</td>
<td>0.066</td>
<td>1.03</td>
<td>0.064</td>
<td>0.095</td>
<td>0.0059</td>
</tr>
<tr>
<td>10.32-15.48</td>
<td>1.10</td>
<td>0.069</td>
<td>1.08</td>
<td>0.067</td>
<td>0.11</td>
<td>0.0067</td>
</tr>
<tr>
<td>15.48-20.64</td>
<td>1.22</td>
<td>0.076</td>
<td>1.20</td>
<td>0.075</td>
<td>0.12</td>
<td>0.0076</td>
</tr>
<tr>
<td>20.64-25.80</td>
<td>1.49</td>
<td>0.093</td>
<td>1.48</td>
<td>0.092</td>
<td>0.15</td>
<td>0.0094</td>
</tr>
<tr>
<td>25.80-30.96</td>
<td>1.97</td>
<td>0.12</td>
<td>1.96</td>
<td>0.12</td>
<td>0.21</td>
<td>0.013</td>
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<tr>
<td>30.96-36.12</td>
<td>2.71</td>
<td>0.17</td>
<td>2.70</td>
<td>0.17</td>
<td>0.30</td>
<td>0.019</td>
</tr>
<tr>
<td>36.12-41.28</td>
<td>3.65</td>
<td>0.23</td>
<td>3.64</td>
<td>0.23</td>
<td>0.44</td>
<td>0.027</td>
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<tr>
<td>41.28-46.44</td>
<td>4.77</td>
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<td>4.74</td>
<td>0.30</td>
<td>0.58</td>
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<td>46.44-51.60</td>
<td>5.84</td>
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<td>5.73</td>
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<td>Counts / period</td>
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<td>1073</td>
<td>16946</td>
<td>1059</td>
<td>1979</td>
<td>124</td>
</tr>
</tbody>
</table>
Required accuracy

Calibration error vs. energy resolution for 1 TeV electrons

Energy resolution can be kept under 3 % with calibration error less than 10 %
Efficiency and purity in each analysis step

0. before selection
1. after track reconstruction
2. after the cut by total deposited energy in TASC
3. after the cut by likelihood parameter
Comparison of distributions

- vertically incident 2 GeV muons (energy deposition)
- selected single protons on orbit (energy deposition)
- selected single protons on orbit (with electronic noise, S/N=3)
- selected protons on orbit (with electronic noise; S/N=3)
MPV and fitting range

Proton

He nuclei

 Counts

 Number of MIPs

 MPV

 Min. Threshold

 Counts

 Number of MIPs

 MPV

 Min. Threshold

 3% 2%
Event rate for each PWO

<table>
<thead>
<tr>
<th>Layer</th>
<th>PWO Log #</th>
<th>Event Rate</th>
<th>Normalized by Averaged Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-16</td>
<td>0.4-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>2</td>
<td>1-16</td>
<td>0.3-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>3</td>
<td>1-16</td>
<td>0.3-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>4</td>
<td>1-16</td>
<td>0.2-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>5</td>
<td>1-16</td>
<td>0.2-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>6</td>
<td>1-16</td>
<td>0.2-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>7</td>
<td>1-16</td>
<td>0.2-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>8</td>
<td>1-16</td>
<td>0.2-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>9</td>
<td>1-16</td>
<td>0.2-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>10</td>
<td>1-16</td>
<td>0.3-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>11</td>
<td>1-16</td>
<td>0.4-0.5</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>12</td>
<td>1-16</td>
<td>0.6-1.0</td>
<td>0.8-1.0</td>
</tr>
</tbody>
</table>

※ normalized by averaged number of events we can get for 1 PWO log in the bottom layer (i.e. proton 2,000 events, He 150 events)
Correction of incident angle

Path length in each log depends on geometrical condition.
→ 1. calculate path length and apply as a correction factor

2. select events which pass the log from the top side to the bottom side .. (a)

Calibration error can be reduced a little (2.0% -> 1.6%) by applying both 1 & 2, but required calibration time increase (1 orbit -> 1.2 orbit).