UV Laser Calibration of TASC PD/APD

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**Motivation (As a reminder)**

**CALET Observation Target**
- Electron: $1 \text{ GeV} - 20 \text{ TeV}$
- Gamma Ray: $4 \text{ GeV} - 10 \text{ TeV}$
- Nuclei: several $10 \text{ GeV} - 1000 \text{ TeV}$

**TASC Capability**
- Fine Energy Resolution
  - $2\% > 100\text{GeV}$ (electron)
- Powerful Particle ID
  - Proton rejection at $10^5$
- Broad Energy Range
  - 6 digit dynamic range

To confirm TASC function and end-to-end calibration, we performed UV pulse laser test to simulate the highest energy CR incidence.
Result of UV Laser Calibration (Example)

By scanning pulse laser intensity through 6 order of magnitude, Four APD/PD output responses are measured in detail for all of 176 PWO logs

Cross talk from APD to PD
• After APD-CSA saturates, crosstalk proportional to input charge becomes significant.
• The response looks complicated in the Log-Log plot, but it is just a simple connection of two linear relations.
What is needed for TASC Energy Calibration

From On-Orbit Data
1 MIP at APD High Gain
• APD_H [ADU/MIP]
Relation between PD_H vs APD_L
• PD_H/APD_L

Calibration method:
APD: uJ to MIP using 1MIP
PD: uJ to MIP using 1MIP and PD/APD coeff.
Calculate saturation point in MIP using APD-CSA saturation point and use coefficient with crosstalk after the saturation point.

From UV Laser Calibration Data
APD-CSA Saturation Point
• APD-L [ADU]
Coefficients
• APD_H [ADU/uJ]
• APD_L [ADU/uJ]
• PD_H [ADU/uJ]
• PD_H(S) [ADU/uJ]
• PD_L [ADU/uJ]
• PD_L(S) [ADU/uJ]

Estimated Error
• estimated error as a function of laser energy
What is needed for TASC Energy Calibration

From On-Orbit Data

\[
\begin{align*}
Q_{ah} &= k_{ah}E \\
Q_{al} &= k_{al}E \\
Q_{ph} &= \begin{cases} \frac{k_{ph}}{k_{al}}E & \text{if } E < E^{\prime\text{sat}} \\
\frac{k_{sat}}{k_{al}}(E - E^{\prime\text{sat}}) + Q_{sat}^{\prime} & \text{if } E \geq E^{\prime\text{sat}} \end{cases} \\
Q_{pl} &= \begin{cases} \frac{k_{pl}}{k_{al}}E & \text{if } E < E^{\prime\text{sat}} \\
\frac{k_{sat}}{k_{al}}(E - E^{\prime\text{sat}}) + Q_{sat}^{\prime} & \text{if } E \geq E^{\prime\text{sat}} \end{cases}
\end{align*}
\]

From UV Laser Calibration Data

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Q_{ah} &= k_{ah}E \\
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Q_{pl} &= \begin{cases} \frac{k_{pl}}{k_{al}}E & \text{if } E < E^{\text{sat}} \\
\frac{k_{sat}}{k_{al}}(E - E^{\text{sat}}) + Q_{sat}^{\prime} & \text{if } E \geq E^{\text{sat}} \end{cases}
\end{align*}
\]

PD: uJ to MIP using 1MIP and PD/APD coeff.

Estimated Error

- estimated error as a function of laser energy

REFERENCE: TASCCalibParams-rev141013.pdf
What is needed for TASC Energy Calibration

**From On-Orbit Data**

- $Q_{ah} = k_{ah}^L E$
- $Q_{al} = k_{al}^L E$
- $Q_{ph} = \begin{cases} k_{ph} E \\ k_{sat} (E - E_{sat}) + Q_{pl} & \text{if } E \geq E_{sat} \end{cases}$
- $Q_{pl} = \begin{cases} k_{pl} E \\ k_{sat} (E - E_{sat}) + Q_{pl} & \text{if } E \geq E_{sat} \end{cases}$

**From UV Laser Calibration Data**

- $Q_{ah} = k_{ah} E$
- $Q_{al} = k_{al} E$
- $Q_{ph} = \begin{cases} k_{ph} E \\ k_{sat} (E - E_{sat}) + Q_{ph}^s & \text{if } E < E_{sat} \\ k_{ph} (E - E_{sat}) + Q_{ph}^s & \text{if } E \geq E_{sat} \end{cases}$
- $Q_{pl} = \begin{cases} k_{pl} E \\ k_{sat} (E - E_{sat}) + Q_{pl}^s & \text{if } E < E_{sat} \\ k_{pl} (E - E_{sat}) + Q_{pl}^s & \text{if } E \geq E_{sat} \end{cases}$

Different coefficient is assumed between on-orbit and UV laser calibration ⇒ taking into account of the possible APD gain difference.

PD: [ADU/uJ] to MIP

PD/APD coeff.

Calculate saturation point in MIP using APD-CSA saturation point and use coefficient with crosstalk after the saturation point.

Energy scale is determined here. TASC light yield is also calibrated using flight data.

Estimated Error
- estimated error as a function of laser energy

REFERENCE: TASCCalibParams-rev141013.pdf
Parameters for TASC Energy Calibration

REFERENCE: TASCCalibParams-rev141013.pdf

\[ Q_{ah} = \alpha_{ah} N \]
\[ Q_{al} = \alpha_{al} N \]
\[ Q_{ph} = \begin{cases} \alpha_{ph} N & \text{if } Q_{ph} < Q_{ph}^{sat} \\ \alpha_{ph}^{sat} (N - N^{sat}) + Q_{ph}^{sat} & \text{if } Q_{ph} \geq Q_{ph}^{sat} \end{cases} \]
\[ Q_{pl} = \begin{cases} \alpha_{pl} N & \text{if } Q_{ph} < Q_{ph}^{sat} \\ \alpha_{pl}^{sat} (N - N^{sat}) + Q_{pl}^{sat} & \text{if } Q_{ph} \geq Q_{ph}^{sat} \end{cases} \]

**Coefficient Ratio**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R )</td>
<td>Coefficient Ratio</td>
</tr>
<tr>
<td>( Q_{mip, ah} )</td>
<td>1MIP Peak</td>
</tr>
<tr>
<td>( Q_{sat, al} )</td>
<td>APD-CSA saturation point</td>
</tr>
<tr>
<td>( k_{ah}, k_{al}, k_{ph}, k_{pl} )</td>
<td>Coefficients of four gains.</td>
</tr>
<tr>
<td>( k_{sat, ph}, k_{sat, pl} )</td>
<td>Coefficients with crosstalk</td>
</tr>
</tbody>
</table>

Laser Energy to MIP Conversion:

\[ E_{mip} = \frac{R \cdot k_{al}}{k_{ph} \cdot k_{ah}} Q_{mip}^{ah} \]

\[ \alpha_{ah} = Q_{mip}^{ah} \]
\[ \alpha_{al} = \frac{k_{al}}{k_{ah}} Q_{mip}^{ah} \]
\[ \alpha_{ph} = R \cdot \frac{k_{al}}{k_{ah}} Q_{mip}^{ah} \]
\[ \alpha_{pl} = R \cdot \frac{k_{pl}}{k_{ph}} \cdot \frac{k_{al}}{k_{ah}} Q_{mip}^{ah} \]
\[ Q_{ph}^{sat} = \frac{R \cdot k_{ph}^{sat}}{k_{ah}^{sat}} Q_{mip}^{ah} \]
\[ Q_{pl}^{sat} = \frac{R \cdot k_{pl}^{sat}}{k_{ph}^{sat}} Q_{mip}^{ah} \]
\[ N^{sat} = \frac{Q_{mip}^{sat}}{k_{ah}^{sat} \cdot k_{al}^{sat}} \]
Parameters for TASC Energy Calibration

**REFERENCE:** TASSCalibParams-rev141013.pdf

\[
Q_{ah} = \alpha_{ah} N \\
Q_{al} = \alpha_{al} N \\
Q_{ph} = \begin{cases} 
\alpha_{ph} N & \text{if } Q_{ph} < Q_{ph}^{sat} \\
\alpha_{ph}^{sat} (N - N_{sat}) + Q_{ph}^{sat} & \text{if } Q_{ph} \geq Q_{ph}^{sat}
\end{cases} \\
Q_{pl} = \begin{cases} 
\alpha_{pl} N & \text{if } Q_{ph} < Q_{ph}^{sat} \\
\alpha_{pl}^{sat} (N - N_{sat}) + Q_{pl}^{sat} & \text{if } Q_{ph} \geq Q_{ph}^{sat}
\end{cases}
\]

\[
\alpha_{ah} = \frac{Q_{ah}^{mip}}{k_{ah}} \\
\alpha_{al} = \frac{k_{al}}{k_{ah}} Q_{ah}^{mip} \\
\alpha_{ph} = \frac{k_{al}}{k_{ah}} Q_{ah}^{mip} \\
\alpha_{pl} = \frac{k_{pl}}{k_{ph}} \frac{k_{al}}{k_{ah}} Q_{ah}^{mip}
\]

\[
Q_{ph}^{sat} = R Q_{al}^{sat} \\
Q_{pl}^{sat} = R Q_{al}^{sat} \\
N_{sat} = \frac{Q_{al}^{sat}}{k_{ah}} \frac{k_{ah}}{k_{pl}}
\]

**Laser Energy to MIP Conversion:**

\[
E_{mip}^{mip} = R \frac{k_{al}}{k_{ph} k_{ah}} Q_{ah}^{mip}
\]

R: Coefficient of MIP to Laser Energy
Q_{mip}^{ah}: 1MIP PicoCoulomb
Q_{sat}^{al}: APD-CSA saturation point
k_{ah}, k_{al}, k_{ph}, k_{pl}: Coefficients of four gains.

k_{sat}^{ph}, k_{sat}^{pl}: Coefficients with crosstalk

Number of particles in each TASC log can be calculated with these equations using ADC data from 4 gain channels.
Calibration of TASC using UV Laser

- All PD/APDs in CALET-TASC are calibrated using UV laser
  - Calibration data were taken for all 176 PWOS from a few MIP to $10^6$ MIP
  ⇒ Calibration parameters were retrieved using parameters described before

Example of UV Laser calibration data

Input/output relation around APD-CSA saturation

Calibration Parameters

<table>
<thead>
<tr>
<th>$k_{ah}$ [ADU/uJ]</th>
<th>$k_{al}$ [ADU/uJ]</th>
<th>$k_{ph}$ [ADU/uJ]</th>
<th>$k_{ph}^{sat}$ [ADU/uJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.63 \times 10^7$</td>
<td>$8.85 \times 10^5$</td>
<td>$3.57 \times 10^4$</td>
<td>$6.29 \times 10^4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Q_{ph}^{sat}$ [ADU]</th>
<th>$k_{pl}^{sat}$ [ADU/uJ]</th>
<th>$Q_{pl}^{sat}$ [ADU]</th>
<th>$E^{sat}$ [uJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.96 \times 10^3$</td>
<td>$2.11 \times 10^3$</td>
<td>$9.43 \times 10^1$</td>
<td>$8.28 \times 10^{-2}$</td>
</tr>
</tbody>
</table>
TACS Dynamic Range Calibration using UV Laser

Calibration Curves

VERY PRELIMINARY

150703 rev.
using improved
MIP calib. params.
Effect of calibration error to energy resolution

◆ Assume calibration errors to all channels (1-20%)

• The influence of calibration error on TASC energy resolution is evaluated using simulation (electrons of 1TeV, 68% Containment)

Energy Resolution vs Calibration Error: electron 1TeV, 68%, simulation

⇒ Target resolution of TASC = 3%

⇒ Calibration error is acceptable up to 10%
The residuals from the fit using UV laser calibration functions

relative difference of data from calibration function

distributions of residuals for all PD/APDs are plotted in each gain range

RMS of the residual distribution in each gain range is below 5%
- Calibration error is less than 10%
⇒ It is possible to achieve 3% energy resolution
TACS Dynamic Range Calibration using UV Laser

Very Preliminary

Under Investigation

7 channels are not plotted because of analysis issue. We will review all the results including other channels.

150703 rev.
using improved MIP calib. params.
Distribution of Calibration Results

1. [Assign (%8.8X)] [list of fitted parameters %.3e)
   - Coefficients
     - k_aph [ADU/uJ]
     - k_apl [ADU/uJ]
     - k_pdh [ADU/uJ]
     - k_pdh^sat [ADU/uJ]
     - k_pdl [ADU/uJ]
     - k_pdl^sat [ADU/uJ]
   - APD-CSA Saturation Point
     - E_sat [uJ]
     - Q_ph^sat [ADU] = k_pdh*E_sat
     - Q_pl^sat [ADU] = k_pdl*E_sat
     - for all 16x11 = 176 channels

2. Estimated Errors (under investigation)
3. preliminary result will contain 1. only.
Distribution of Calibration Results

1. [Assign (%8.8X)] [list of fitted parameters %.3e)
   - Coefficients
     - $k_{aph}$ [ADU/μJ]
     - $k_{apl}$ [ADU/μJ]
     - $k_{pdh}$ [ADU/μJ]
     - $k_{pdl}$ [ADU/μJ]
     - $k_{pdh}^{sat}$ [ADU/μJ]
     - $k_{pdl}^{sat}$ [ADU/μJ]
   - APD - CSA Saturation Point
     - $E_{sat}$ [μJ]

   (Following parameters are removed because of redundancy)
   - $Q_{ph}^{sat}$ [ADU] = $k_{pdh} \times E_{sat}$
   - $Q_{pl}^{sat}$ [ADU] = $k_{pdl} \times E_{sat}$

   - for all 16x11 = 176 channels

2. Estimated Errors (under investigation)

3. Preliminary result will contain 1. only.

   • Although parameters themselves are ready to be distributed, we found that some of the fitting need to be revisited.
   • To avoid not necessary confusion, we would like to postpone the distribution of the TASC dynamic range calibration parameters.
   • The extended deadline for distribution would be end of July.