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Calibration of the Surface Array of the Pierre Auger Observatory

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Abstract

The Pierre Auger Observatory is designed to study cosmic rays of the highest energies ($> 10^{19}$ eV). The ground array of the Observatory will consist of 1600 water Cherenkov detectors deployed over 3000 km². The remoteness and large number of detectors require a robust, automatic self-calibration procedure. It relies on the measurement of the average charge collected by a photomultiplier tube from the Cherenkov light produced by a vertical and central through-going muon, determined to 5 – 10% at the detector via a novel rate-based technique and to 3% precision through analysis of histograms of the charge distribution. The parameters needed for the calibration are measured every minute, allowing for an accurate determination of the signals recorded from extensive air showers produced by primary cosmic rays. The method also enables stable and uniform triggering conditions to be achieved.

1 Introduction

At energies above 10¹⁹ eV, the cosmic ray flux is very low ($\sim 1 \text{ km}^{-2} \text{ sr}^{-1} \text{ year}^{-1}$) requiring a very large area, sparse, simple, and reliable design, and the ability to identify rare shower candidates from a large background. The Pierre Auger Observatory is a hybrid device optimized for energies above 10¹⁹ eV consisting of an air fluorescence detector as well as a surface detector (SD) using water Cherenkov tanks. The water Cherenkov detector method has been used prominently in previous cosmic ray air shower experiments (*e.g.* [1]). The SD obtains a measurement of the Cherenkov light produced by shower particles passing through the detector at ground, and reconstructs the air shower by fitting the observed signal as a function of lateral distance from the shower core. The Cherenkov light is measured in units of the signal produced by a vertical and central through-going (VCT) muon, termed a vertical-equivalent muon (VEM).

The SD consists of 1600 water tanks, with 10 m² water surface area and 1.2 m water height and three 9" Photonis XP1805PA/1 photomultiplier tubes (PMTs) looking into a Tyvek[®] reflective liner through optical coupling material [2]. The signal from the 3 PMTs is digitized by local electronics, and the data are sent to a central data acquisition system (CDAS) when requested.

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20 The total bandwidth available from each surface detector to the CDAS is
21 approximately 1200 bits per second [3] which implies that the calibration must
22 be done by the local electronics. The local processor is an 80 MHz PowerPC
23 403GCX lacking floating-point hardware, which forces the calibration to be
24 as simple as possible. Finally, the remoteness of the detectors implies that the
25 calibration procedure must be robust, accepting the possibility of failures of
26 individual PMTs, to allow for recovery of these stations in data analysis.

27 The SD electronics uses six 40 MHz AD9203 10-bit flash analog-to-digital con-
28 verters (FADCs) to digitize the signals from the 3 PMTs. Two signals are taken
29 from each PMT - one directly from the anode, and the other from the last
30 dynode, amplified and inverted by the base electronics to a total of nominally
31 32 times the anode. The two signals are used to provide enough dynamic
32 range to cover with good precision both the particle flux near the shower core
33 (~ 1000 particles μs^{-1}) and far from the shower core (~ 1 particle μs^{-1}). The
34 two signals are called simply the anode and dynode, respectively. The signal
35 recorded by the FADC is referred to in units of channels (ch), with a range
36 of 0 – 1023, corresponding to an input range of 0 – 2 V. Each FADC bin
37 corresponds to 25 ns.

38 **2 The vertical-equivalent muon**

39 The primary signal calibration information required from the SD is the ave-
40 rage charge measured for a VCT muon, named the vertical-equivalent muon
41 (VEM, or Q_{VEM} when needed for clarity). During shower reconstruction, the
42 signal recorded by the tanks is converted into units of VEM, and the shower
43 characteristics, *i.e.* total energy and arrival direction, are fit using a lateral
44 distribution function and energy conversion based upon hybrid analysis using
45 the fluorescence detector. The conversion to units of VEM is done either to
46 provide a common reference level between tanks or to calibrate against the
47 detector simulations for other Monte Carlo based studies. Therefore, the goal
48 of the calibration is to obtain the value of 1 VEM in electronics units (*i.e.*
49 integrated channels).

50 In addition, to maintain a uniform trigger condition for the array, the station
51 must also be able to set a common trigger threshold in detector-independent
52 units. This will allow for a tank-independent analysis of the acceptance of the
53 array by modeling the trigger [4].

54 There are several quantities which are strongly related to a VEM, but are
55 determined with different methods. These quantities are listed in Table 1 for
56 easy reference.

Symbol	Definition	Section
VEM or Q_{VEM}	Charge deposited in PMT by light from VCT muon	2
Q_{VEM}^{peak}	Peak in a charge histogram	2.1
$Q_{VEM}^{est.}$	On-line estimated value of Q_{VEM}^{peak}	3.2
I_{VEM}	Pulse height of light from VCT muon	2.2
I_{VEM}^{peak}	Peak in a pulse height histogram	2.2
$I_{VEM}^{est.}$	On-line estimated value of I_{VEM}^{peak}	3.2

Table 1

Reference for calibration terms.

57 *2.1 Charge histograms and their relation to a VEM*

58 Atmospheric muons passing through the detector at a rate of approximately
59 2500 Hz give an excellent method for measuring 1 VEM precisely, but the
60 surface detector in its normal configuration has no way to select only VCT
61 muons. However, the distribution of the light from atmospheric muons also
62 produces a peak in a charge distribution [5]. This peak (Q_{VEM}^{peak}) is at approxi-
63 mately 1.09 VEM for the sum of the 3 PMTs and (1.03 ± 0.02) VEM for each
64 PMT, both measured with a muon telescope providing the trigger in a ref-
65 erence tank [6]². The difference between these two cases is due to the fact
66 that the sum of the PMTs measures the total signal, whereas the individual
67 PMTs primarily measure the portion of the signal deposited closest to them.
68 Example charge and pulse height histograms produced by a surface detector
69 are shown in Fig. 1. The peak produced by the response of atmospheric muons
70 in the tank is clearly visible. The relation of Q_{VEM}^{peak} to Q_{VEM} can be under-
71 stood using a simple geometrical model [7]. The shift observed is caused by
72 the convolution of photoelectron statistics on an asymmetric peak in the track
73 length distribution and local light collection effects.

74 *2.2 Pulse height histograms and their relation to the trigger*

75 The SD uses two triggers to identify shower candidates [8]. The first is a simple
76 threshold trigger, which is satisfied when the signal from all 3 PMTs exceeds a
77 set threshold, and is designed for signals close to the shower core. The second
78 is a time-over-threshold trigger, which requires that the signal from 2 of the
79 3 PMTs exceed a much lower threshold than the first trigger for a number of
80 time bins within a given time window, and is designed for signals far from the
81 shower core. These triggers are set in electronics units (channels) – a measure

² Based on more recent data from [6] and a similar setup with a different tank.

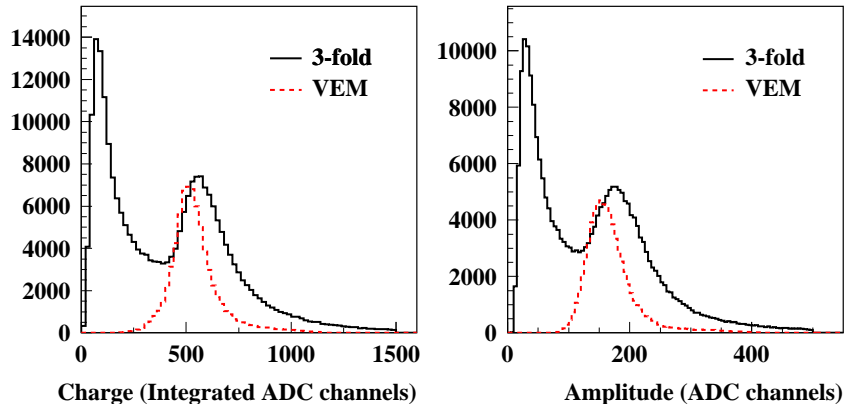


Figure 1. Charge and pulse height histograms from an SD station, triggered by a 3-fold coincidence between all 3 PMTs at a trigger level of 5 channels above baseline, with the signal from all 3 PMTs summed. The dashed histogram is produced by an external muon telescope providing the trigger to select only vertical and central muons. The first peak in the black histogram is caused by the convolution of the trigger on a steeply falling distribution from low-energy particles. The second peak is due to vertical through-going atmospheric muons [6].

82 of the current from the PMT – so the station must have a reference unit
 83 for current as well. Atmospheric muons again provide this reference, as the
 84 same mechanism (see Sec. 2.1) that produces a peak in the charge histogram
 85 also produces a peak in a pulse height histogram (I_{VEM}^{peak}), which is then used
 86 as the common reference unit for threshold levels. This peak, like the charge
 87 histogram peak, is related to the peak current produced by a vertical through-
 88 going muon (I_{VEM}).

89 The target trigger threshold is $3.2 I_{VEM}^{peak}$ for the simple threshold trigger, and
 90 $0.2 I_{VEM}^{peak}$ for the time-over-threshold trigger.

91 The conversion from electronics units to I_{VEM}^{peak} must be continually updated in
 92 order to maintain the proper trigger level. The accuracy of this determination
 93 does not have to be high – the trigger units are quantized in channels – and
 94 the target trigger level of $0.2 I_{VEM}^{peak}$ ($\simeq 10$ ch - see Sec. 3) for the lower of the
 95 two triggers implies that the precision of the on-line calibration does not need
 96 to be much better than 10% (1 part in 10 channels) before the quantization
 97 of the trigger dominates.

98 In addition, the initial end-to-end gains of the 3 PMTs - that is, I_{VEM}^{peak} - must
 99 be roughly equivalent. This ensures that the signals recorded from the PMTs
 100 are similar in amplitude, and sets the proper dynamic range and signal size
 101 for the electronics.

103 There are three main steps to the calibration to VEM units.

- 104 (1) Set up the end-to-end gains of each of the 3 PMTs to have I_{VEM}^{peak} at 50 ch.
- 105 (2) Continually perform a local calibration to determine I_{VEM}^{peak} in channels
- 106 to adjust the electronics-level trigger. This compensates for drifts which
- 107 occur after step #1.
- 108 (3) Determine the value of Q_{VEM}^{peak} to high accuracy using charge histograms,
- 109 and use the known conversion from Q_{VEM}^{peak} to 1 VEM to obtain a conver-
- 110 sion from the integrated signal of the PMT to VEM units.

111 3.1 End-to-end gain setup

112 The end-to-end gains (*i.e.* I_{VEM}^{peak} in electronics units) of each of the 3 PMTs
 113 are set up by matching a point in the spectrum to a measured rate from a
 114 reference tank (see [6]). The reference tank is calibrated by obtaining a charge
 115 histogram and adjusting the PMT high voltage until the peak (Q_{VEM}^{peak}) of the
 116 three histograms agree. The singles rate spectrum of each of the PMT (*i.e.*
 117 no coincidence between the PMTs required) is then obtained as a reference.
 118 A point on the spectrum convenient as a trigger threshold was chosen as a
 119 target calibration point for all tanks - that is, the singles rate of a PMT
 120 at 150 ch above baseline was required to be 100 Hz, which corresponds to a
 121 trigger point of roughly $3 I_{VEM}^{peak}$. This choice sets up each of the PMTs to have
 122 approximately 50 ch/ I_{VEM}^{peak} .

123 When the local station electronics is first turned on, each of the 3 PMTs is
 124 forced to satisfy this condition by adjusting the high voltage until the rate
 125 is 100 Hz at a point 150 ch above baseline. This balances the PMTs to ap-
 126 proximately 5%. The PMTs have a range of temperature coefficients so that
 127 subsequent drifts from the initial settings are inevitable. Thus, high precision
 128 is not required. For a sample of 661 tanks, the mean RMS spread in I_{VEM}^{peak}
 129 between the 3 PMTs was 4.4%.

130 The end-to-end gain measurement implies that the PMTs in the surface de-
 131 tectors will *not* have equivalent gains - indeed, even PMTs within the same
 132 tank may not have equivalent gains. If a water tank produces more photons
 133 per vertical muon than an average tank, then the PMTs in the tank will be
 134 at a lower gain than an average tank to compensate. Likewise, if a PMT has
 135 a worse optical coupling than the others in the same tank, resulting in fewer
 136 photons seen per vertical muon, the PMT will be run at a higher gain. Thus,
 137 we would expect to see an inverse relationship between the gain of each PMT
 138 and the number of photoelectrons (n_{pe}) per VEM for all the PMTs in the

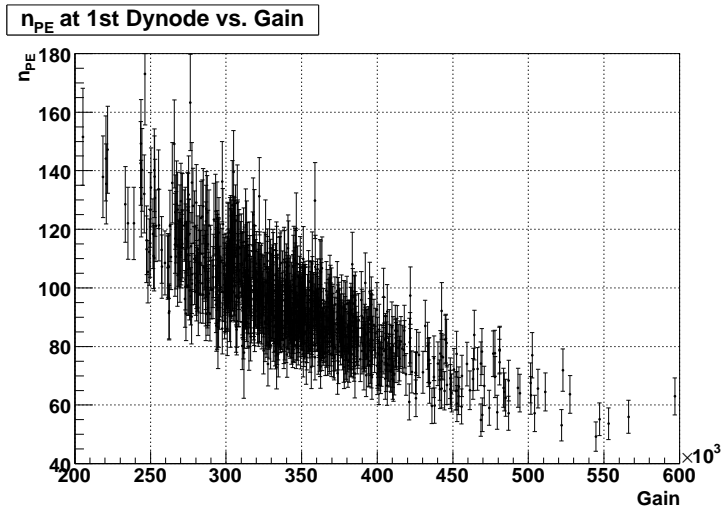


Figure 2. Number of photoelectrons (n_{pe}) at the first dynode versus PMT gain. As the end-to-end gain setup is designed to produce equivalent FADC channels for a charge deposition of 1 VEM, an inverse relationship is expected between gain and n_{pe} . n_{pe} at the first dynode is calculated as described in Sec. 3.2. The mean gain for the PMTs in the SD is 3.4×10^5 , and the mean n_{pe}/VEM is 94 pe.

139 surface detector. This is shown in Fig. 2. The inverse relationship is quite
 140 clear, showing that the initial end-to-end gain setup is operating correctly.
 141 The choice of $50 \text{ ch}/I_{VEM}^{peak}$ results in a mean gain of approximately 3.4×10^5
 142 for a mean $n_{pe}/\text{VEM} \sim 94$ pe.

143 3.2 Continual on-line calibration

144 Once the gains of the 3 PMTs are set up, the drifts of the value of I_{VEM}^{peak}
 145 in electronics units for each detector must be compensated to ensure that the
 146 surface array triggers uniformly. This compensation is done via adjusting the
 147 trigger levels based on a continual on-line calibration. The PMT high voltage is
 148 not changed during normal operation, which implies that the dynamic range of
 149 the SD will be slightly non-uniform. For normal operation, this non-uniformity
 150 is minimal ($\sim 10\%$). Detectors which have drifted significantly (> 20 ch) from
 151 the nominal I_{VEM}^{peak} of 50 ch are re-initialized following the procedure in Sec. 3.1.
 152 The average value of I_{VEM}^{peak} for the PMTs of the SD is currently (46 ± 4) ch.

153 The value of I_{VEM}^{peak} as defined in section 2.2 is not obtained on-line since this
 154 would increase the dead time of the detector to unacceptable levels. Instead,
 155 the trigger levels are set with respect to an estimate of I_{VEM}^{peak} . This estimate
 156 (I_{VEM}^{est}) is defined implicitly for a given PMT by requiring that the rate of
 157 events satisfying a “calibration trigger” be 70 Hz. An event satisfies the cali-
 158 bration trigger if the signal is above $2.5 I_{VEM}^{est}$ for the given PMT *and* above
 159 $1.75 I_{VEM}^{est}$ for all three PMTs. The value of the rate (70 Hz) was obtained from

160 the reference tank.

161 To obtain the value of I_{VEM}^{est} , a $\sigma - \delta$ convergence algorithm is used, where a
162 test value (I_{VEM}^{est}) is altered by an adjustment δ if a measured value (the rate)
163 is outside of a bound σ . This algorithm is implemented as follows:

- 164 (1) Start with a value of $I_{VEM}^{est} = 50$ ch.
- 165 (2) Measure, for each PMT, the rate of events satisfying the calibration trig-
166 ger by counting these events for a time t_{cal} , initially set to 5 s.
- 167 (3) If, for a given PMT, the rate is above $70 + \sigma$ Hz, increase I_{VEM}^{est} by δ .
168 Likewise, if the rate is below $70 - \sigma$ Hz, decrease I_{VEM}^{est} by δ , with $\sigma = 2$ Hz
169 and $\delta = 1$ ch initially.
- 170 (4) If the rate of any single PMT is more than 10σ away from 70 Hz, adjust
171 I_{VEM}^{est} by 5 ch in the appropriate direction, set t_{cal} to 10 s, $\delta = 1$ ch, and
172 repeat from step 2.
- 173 (5) Otherwise, if $t_{cal} < 60$ s, increase t_{cal} by 5 s. If $\delta > 0.1$ ch, decrease δ by
174 0.1 ch, and repeat from step 2.

175 As the calibration trigger is a single PMT trigger within a 3-fold coincidence, a
176 small drift in the calibration trigger rate of one PMT should not affect the rate
177 of another. Step 4 allows the algorithm to switch back to a coarser tracking
178 mode to minimize the effect that one PMT can have on the other two. In
179 practice, changes of less than 10% in a period of t_{cal} do not affect the other
180 PMTs significantly.

181 A minimum value of $\delta = 0.1$ ch was chosen to allow I_{VEM}^{est} to compensate for
182 drifts in the baseline of each channel as small as 0.1 ch without significantly
183 affecting the error in the estimate. The value of $\sigma = 2$ Hz is equal to $\sim 2\times$
184 the Poisson fluctuation over that time period, and is reasonable given the
185 requirement of $< 10\%$ accuracy.

186 A simple test of the success of the convergence algorithm is to look at the
187 trigger rates for the simple threshold trigger, which is just a 3-fold coincidence
188 trigger at $3.2 I_{VEM}^{peak}$. On a reference tank, with 3 PMTs tuned to equal I_{VEM}^{peak}
189 values, this gives a rate of ~ 20 Hz. The 3-fold coincidence rates for 21 tanks
190 before and after the convergence algorithm is applied is shown in Fig. 3. The
191 rapid convergence to ~ 20 Hz shows that the method described enables the
192 uniform trigger levels to be established rapidly.

193 A comparison of the converged I_{VEM}^{est} value with values obtained from a pulse
194 height histogram gives $I_{VEM}^{est} = (0.94 \pm 0.06) I_{VEM}^{peak}$. The systematic offset is
195 due to a slight inaccuracy in the required calibration trigger rate (*i.e.* $2.5 I_{VEM}^{peak}$
196 results in 70 Hz) and is unimportant.

197 The on-line calibration also estimates Q_{VEM}^{peak} as well (Q_{VEM}^{est}), by computing
198 the charge of pulses with a peak of exactly I_{VEM}^{est} , and using a $\sigma - \delta$ convergence

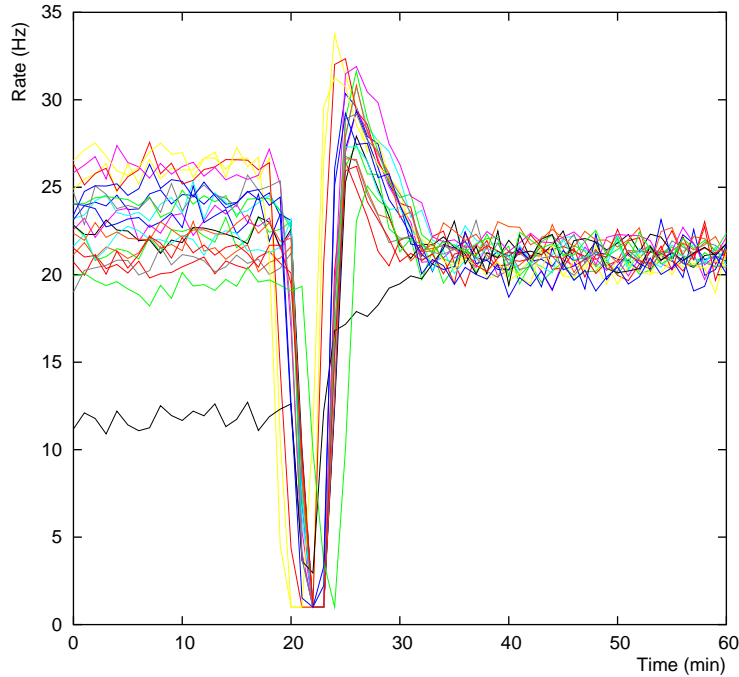


Figure 3. Convergence of the 3-fold coincidence trigger at $3.2 I_{VEM}^{est}$ to ~ 20 Hz after the convergence algorithm based on the $2.5 I_{VEM}^{est}$ singles rate for 21 SD stations (station ID is on the right). The convergence algorithm was turned on at $t \approx 20$ min. The drop to 0 Hz was caused by the re-boot of the SD stations to enable the convergence algorithm.

199 algorithm on Q_{VEM}^{est} , determined initially from the charge of the first pulse.
 200 A comparison of the converged Q_{VEM}^{est} and Q_{VEM}^{peak} determined from a peak fit
 201 to the charge histograms yields $Q_{VEM}^{est} = (0.96 \pm 0.03) Q_{VEM}^{peak}$. During operation,
 202 Q_{VEM}^{est} is used to monitor the status of the detector continuously and to
 203 provide a cross-check on the Q_{VEM} histogram measurement. Since Q_{VEM} is
 204 just the number of photoelectrons per muon (n_{pe}) times the PMT gain, the
 205 dynode/anode ratio, and the electronic gain, Q_{VEM}^{est} can be used to calculate
 206 n_{pe} for all detectors as well.

207 The history over the last 7 t_{cal} (60s) periods of the adjustments to I_{VEM}^{est} is
 208 included with each event, along with I_{VEM}^{est} , Q_{VEM}^{est} , and the last 70 Hz rates
 209 for each of the 3 PMTs.

210 3.2.1 Pressure dependence of the on-line calibration

211 The ratio of I_{VEM}^{peak} to I_{VEM}^{est} was found to have a very slight pressure depen-
 212 dence, which is expected since the on-line calibration uses the rate of atmo-
 213 spheric muons at $1.75 I_{VEM}^{peak}$ to determine I_{VEM}^{peak} . The dependence is clearer for
 214 technical reasons for $Q_{VEM}^{est}/Q_{VEM}^{peak}$, and is shown in Fig. 4. The correlation
 215 is $0.1\% \text{ g}^{-1} \text{ cm}^2$. The typical pressure change of the SD over 1 year is about

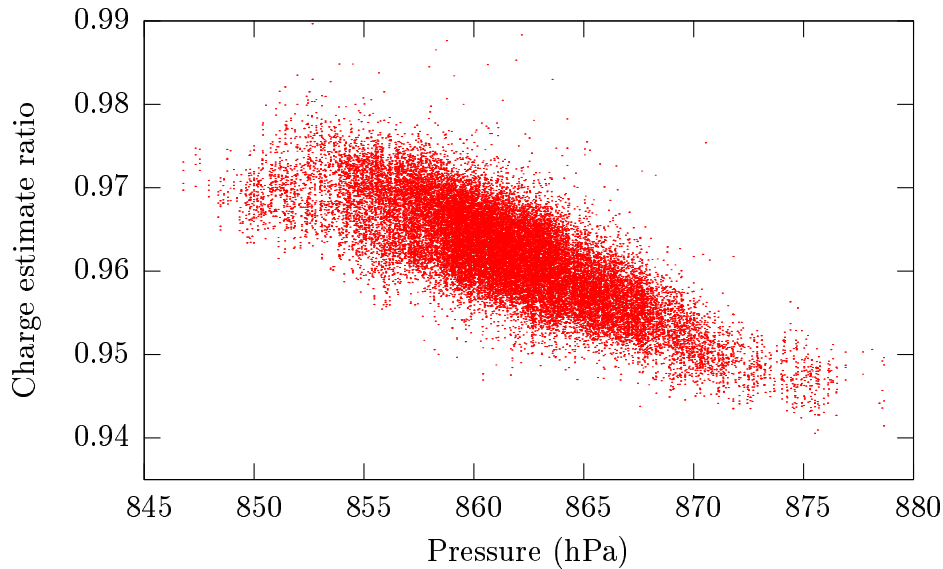


Figure 4. Correlation of the ratio $Q_{VEM}^{est}/Q_{VEM}^{peak}$ to atmospheric pressure as measured by a weather station located at the Los Leones fluorescence site. Note $1 \text{ hPa} = 1.020 \text{ g cm}^{-2}$ in atmospheric depth. The effect ($\sim 0.1\% \text{ g}^{-1} \text{ cm}^2$) on the trigger level over the course of a year is approximately 3%.

216 30 g cm^{-2} , implying a maximum 3% yearly variation in the trigger level.

217 3.3 Q_{VEM}^{peak} determination from charge histograms

218 The SD electronics has a separate trigger designed specifically for collecting
 219 high-rate data with fewer bins (20 bins instead of 768 for the event data) at
 220 low threshold ($0.1 I_{VEM}^{est}$). Once the calibration procedure has stabilized I_{VEM}^{est} ,
 221 this trigger is enabled and sets of histograms of various quantities are collected
 222 over 60 second intervals - approximately 150,000 entries per histogram. These
 223 histograms are sent to the CDAS along with any events that are requested
 224 - therefore, each event has a high-statistics set of charge and pulse height
 225 histograms from the previous minute accompanying the data.

226 The histograms created every minute are:

- 227 • Charge histograms for each individual PMT
- 228 • Charge histogram for the sum of all 3 PMTs
- 229 • Pulse height histograms for each individual PMT
- 230 • Histograms of the baseline of each FADC channel

231 The average of all pulse shapes with an integrated charge of $1.0 \pm 0.1 Q_{VEM}^{est}$
 232 is also sent. An example of the histograms and pulse shape average sent with
 233 each event is shown in Fig. 5.

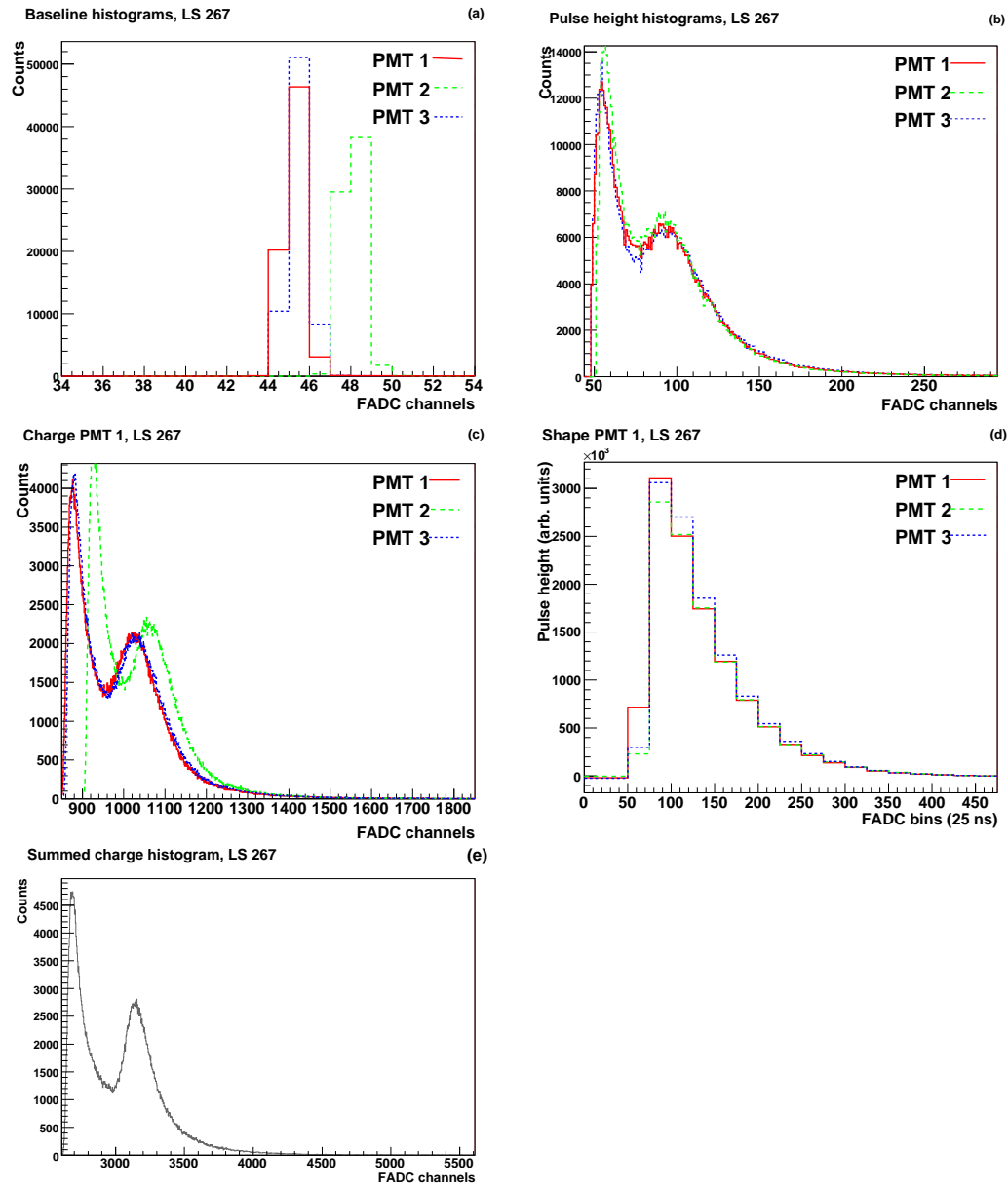


Figure 5. Example calibration data which are sent back with candidate event data, built from approximately 150,000 pulses collected in the minute prior to the event. It includes (a) baseline histograms for all 3 dynode channels, (b) pulse height histograms, (c,e) charge histograms for the three PMTs and the sum of the PMTs, and (d) the pulse shape of pulses with an integrated charge of $1.0 \pm 0.1 Q_{VEM}^{est.}$. The RMS spread in the I_{VEM}^{peak} values of the 3 PMTs was 3.3% (the mean for a random sample of 661 tanks was 4.4%). The baselines are not subtracted in the charge or pulse height histograms.

234 During data analysis, the second peak of the individual charge histograms
 235 (Fig. 5c) is fit by a quadratic function to obtain the value of Q_{VEM} used to
 236 convert the integrated signal into units of VEM. The agreement of $Q_{VEM}^{est.}$ and
 237 Q_{VEM}^{peak} is a good indication that this peak is resolvable for all the SD stations.

238 The Q_{VEM} obtained from charge histograms can also be crosschecked using
239 measurements of the charge deposited in the PMT by the Cherenkov light from
240 a decay electron from a stopped muon. These two measurements were found
241 to agree to 0.5%, well within the 4% uncertainty of the Q_{VEM} measurement
242 from the decay electron.

243 4 Additional parameters

244 In addition to the primary conversion from integrated channels to VEM units,
245 the calibration must also be able to convert the raw FADC traces into inte-
246 grated channels. There are two primary parameters needed for this.

- 247 (1) The baselines of all 6 FADC inputs
- 248 (2) The gain ratio between the dynode and the anode (called the “dynode/anode
249 ratio”)

250 The baseline is computed from each of the 100 Hz calibration triggers obtained
251 over a 60 second interval (~ 6000 total triggers) as well as the standard devia-
252 tion of each of the 6 inputs. This information is also included with each event,
253 and can be cross-checked against histograms of the baseline for the 3 dynode
254 channels.

255 4.1 Dynode/anode ratio (D/A)

256 The dynode/anode ratio (D/A) is slightly more complicated to measure. The
257 only pulses available to measure D/A are muon-like pulse shapes - either
258 from atmospheric muons or from an onboard LED flasher (used for linearity
259 measurements). A muon-like signal can be described essentially as a falling
260 exponential after the peak, with a typical decay constant of ~ 60 ns (see Fig.
261 5d). The signal/noise of the sum therefore decreases as bins farther from the
262 peak are included in the summation.

263 The nominal gain between the dynode and the anode is 32 - that is, 5 bits
264 of overlap out of a 10 bit FADC, giving 15 total bits of dynamic range. For a
265 signal which is nearly saturated on the dynode (~ 950 ch with a 50 ch baseline),
266 the anode signal will be merely 30 ch above baseline, The RMS noise of the
267 anode and dynode channels is $\sim 0.5 - 0.8$ ch, which implies that a signal with
268 a decay constant of ~ 60 ns will only be above the noise level on the anode
269 for 4 bins (200 ns), as compared to 17 bins for the dynode.

270 Ideally, the best measurement of D/A would occur simply by taking the peak
271 of the dynode divided by the peak of the anode, and averaging over many sam-

272 ples. Unfortunately, the dynode signal is *not* simply the anode signal multiplied
 273 by D/A - the dynode is amplified by two Analog Devices AD8012 amplifier
 274 stages, each of which has a phase delay of approximately 2-3 ns. Thus the
 275 dynode is actually delayed by 4-6 ns, which is approximately 1/4 of a 25 ns
 276 clock cycle. This prevents a direct peak-to-peak comparison. An alternative
 277 approach would be summing the signal and dividing the sum of the anode
 278 by the sum of the dynode. This, however, is also not possible, as the error
 279 associated with the RMS noise of the dynode and anode becomes quite signif-
 280 icant. Structured noise (below the RMS noise level) due to channel-to-channel
 281 crosstalk or other temporally correlated noise sources prevents obtaining an
 282 accurate ($< 5\%$) D/A measurement even with large statistics.

283 D/A is therefore measured by modelling the anode signal shape (A) from the
 284 dynode (D) as

$$285 \quad A(t) = \frac{1}{R} ((1 - \epsilon) D(t) + \epsilon D(t + 1))$$

286 where t is the time bin, R is D/A, and ϵ is the fractional bin offset of the dyn-
 287 ode. R and ϵ are determined using χ^2 minimization. D and A are determined
 288 with about 100 pulses taken within 3 minutes. Here, ϵ is known to be positive,
 289 but is allowed to vary for the fit. This procedure also has the advantage of
 290 measuring the phase delay and any time dependence it may have.

291 An example of the fit (and the fit region) is shown in Fig. 6, for a version of
 292 the front end electronics with higher noise characteristics than the production
 293 version. The two pulses were generated by a resistively-divided pulse genera-
 294 tor, which had no phase delay between the dynode and the anode. For these
 295 pulses, the “dynode/anode” ratio was 33.9 by design, and measured independ-
 296 ently with an oscilloscope. This procedure gave a dynode/anode ratio of 33.3,
 297 accurate to within 2%. The fitting procedure correctly gave a very small value
 298 for ϵ for this fit ($< 10^{-6}$). For actual stations, however, ϵ is measured to be
 299 on average 0.23, with an individual precision of 0.04. This corresponds to a
 300 delay of 5.8 ns, in agreement with our expectations. D/A determined with this
 301 method are also in good agreement with direct measurements of the D/A on
 302 the PMT base. However, estimating the accuracy of this comparison is quite
 303 difficult as the dependence of D/A on the high voltage of the PMT is poorly
 304 measured.

305 5 Conclusion

306 The main calibration goal for the surface detector is to convert the integrated
 307 flash ADC signal into vertical equivalent muon (VEM) units, and to provide

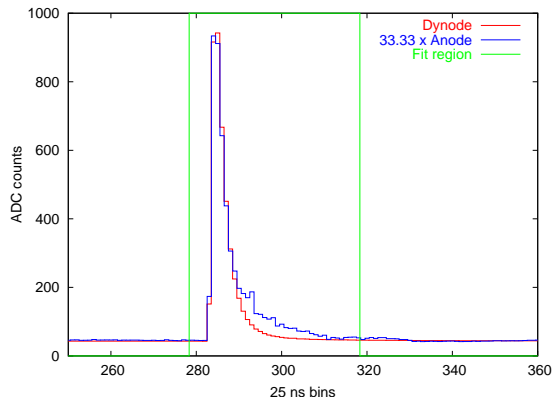


Figure 6. Example of the D/A fit to a resistively-divided pulse with the preproduction front end electronics. The pulse generator had an intrinsic D/A of 33.9, and the D/A fit method gave a D/A of 33.3, within 2%. The excess in the anode seen near 300 time bins is ~ 1 ch, which is the noise level of the preproduction electronics. The fit clearly determines the proper D/A even in the presence of < 1 ch noise.

308 a stable and uniform trigger for the detector. The conversion to VEM units is
 309 done by determining Q_{VEM} through their relation to a peak in charge (Q_{VEM}^{peak})
 310 histograms, which is determined through an independent experiment. Q_{VEM}^{peak}
 311 is measured with a high-statistics (150,000 entries) charge histogram every
 312 minute, and agrees with an independent local software estimate to 3%.

313 Conversion of the anode signal requires the determination of the dynode/anode
 314 ratio (D/A), which is done by averaging large pulses and performing a linear
 315 time-shifted fit to determine both the D/A and the phase delay between the
 316 two signals. This method, when performed on two resistively divided signals
 317 determined the D/A to 2%.

318 Uniform trigger levels are provided by estimating I_{VEM}^{peak} - the peak in a pulse
 319 height histogram - via a $\sigma - \delta$ convergence algorithm on a 70 Hz singles rate
 320 inside a 100 Hz 3-fold coincidence. This measurement is precise to 6%. The use
 321 of a rate to determine I_{VEM}^{peak} introduces a small systematic pressure dependence
 322 in the trigger level of approximately $0.1\% \text{ g}^{-1} \text{ cm}^{-2}$ leading to less than a 3%
 323 effect over the course of a year.

324 The calibration parameters mentioned here are determined every 60s and
 325 returned to the central data acquisition system (CDAS) with each event and
 326 stored along with the event data. Each event therefore contains a large amount
 327 of information about the state of each surface detector in the minute preceding
 328 the trigger, allowing for an accurate calibration of the data.

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