Full Dynamic Range Energy Calibration of CALET Onboard the International Space Station

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In August 2015, the CALET (CALorimetric Electron Telescope)instrument, designed for long exposure observations of high energy cosmic rays, docked with the ISS (International Space Station) and shortly thereafter began to collect data. CALET will measure the cosmic ray electron spectrum over the energy range of 1 GeV to 20 TeV with a very deep calorimeter with both total absorption and imaging (TASC and IMC) units. Each TASC readout channel must be carefully calibrated over the extremely wide dynamic range of CALET that spans six orders of magnitude to obtain a degree of precision necessary to achieve high energy resolution. The entire dynamic range is covered by four different gain ranges. The energy calibration process consists of three steps. First step is determination of conversion factor between ADC units and the energy deposit. Next step is linearity measurements over each gain range. Third step is correlation measurements between adjacent gain ranges. Then the conversion factor of all readout channels can be determined. Finally, using the estimated calibration errors and measured detector responses, such as the pedestal noise, the errors in the energy deposit sum were calculated for simulated electron events from 1 GeV to 20 TeV. As a result, 2% precision level energy calibration was achieved over the entire dynamic range above 10 GeV.

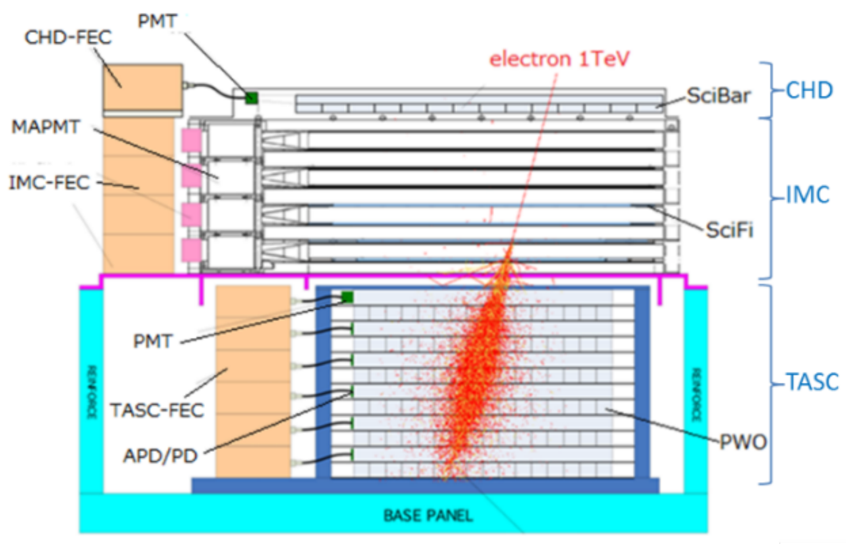
CALET: CALorimetric Electron Telescope

- **Primary purpose of CALET**

To make full use of a total-containment and well-segmented calorimeter with precision measurements of electron and gamma ray spectra over a wide energy range,
- discovering nearby cosmic-ray accelerators
- searching for dark matter

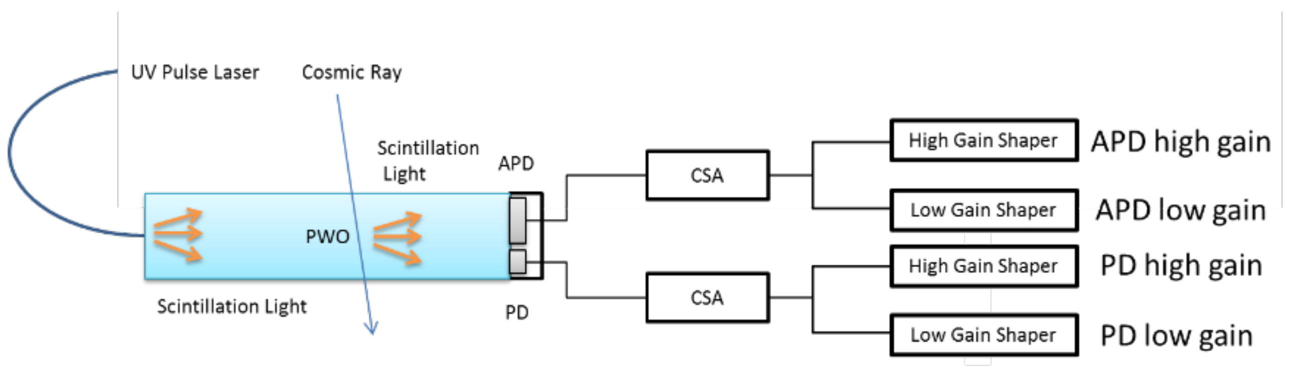
- **Characteristics of CALET**

Thick 30 radiation length calorimeter
- High energy resolution ~2%(>100GeV)
- High electron/positron separation ability proton rejection power ～10^5@TeV



Overview of the CALET

Readout system of TASC

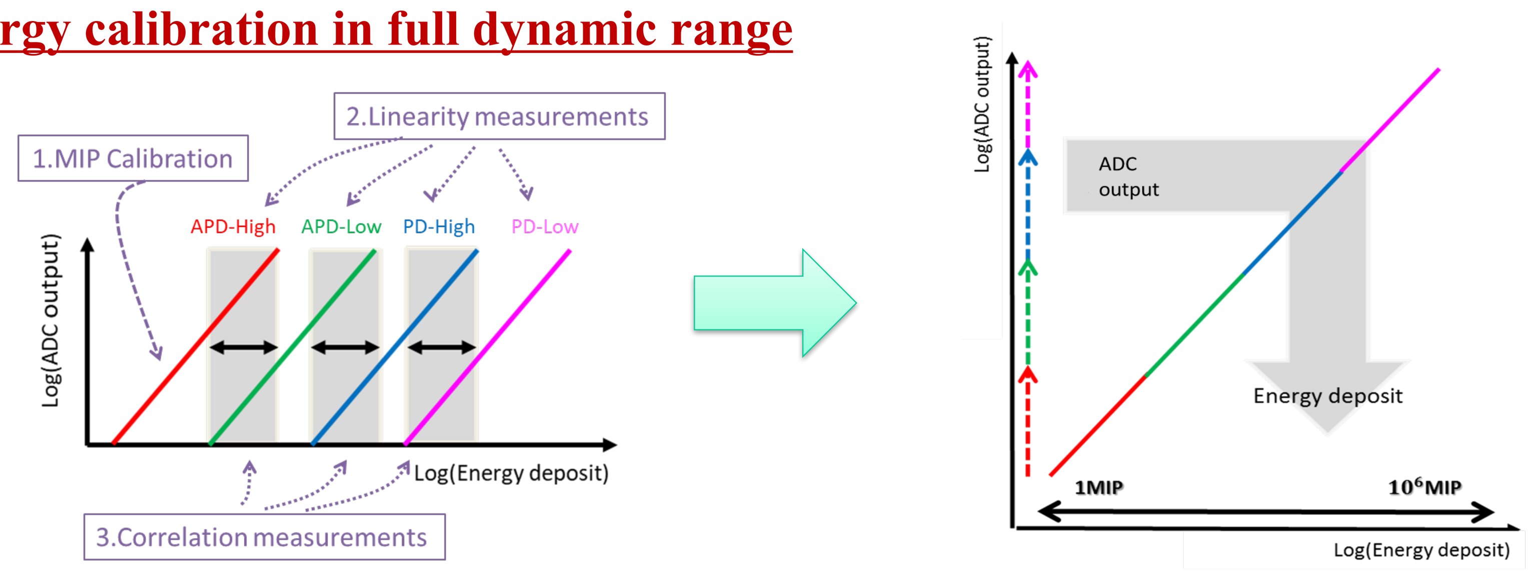


TASC readout system

Dual packaged APD/PD

- TASC has an overall depth of $27X_0$.
- 12 detection layers, each comprised of 16 lead tungstate crystal (PbWO4 or PWO) logs with dimensions of $2.0\times1.9\times32.6\mathrm{cm}^3$.
- A PD in conjunction with an APD reads the photons generated by each PWO, employing dual shaping amplifiers with 2 different gains. (the 1st layer use PMTs instead of APD)
- APDs have a 20 times larger area and a 50 times higher gain → **10^6dynamic range is accomplished.**

Energy calibration in full dynamic range



1.MIP Calibration *see PoS(ICRC2017)206 for details
The conversion factor between ADC and the energy of APD high gain is determined.

2.Linearity measurements
The linearity over each gain range was confirmed by on-ground calibration using a UV pulse laser.

3.Correlation measurements
The adjacent gain ranges were subsequently cross-calibrated based on their gain ratios.

→ *The energy over the full dynamic range can be calculated*!

Linearity measurements

UV pulse laser calibrations were performed on ground.
-Simulating scintillation photon by the laser through 6 orders.
-Performing detailed measurements for 176PWO logs × 4 readouts.
-Fitting acquired data by linear and broken linear functions.

The distributions of residuals from the fitting functions were assessed. From RMS of each distribution, the error were estimated in right table.

Linearity of each gain

APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

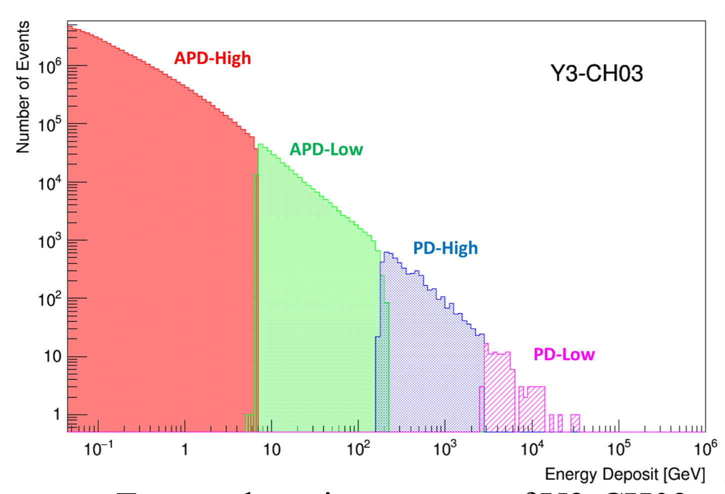
Correlation measurements

Measuring gain correlations between adjacent gain ranges to correct for gain changes between ground and onboard.

The errors on the gain ratios were determined from the parameter errors in the linear fittings, shown in right table.

Gain correlation errors

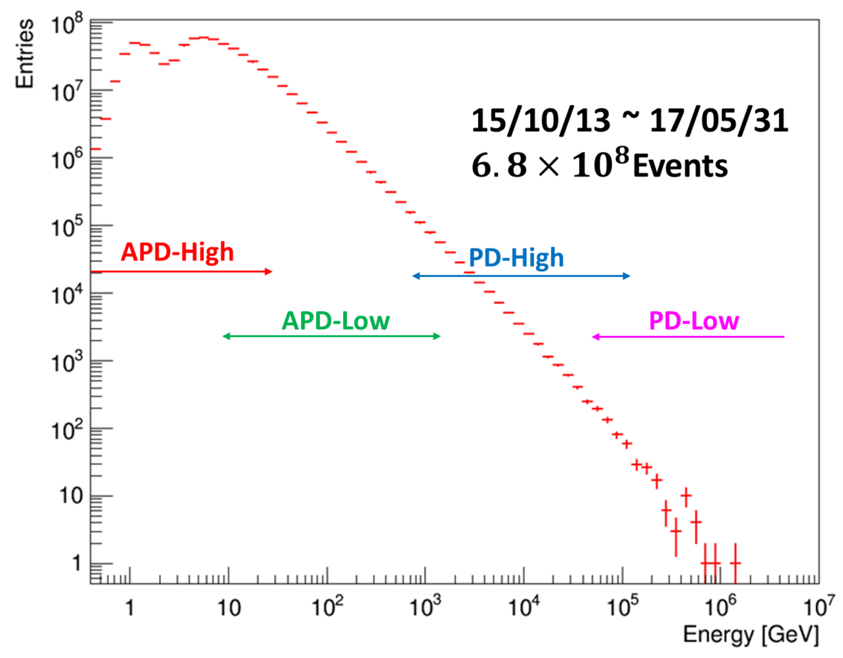
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%



Energy deposit spectrum of Y3-CH03

Since the UV laser tests confirmed the linearity of each gain range, calibration over the entire dynamic range is now possible by applying the conversion factor to the subsequent gain range using the gain ratios. Left figure shows a typical calibrated energy deposit spectrum for one TASC channel. A smooth transition between adjacent gain ranges is clearly observed.

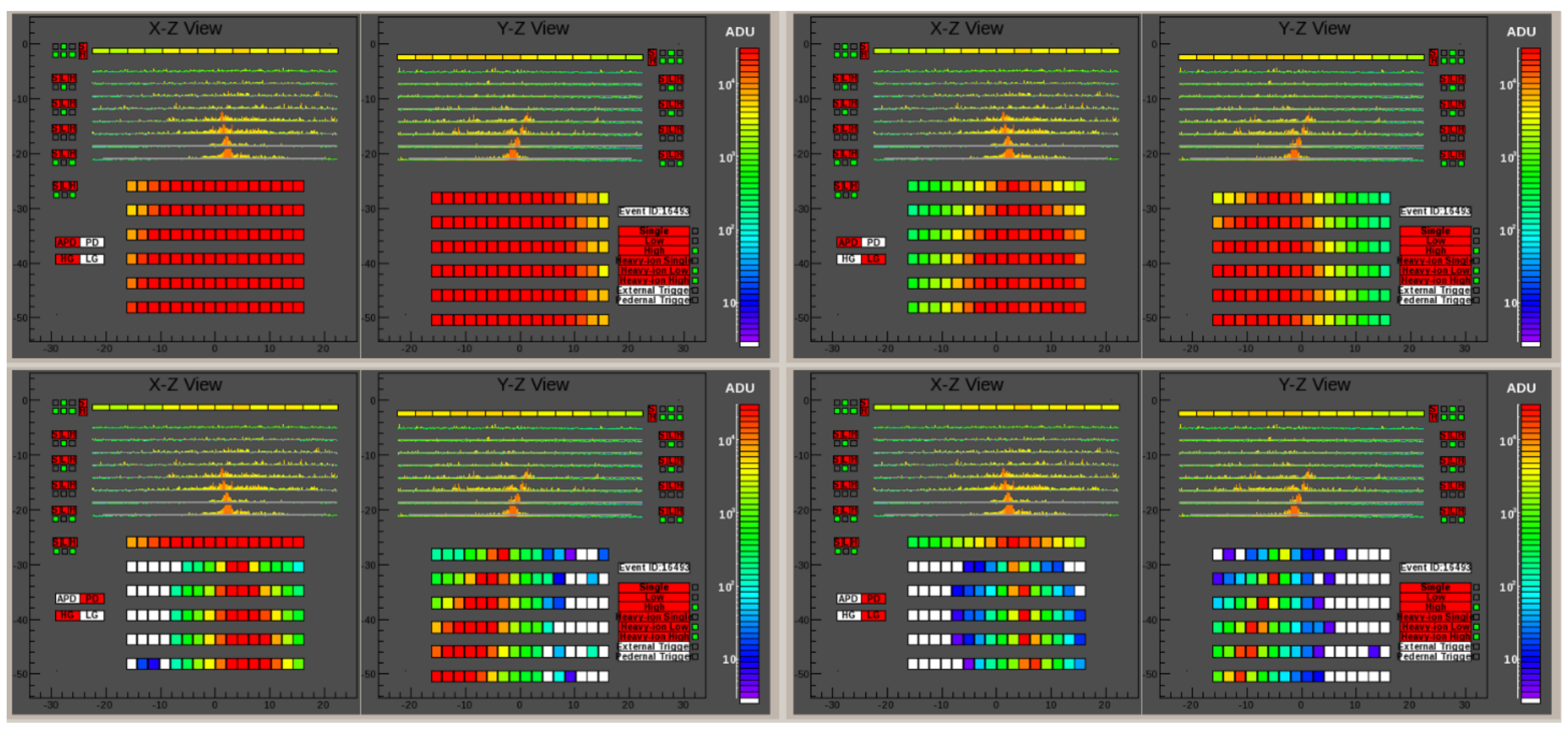
Calibrated energy deposit spectrum & Highest energy event



Energy deposit sum spectrum of TASC

Left figure shows the all particle energy deposit sum spectrum of TASC 192 channels during 151013 to 170531. It is shown that 10^6 range observation is accomplished. The figure also shows which gain contributes mainly.

Bellow figure represents the highest energy event penetrating whole detectors (1PeV). In this figure, top left shows APD high gain view, top right APD low gain, bottom left PD high gain and bottom right PD low gain respectively. It is clearly seen that the four gains cover a whole range of the energy measurements



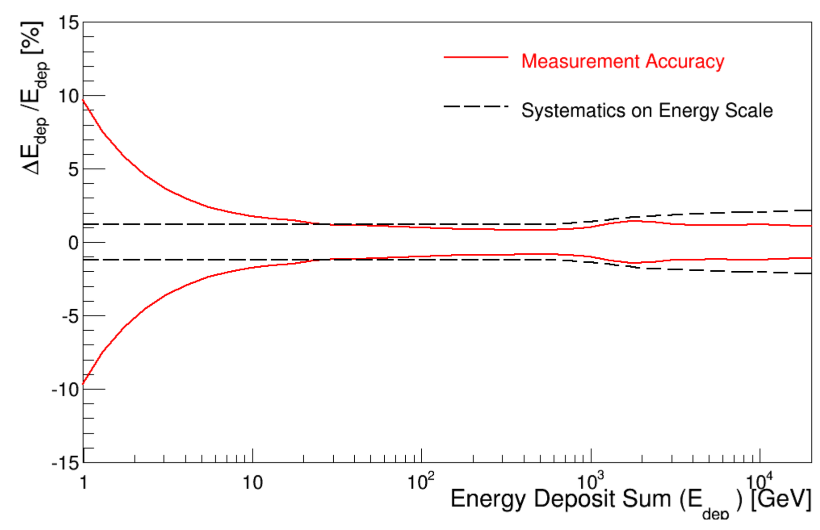
The view of highest energy event candidate during 151013 to 170531
APD-High(Top Left), APD-Low(Top Right), PD-High(Bottom Left), PD-Low(Bottom Right)

Energy measurement : Error and Resolution

Using the estimated calibration errors and measured detector responses, the errors in the energy deposit sum were calculated for simulated electron events from 1GeV to 20TeV.

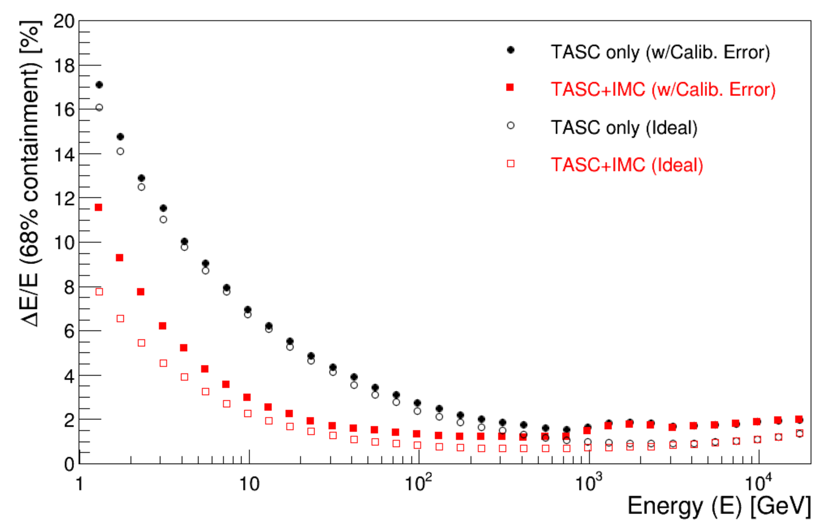
The sum of error of each channel is ~3%
(MIP~2%, Linearity~2%, Gain ratio~1%),
but in TeV region, dozen channels(N channels) are contributed to energy.
⇒ measurements accuracy ~1% ($1/\sqrt{N}$)

Measurement accuracy
- Pedestal noise affects mainly at low energy
- A 2% precision level energy calibration was achieved over the entire dynamic range above 10GeV.
- The systematic uncertainty in the energy scale was estimated to be less than ~2%
- PD range becomes important at ~ 1TeV
  →systematic uncertainties are larger but the accuracy is still satisfactory.



Energy dependence of measurement accuracy

Energy resolution
- Calculated for w/ & w/o calibration error.
- TASC w/ & w/o IMC for each case.
- Better resolution is given by using IMC
- 2% level energy resolution is accomplished > 1TeV



Energy dependence of energy resolution

Conclusion

Energy calibration of the CALET was performed using flight data and ground data before launch, and Successful calibration was achieved over full range of six orders of magnitude for each TASC channel.

- Linearity measurements over each gain were done on ground and linearities were estimated as follows;
  APD-H : 1.4%, APD-L : 1.5%, PD-H : 2.5%, PD-L : 2.2%
- Correlation measurements between adjacent gain ranges were done and its errors were;
  APD-H vs APD-L : 0.1%, APD-L vs PD-H : 0.7%, PD-H vs PD-L : 0.1%
- Long term stability of the MIP calibration(~0.97%) was confirmed.

By combining above calibrations,
- we got a fine resolution of 2% above 100GeV .
- The systematic error in the energy scale was found to be < 2%.