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Gamma-ray Large Area Space Telescope (GLAST)

Large Area Telescope (LAT)

Calorimeter Flight Model

Electronic and Muon Calibration Suite Definition

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01	30 Aug 2004	Initial Release

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1 INTRODUCTION

1.1 PURPOSE

This document details the sequence and methods to be followed in performing electronic and muon calibrations of the Flight GLAST Calorimeter (CAL) Modules.

1.2 SCOPE

The electronic and muon calibrations defined here shall be applied to all Flight CAL Modules during the Assembly and Test sequence at NRL. They shall also be executed during instrument Integration and Test at SLAC, as well as subsequent integration with the spacecraft, although they may be modified to better suite those environments.

1.3 APPLICABLE DOCUMENTS

The following documents are applicable to the extent specified within. Unless otherwise indicated, the latest issue in effect shall apply.

LAT-SS-00010	LAT Performance Specification – Level II (b) Specification
LAT-SS-00018	LAT CAL Subsystem Specification - Level III Specification
LAT-SS-00210	LAT CAL Subsystem Specification – Level IV Specification
LAT-TD-01502	LAT Calorimeter Subsystem Test Descriptions
LAT-MD-01370	Calorimeter Functional Test Definition

1.4 DEFINITIONS AND ACRONYMS

1.4.1 Acronyms

CAL	Calorimeter Subsystem of the LAT
CDE	Crystal Detector Element
GLAST	Gamma-Ray Large Area Space Telescope
LAT	Large Area Telescope
PDA	PhotoDiode Assembly
TBD	To Be Determined
TBR	To Be Resolved

1.4.2 Definitions

CAL Tower Module	The integrated Calorimeter Module, Tower Electronics Module, and Tower Power Supply
Analysis	A quantitative evaluation of a complete system and/or subsystems by review/analysis of collected data
Demonstrate	To prove or show, usually without measurements of instrumentation, that the project/product complies with requirements by observation of the results.
Test	A measurement to prove or show, usually with precision measurement or instrumentation, that the product complies with requirements.
Validate	To assure the requirement set is complete and consistent, and that each requirement is achievable.
Verify	To ensure that the selected solutions meet specified requirements and properly integrate with interfacing products

2 INTRODUCTION

2.1 TEST ENVIRONMENT

Electronic and muon calibration of the CAL shall be performed within the LATTE test environment using test scripts and suites maintained under a configuration management system.

Data products and test reports shall be logged to disk in real time and later archived to a long-term storage medium. A description of the CAL data products, test scripts, and test suites can be found in LAT-TD-01502.

The LATTE Environmental Monitoring and Housekeeping shall be enabled at all times during the CAL calibration. Environmental data products shall be logged to disk in real time and later archived to a long-term storage medium. The quantities thus monitored for each CAL Tower Module are the CAL analog and digital 3.3V voltage, the diode bias voltage and current, and one temperature on each of the four AFEE boards.

All calibration shall be executed under approved and released work orders by trained personnel.

2.2 TEST PERSONNEL

Test personnel are defined below.

2.2.1 Test Director

The Test Director will have primary responsibility for directing functional test activities. The Test Director will be responsible for coordinating the inputs from the Test Conductor and Quality Assurance representatives, modifying the text script as circumstances dictate, and executing the as-run test approval sheet.

2.2.2 Test Conductor

The Test Conductor will be responsible for monitoring the state of instrument electronics, executing specific functional test activities, and maintaining the test data logbook.

2.2.3 Analysis Support

The Analysis Support will be responsible for analyzing data collected during electrical functional testing and muon performance testing.

3 ELECTRONIC CALIBRATION

3.1 PURPOSE OF ELECTRONIC CALIBRATION

The goal of the electronic calibration suite is the establishment of calibration tables for the following features of each GCFE. These calibration tables give the correspondence between relevant DAC setting and output ADC bin or energy, as appropriate.

- Pedestal centroid and width for all energy ranges in all gain settings. An estimate of the electronic noise can be derived from the pedestal width.
- FE transfer function for all energy ranges, i.e. the integral non-linearity of the analog and digital chain for each energy range. The electronic gain of each energy range is given by the linear term of the correspondence between injected charge and output ADC bin.
- Calibration of the low-energy discriminator (FLE) DAC.
- Calibration of the high-energy discriminator (FHE) DAC.
- Calibration of the zero-suppression threshold (LAC) DAC.
- Calibration of the auto-ranging discriminator (ULD) DAC.

Units of the calibration tables can be converted to MeV in all gain settings through the *adc2nrgy* and *relgain* tables. Software tools shall be provided to make this conversion and to generate command tables to set these parameters in energy units.

3.2 ELECTRONIC CALIBRATION PROCEDURE

The electronic calibration suite (ECS) is comprised of a series test scripts that form a suite executed under LATTE. The suite is outlined below as an ordered list of scripts. The motivation for each script is given in Sections 3.2.1 and 3.2.2, along with a description of the script algorithms and configurations. A detailed definition of each script is given in LAT-TD-01502.

For each GCFE, the electronic calibration suite shall provide calibration of the electronic gain of all four energy ranges, the FLE and FHE discriminator settings, the LAC discriminator setting, and the range ULD settings. The calibration is performed in both the flight gain settings and the ground-level muon test gain settings.

The ECS shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the ECS, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALF_PEDESTALS_CI: Compute pedestals.
3. CALU_INIT: Redefine pedestal file.
4. CALU_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection.
5. CALF_TRG_P03: Calibrate FLE and FHE DAC settings with charge injection.
6. CALF_SUPP_P01: Calibrate LAC DAC settings with charge injection.
7. CALU_INIT: Redefine lac2dac.
8. CALF_RNG_P01: Calibrate ULD DAC settings with charge injection.

3.2.1 Calibration in Flight Gain

The ECS begins with a sequence of tests in nominal flight gain.

1. CALU_INIT: Initialize the Calorimeter

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the calibration suite in a defined configuration.

The default CAL test configuration is given in Table 1 below.

Parameter	**Configuration**
Diode bias	On, DAC set to 3072 (0xC00), equates to approx. 75 volts. 20 second wait is implemented to ensure bias has stabilized if setting change is needed
GCCC config	Configuration = 0x80090906 (per SLAC direction) Layer_mask_0/1 set based on schema FIFO_Status is cleared Latched Status is cleared Event Timeouts = 0 Trg_alignment = 0xa0f00 (per SLAC suggestion).
GCRC config	Delay_1 = nominal (30 clock tics with 20 MHz Clock) Delay_2 = nominal (60 clock tics with 20 MHz Clock) Delay_3 = nominal (144 clock tics with 20 MHz Clock)
GCFE config	FLE DAC = 127; FHE DAC = 127; LAC DAC = 127; ULD DAC = 127; REF_DAC = 127. Config_0 = 0 Config_1 = 0
PDU config	CAL Analog voltage DAC = 2048 (3.3V) nominal CAL Digital voltage DAC = 2048 (3.3V) nominal
Miscellaneous	Clock Frequency (saved for time calculations)

Table 1: Default CAL configuration

2. CALF_PEDESTALS_CI: Compute pedestals.

Pedestals for all energy ranges in all gain settings shall be computed by generating solicited triggers with zero charge injected. To avoid crosstalk or chatter, the FLE and FHE discriminators shall be set to their maximum values (i.e. 127). The pedestal is given by the centroid of a Gaussian fit to the observed ADC value from a large number (i.e. ~1000) of triggers at each gain setting. (Because the width of the pedestal distribution in the LEX1 and HEX1 ranges is ~1 bin, Gaussian fitting is ill-conditioned. Therefore, the pedestal centroid and width in these ranges shall be estimated by a simple mean and rms of the 5 ADC bins centered on the pedestal mode.)

Both the centroid and the width of the Gaussian shall be recorded for trending analysis. The pedestal value will be used in subsequent functional tests whenever conversion to energy units is required.

3. CALU_INIT: Redefine pedestal file.

The initialization script shall be executed again to load the new pedestal table generated in the previous step.

If so instructed by the controlling WOA, this redefinition and reinitialization step may be eliminated.

4. CALU_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection.

The electronic gain scale of each energy range shall be measured with charge-injection data. Charge shall be injected simultaneously into a limited number of GCFE chips to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13). A modest number of pulses (~100) shall be generated at amplitudes spanning the LEX8 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 512 in steps of 16, followed by 544 to 4095 in steps of

32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in auto-range order, and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

The data shall be analyzed to determine the maximum integral non-linearity and noise in each energy range. A linear least-squares fit shall be performed to the mean pedestal-subtracted ADC value at each pulse amplitude, and the maximum deviation from the linear model shall be determined and expressed as a fraction of the maximum unsaturated ADC value. The rms width of the ADC value at each pulse amplitude shall be calculated; this is a measure of the noise in each channel as a function of pulse amplitude (although it contains a contribution from the charge-injection system).

The slope of the linear fit, the maximum deviation from the linear fit, the mean noise in each range, and the maximum noise (i.e. maximum rms width) shall be recorded for trending analysis. Trending data from CALU_COLLECT_CI_SINGLEX16 shall be marked as having minimal crosstalk.

5. CALF_TRG_P03: Calibrate FLE and FHE DAC settings with charge injection.

The pulse amplitudes at which the FLE and FHE discriminators fire shall be calibrated with charge injection.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13). For each column of GCFEs sequentially, the FLE DAC shall be set to each of the 128 settings spanning fine and coarse ranges, and the charge-injection DAC shall be ramped upward one step at a time, with a small number of pulses (~20) generated at each amplitude. The trigger diagnostic data shall be inspected to determine if the FLE discriminators have fired. If the FLE fires for >90% of the pulses, the corresponding mean ADC value shall be recorded. This process shall then be repeated for the FHE DAC.

The output of this process is tables of correspondence between FLE/FHE DAC setting and ADC bin number in the nominal flight gain (“fle2adc” and “fhe2adc”).

Note that this calibration is not a precise calibration of the discriminator thresholds in energy units because the charge injection pulse shape is not identical to the scintillation pulse shape; the ratio of fast-shaped to slow-shaped signals is therefore different for charge injection pulses than for scintillation pulses. The correspondence into energy units is calibrated with CALF_TRG_MU.

6. CALF_SUPP_P01: Calibrate LAC DAC settings with charge injection.

The pulse amplitudes at which the Log-Accept discriminators fire shall be calibrated with charge injection.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13). Because the LAC functions as the logical OR of the discriminators at both end faces of a CDE, the faces must be tested separately. Thus, all Plus-face discriminators shall be tested together, then all Minus-face discriminators. All Plus-face discriminators shall be tested simultaneously. On the face not under test, all LAC DACs shall be set to the maximum value (i.e. 127). The LAC DAC shall be set one of its 128 levels (beginning at 0 and stepping upward to 127), and the charge-injection DAC shall be ramped upward one step at a time, with a small number of pulses (~20) generated at each amplitude, until all LACs have fired. The LEX8 event data for each CDE shall be inspected to determine if the LAC discriminator has fired. For each GCFE, the mean ADC value for the lowest charge-injection setting that causes that GCFE to be present in the event readouts for >90% of the samples shall be recorded.

This process shall then be repeated with the Plus and Minus LAC DACs incremented together to test the functionality of the OR of the CDE faces, i.e. the LAC threshold should be equal to the lesser of the Plus and Minus face thresholds.

The output of this process is a table of correspondence between the LAC DAC setting and LEX8 ADC bin number in the nominal flight gain (“lac2adc”).

All channels with a lowest-effective LAC DAC setting above 5 MeV shall be recorded as “noisy” in the Noisy Channel table. If this test finds no such channels in the Module under test, a null Noisy Channel table shall be created.

7. CALF_RNG_P01: Calibrate ULD DAC settings with charge injection.

The correspondence between the Upper Level Discriminator (ULD) DAC setting and the ADC value at which the range selection is made shall be calibrated with charge injection.

This test shall be performed in the nominal flight gain (LE = 5; HE = 13) with the data read out in one-range, auto-range order. The ULD DAC shall be set one of ten levels spanning the fine and coarse ranges (i.e. 0, 4, 21, 42, 63, 64, 68, 85, 106, and 127), and the charge-injection DAC shall be ramped upward one step at a time, with a small number of pulses (~20) generated at each amplitude. The ADC values at which LEX8 transitions to LEX1, LEX1 transitions to HEX8, and HEX8 transitions to HEX1 shall be recorded at each ULD DAC setting.

3.2.2 Calibration in Muon Gain

The ECS shall then proceed with calibrations in muon gain. These are necessary primarily to ensure that energy measurements made in the HE ranges during ground test are properly calibrated.

8. CALU_COLLECT_CI_SINGLEX16: Determine front-end integral non-linearity and noise with charge injection.

The electronic gain scale of each energy range shall be measured with charge-injection data. Charge shall be injected simultaneously into a single column of GCFE chips on each AFEE board to minimize the bias introduced into the gain and linearity measurement by cross talk between neighboring GCFEs.

This test shall be performed in muon test gain (LE = 5; HE = 0). A modest number of pulses (~100) shall be generated at amplitudes spanning the LEX8 range in a pattern chosen to map the known regions of non-linearity. The default pattern sets the charge injection DAC from 0 to 512 in steps of 16, followed by 544 to 4095 in steps of 32. To maximize the information gathered for subsequent analysis, all four energy ranges shall be read out in auto-range order, and zero-suppression shall be disabled. Charge is injected simultaneously into one column of four GCFEs on each AFEE board.

A Gaussian fit to the observed ADC value from each of the charge-injection amplitudes shall be performed, and a table of correspondence between charge-injection amplitude and output ADC bin generated. A linear least-squares fit shall be performed to the mean pedestal-subtracted ADC value at each pulse amplitude, and the maximum deviation from the linear model shall be determined and expressed as a fraction of the maximum unsaturated ADC value. The rms width of the ADC value at each pulse amplitude shall be calculated; this is a measure of the noise in each channel as a function of pulse amplitude (although it contains a contribution from the charge-injection system).

9. CALF_TRG_P03: Calibrate FLE and FHE DAC settings with charge injection.

The pulse amplitudes at which the FLE and FHE discriminators fire at muon gain shall be calibrated with charge injection.

This test shall be performed in muon gain (LE = 5; HE = 0). For each column of GCFEs sequentially, the FLE DAC shall be set to each of the 128 settings spanning fine and coarse ranges, and the charge-injection DAC shall be ramped upward one step at a time, with a small number of pulses (~20) generated at each amplitude. The trigger diagnostic data shall be inspected to determine if the FLE discriminators have fired. If the FLE fires for >90% of the pulses, the corresponding mean ADC value shall be recorded. This process shall then be repeated for the FHE DAC.

The output of this process is tables of correspondence between FLE/FHE DAC setting and ADC bin number in the muon gain (“fle2adc” and “fhe2adc”). These tables shall be identified as having been created in muon gain.

Note that this calibration is not a precise calibration of the discriminator thresholds in energy units because the charge injection pulse shape is not identical to the scintillation pulse shape; the ratio of fast-shaped to slow-shaped signals is therefore different for charge injection pulses than for scintillation pulses. The correspondence into energy units is calibrated with CALF_TRG_MU.

4 MUON CALIBRATION

4.1 PURPOSE OF MUON CALIBRATION

The goal of the muon calibration (MuC) suite is primarily the calibration of the "optical gain" of each photodiode, from which the correspondence between ADC bin and energy deposited is established. From this calibration, the following are achieved.

- Optimization of the time delay between trigger and peak hold to give maximal light yield for the ensemble of CDEs in a Module.
- Verification of the calibration in energy units of the FLE and FHE tables generated in the electronic calibration.
- Fitting of the muon peak in each LE and HE photodiode in muon test gain setting. From the muon peak, the *adc2nrgy* table is created.
- Mapping of the light taper and light asymmetry in each CDE as a function of position.

There are two forms of MuC, the first with CAL internally triggering ("self-triggering") on muons, and the second with an ancillary detector generating external triggers for the CAL Tower Module. The self-triggered MuC is simpler and requires no additional hardware, but it results in a modestly biased energy calibration. The externally triggered MuC does not create a biased calibration, and therefore is used to generate the final energy calibration of each channel.

4.2 MUON CALIBRATION PROCEDURE

The muon calibration suite is comprised of a series test scripts that form a suite executed under LATTE. The suite is outlined below as an ordered list of scripts. The motivation for each script is given in Sections 4.2.1 and 4.2.2, along with a description of the script algorithms and configurations. A detailed definition of each script is given in LAT-TD-01502.

The MuC shall be comprised of the following test procedures. As defined herein, they are executed sequentially on a single CAL Tower Module. At all times during the calibration, Environmental Monitoring and Housekeeping shall be enabled.

1. CALU_INIT: Initialize the Calorimeter.
2. CALF_SHP_MUONS: Find optimal time-to-peak for muons under CAL self-triggered readout.
3. CALF_TRG_MU: Calibrate FLE and FHE DAC settings with muons
4. CALU_COLLECT_MU: Collect muons under CAL self-triggered readout.
5. CALF_MAP_MU: Analyze muon data to map CAL CDE response.

The total run time for the muon calibration defined here is approximately 29 hours.

4.2.1 Muon calibration under CAL self-trigger

6. CALU_INIT: Initialize the Calorimeter

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration.

The default CAL test configuration is given in Table 1 above.

7. CALF_SHP_MUONS: Find optimal time-to-peak for CAL self-triggering with muons.

The LE and HE slow shaping amplifier outputs shall be mapped and the optimal Tack time delay for scintillation pulses under self-triggered readout shall be determined with muons.

If so directed by the authorizing Work Order – e.g., if the optimal time-to-peak is already defined for this instrument configuration – this test may be deleted.

This test shall be performed in muon test gain (LE = 5; HE = 0) with the data read out in commanded-range (LEX8 first), four-range mode. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled, with the FLE discriminators set to 8 MeV or below. The Tack delay shall be set to one of five values (i.e. 20, 60, 100, 150, and 200) in sequence. Muons shall be collected for 20 minutes (longer if authorized by the WOA) at each Tack delay setting.

The muon data shall then be analyzed at each Tack delay. "Penetrating" muons – viz. those that pass through the top and bottom layers of the CAL Module – shall be selected by requiring that both layer 0 and layer 7 LEX8 ADC values shall be at least 100 bins above pedestal. The CAL-wide total LEX8 and HEX8 pedestal-subtracted ADC values for penetrating muons shall be histogrammed and fit with a log-normal function to find the muon peak. The muon peak shall then be fit as a function of Tack delay – independently for LEX8 and HEX8 – with the following function that describes the output of the GCFE shaping amplifier.

$$y = A\left(1 + (t - t_{pk}) / \tau\right)\exp[-(t - t_{pk}) / \tau]$$

The optimal Tack Delay shall be defined to be average of the t_{pk} values for LEX8 and HEX8.

The optimal Tack Delay for muons under self-triggered readout shall be recorded for trending analysis.

8. CALF_TRG_MU: Calibrate FLE and FHE DAC settings with muons.

The energies at which the FLE and FHE discriminators fire shall be calibrated with muons. While only a limited number of DAC settings are examined here, in combination with the results of CALF_TRG_P03 performed during an Electronic Calibration suite, the complete energy calibration can be derived.

If so directed by the authorizing Work Order – e.g., if the correction factor is already defined for this instrument configuration – this test may be deleted.

This test shall be performed in muon gain (LE = 5; HE = 0). To calibrate the FLE discriminators, the data shall be read out in commanded-range (LEX8 first), 4-range mode to provide cross-calibration in LEX8 and LEX1 ranges. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

The FLE discriminators shall be set to 6 MeV. The trigger mask shall be set to enable FLE on the even-numbered columns (i.e. 0, 2, 4, 6, 8, and 10) of all X and Y layers. Muon data shall be collected for 30 minutes. A histogram of each log end that has FLE enabled shall be accumulated. At the same time, a histogram of each enabled log end shall be accumulated for the subset of events where Diagnostic data shows that its layer-end issued a trigger request. Because the overwhelming majority of muons pass through at most one and only one of the enabled CDEs in each layer, it is possible to know unambiguously which FLE caused the layer-end to request a trigger. The ratio of the histograms is then a measure of the FLE trigger efficiency for each enabled GCFE. The trigger threshold shall be defined to be the ADC bin with trigger efficiency > 70%.

The FLE discriminator shall be set to 12 MeV, and a second 30-minute run shall be accumulated and analyzed.

These two 30-minute runs shall be repeated with the FLE enabled on the odd columns of the X and Y layers. The complete FLE calibration for the X layers thus requires two hours of muon data.

This test shall be repeated to calibrate the FHE discriminators. The data shall be read out in commanded-range (HEX8 first), 4-range mode to provide cross-calibration in HEX8 and HEX1 ranges. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-HI enabled and CAL-LO disabled, with the FHE discriminators set to 12 MeV or below. The Tack delay shall be set to the optimal delay for CAL self-triggered readout. Readout of trigger Diagnostic data shall be enabled.

The process of sequentially enabling columns and swapping roles of X and Y layers shall be repeated with the FHE discriminators set to 12 MeV. Because of the large granularity of the FHE discriminator settings, only one FHE setting shall be tested. Thus the complete FHE calibration shall require one hour.

The total accumulation time for both FLE and FHE calibrations is therefore three hours.

The output of this process is a set of conversion factors between the FLE and FHE calibration tables derived in the electronic calibration (*fle2adc* and *fhe2adc*, in combination with the *adc2nrgy* and *relgain* tables). If the electronic calibrations are well understood, these correction factors should be close to unity. Recall that the electronic calibrations of FLE and FHE were not precise calibrations of the discriminator thresholds in energy units because the charge injection pulse shape is not identical to the scintillation pulse shape; the ratio of fast-shaped to slow-shaped signals is therefore different for charge injection pulses than for scintillation pulses.

9. CALU_COLLECT_MU: Collect muons under self-triggered readout.

Muon data shall be collected to calibrate the optical gain of each photodiode and create maps of light taper and light asymmetry.

This test shall be performed in muon test gain (LE = 5; HE = 0). At this gain setting, the muon peak appears at ~5% of full scale in LEX8 and ~3% of full scale in HEX8. The data shall be read out in commanded-range (LEX8 first), 4-range mode to allow simultaneous verification of the LE and HE photodiodes. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall self-trigger with CAL-LO enabled and CAL-HI disabled, with the FLE discriminators set to 8 MeV or below. The Tack delay shall be set to the optimal delay for CAL self-triggered readout.

The total muon run time shall be 24 hours, unless otherwise instructed by the authorizing Work Order. This run time is sufficient to create light taper and light asymmetry maps with a precision of ~1%.

10. CALF_MAP_MU: Analyze muon data to map CAL CDE response.

Muon data accumulated with CALU_COLLECT_MU shall be analyzed to estimate the light yield and map the light taper and light asymmetry in each CDE. The procedure described here is employed at the CDE assembly level, the PEM assembly level, and here at the CAL Module level.

Muon events shall be analyzed with the Module divided into pairs of X and Y layers, one pair of layers at a time. Events that hit one-and-only-one X CDE and one-and-only-one Y CDE shall be selected. The criteria for "one-and-only-one" hit in a layer shall be LEX8 pulse heights > 100 ADC bins in both ends of one CDE and LEX8 pulse heights < 5σ (σ = pedestal rms) above pedestal in all other CDEs of that layer. The X and Y coordinates of each muon trajectory in the selected layers is thereby pixelized. Histograms of the pedestal-subtracted LEX8, LEX1, HEX8, and HEX1 pulse heights, the LEX8 and HEX8 root-products, the LEX8 and HEX8 light asymmetry, and the LEX8 and HEX8 log-ratio shall be accumulated in each pixel.

The root-product is defined to be the square root of the product of the Plus and Minus face pedestal-subtracted pulse heights.

$$RP = \mathrm{sqrt}(\mathrm{Plus} \times \mathrm{Minus})$$

The light asymmetry is defined to be the ratio of the difference of Plus and Minus face pedestal-subtracted pulse heights to the sum of Plus and Minus face pedestal-subtracted pulse heights.

$$A = (\mathrm{Plus} - \mathrm{Minus}) / (\mathrm{Plus} + \mathrm{Minus})$$

The log-ratio is defined to be the natural logarithm of the ratio of pedestal-subtracted pulse heights from the Plus and Minus faces in the specified energy range.

$$LR = \log(\mathrm{Plus} / \mathrm{Minus})$$

In each pixel, the pulse-height histograms shall be fit with a log-normal function. The muon peak shall be defined to be the peak of the log-normal function, and it shall be assigned an energy deposition of 11.3 MeV, which is the GEANT4-calculated most-probable energy deposition for relativistic sea-level muons passing full through the 1.99 cm height of a CDE. The light taper map for each face of each CDE is therefore the muon peak as a function of pixel number along the length of the CDE.

In each pixel, the light asymmetry and log-ratio histograms shall be fit with a Gaussian. The maps of the light asymmetry and log-ratio are therefore the Gaussian centroids as a function of pixel number along the length of the CDE.

The light taper, light asymmetry, and log-ratio maps shall then be stored in a format compatible with the SAS environment.

4.2.2 Muon calibration with external trigger

Prior to shipment from NRL, each CAL Module shall be calibrated with muons with a pair of plastic scintillator paddles generating triggers. This externally triggered MuC does not create a biased calibration, and therefore is used to generate the final energy calibration of each channel.

1. CALU_INIT: Initialize the Calorimeter

The CAL initialization script shall be executed to ensure that the CAL is powered and begins the muon calibration in a defined configuration.

The default CAL test configuration is given in Table 1 above.

2. CALF_SHP_EXT: Find optimal time-to-peak for external trigger.

The LE and HE slow shaping amplifier outputs shall be mapped, and the optimal Tack time delay for scintillation pulses under external-trigger from the plastic paddles shall be determined.

If so directed by the authorizing Work Order – e.g., if the optimal time-to-peak is already defined for this instrument configuration – this test may be deleted.

This test shall be performed in muon test gain (LE = 5; HE = 0) with the data read out in commanded-range (LEX8 first), four-range mode. The CAL shall trigger externally, with the FLE and FHE discriminators set to maximum (i.e. 127) to eliminate any bias from dicriminator firing. The Tack delay shall be set to one of five values (i.e. 20, 60, 100, 150, and 200) in sequence. Muons shall be collected for 20 minutes (longer if authorized by the WOA) at each Tack delay setting.

The muon data shall then be analyzed at each Tack delay. “Penetrating” muons – viz. those that pass through the top and bottom layers of the CAL Module – shall be selected by requiring that both layer 0 and layer 7 LEX8 ADC values shall be at least 100 bins above pedestal. The CAL-wide total LEX8 and HEX8 pedestal-subtracted ADC values for penetrating muons shall be histogrammed and fit with a log-normal function to find the muon peak. The muon peak shall then be fit as a function of Tack delay – independently for LEX8 and HEX8 – with the following function that describes the output of the GCFE shaping amplifier.

$$y = A\left(1 + (t - t_{pk})/\tau\right)\exp[-(t - t_{pk})/\tau]$$

The optimal Tack Delay shall be defined to be average of the t_{pk} values for LEX8 and HEX8.

3. CALU_COLLECT_EXT: Collect muons under externally-triggered readout.

Muon data shall be collected to calibrate the optical gain of each photodiode without the energy bias introduced by FLE and FHE firing.

This test shall be performed in muon test gain (LE = 5; HE = 0). At this gain setting, the muon peak appears at ~5% of full scale in LEX8 and ~3% of full scale in HEX8. The data shall be read out in commanded-range (LEX8 first), 4-range mode to allow simultaneous verification of the LE and HE photodiodes. Zero-suppression shall be disabled to ensure that pedestals are registered in the dataset. The CAL shall trigger externally on the plastic paddles, and the Tack delay shall be set to the optimal value for the paddle trigger.

The total muon run time shall be 24 hours, unless otherwise instructed by the authorizing Work Order. This run time is sufficient to create light taper and light asymmetry maps with a precision of ~1%.

4. CALF_MAP_MU: Analyze muon data to map CAL CDE response.

Muon data accumulated with CALU_COLLECT_EXT shall be analyzed to estimate the light yield and map the light taper and light asymmetry in each CDE. The procedure described here is employed at the CDE assembly level, the PEM assembly level, and here at the CAL Module level.

Muon events shall be analyzed with the Module divided into pairs of X and Y layers, one pair of layers at a time. Events that hit one-and-only-one X CDE and one-and-only-one Y CDE shall be selected. The criteria for “one-and-only-one” hit in a layer shall be LEX8 pulse heights > 100 ADC bins in both ends of one CDE and LEX8 pulse heights < 5σ (σ = pedestal rms) above pedestal in all other CDEs of that layer. The X and Y coordinates of each muon trajectory in the selected layers is thereby pixelized. Histograms of the pedestal-subtracted LEX8, LEX1, HEX8, and HEX1 pulse heights, the LEX8 and HEX8 root-products, the LEX8 and HEX8 light asymmetry, and the LEX8 and HEX8 log-ratio shall be accumulated in each pixel.

The root-product is defined to be the square root of the product of the Plus and Minus face pedestal-subtracted pulse heights.

RP = sqrt(Plus * Minus)

The light asymmetry is defined to be the ratio of the difference of Plus and Minus face pedestal-subtracted pulse heights to the sum of Plus and Minus face pedestal-subtracted pulse heights.

A = (Plus – Minus) / (Plus + Minus)

The log-ratio is defined to be the natural logarithm of the ratio of pedestal-subtracted pulse heights from the Plus and Minus faces in the specified energy range.

LR = log(Plus / Minus)

In each pixel, the pulse-height histograms shall be fit with a log-normal function. The muon peak shall be defined to be the peak of the log-normal function, and it shall be assigned an energy deposition of 11.3 MeV, which is the GEANT4-calculated most-probable energy deposition for relativistic sea-level muons passing full through the 1.99 cm height of a CDE. The light taper map for each face of each CDE is therefore the muon peak as a function of pixel number along the length of the CDE.

In each pixel, the light asymmetry and log-ratio histograms shall be fit with a gaussian. The maps of the light asymmetry and log-ratio are therefore the gaussian centroids as a function of pixel number along the length of the CDE.

The light taper, light asymmetry, and log-ratio maps shall then be stored in a format compatible with the SAS environment.