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Calculation of the number of photoelectrons produced per tank based on PMT test data and station monitoring data

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Abstract

The calculation of the total number of photoelectrons at the first dynode produced per vertical-equivalent muon (VEM) is an important measure of water quality, though attempting to calculate this number based on the station monitoring data is a difficult task due to the number of factors involved in the conversion. A proper calculation of the total number of photoelectrons produced per VEM will be examined, and the calculation will be performed on a large number of tanks in the array to show the total spread in water quality.

1 Introduction

The number of photoelectrons produced in a surface detector per vertical-equivalent muon (VEM) is one of the most important factors in the quality of data received by the surface detectors. As the signal fluctuation is driven by the square root of the number of photoelectrons, the total fluctuation in the signal received by the tank is driven by the number of photoelectrons per VEM ($n_{PE}(VEM)$). Thus, it is extremely important to be able to calculate this quantity.

An important note: what actually is calculated is the number of photoelectrons at the first dynode. In other words, it is after the Quantum Efficiency (QE) and the Collection Efficiency (CE) of the photomultiplier tube (PMT) are taken into account. When the gain of a PMT is calculated based on a single photoelectron distribution, this definition of gain does not include QE and CE. To get a conversion from charge at the anode of the PMT to incident number of photons, we would need to know QE and CE. Since these quantities are notoriously difficult to measure, they are not included in the following calculations. Hence, n_{PE} is the number of photoelectrons at the first dynode.

It is first important to examine the standard method by which $n_{PE}(VEM)$ is calculated on an isolated test tank, usually with either dedicated electronics or an oscilloscope. In this case, there are two primary steps to calculating

$n_{PE}(VEM)$ - first, the charge of a photoelectron must be determined (Q_{PE}), and second, the charge of a VEM must be determined (Q_{VEM}). In the case of an isolated test tank that can be equipped with a muon telescope and on which the high voltage of each PMT can be altered, this procedure is relatively straightforward. First, one determines Q_{PE} by setting the high voltage so that single photoelectrons can be observed, and performing a charge histogram of the recorded traces. The peak in this histogram will be Q_{PE}. Second, one determines Q_{VEM} by equipping a muon telescope (a pair of scintillator paddles above and below the tank) and recording only throughgoing vertical particles, with the tank at the same high voltage as before. The peak in a charge histogram of these events would be Q_{VEM}. $n_{PE}(VEM)$ is then just Q_{VEM}/Q_{PE}. In this case, it does not matter what the electronic gain of the detector itself is, nor the gain of whatever is used to measure the charge, since both Q_{PE} and Q_{VEM} were measured.

For the case of a running tank taking data in the surface detector, however, it is not feasible to alter the high voltage or equip each tank with a muon telescope. In addition, the operating high voltage is not sufficient to observe the single photoelectron peak. Therefore, the only option left is to account for the entire conversion of the original signal (photoelectrons produced by the photocathode) into the signal which is read out (the FADC trace). While the errors involved in this calculation will be certainly higher than the "standard" method, this procedure can be calculated simply from the monitoring data currently available with no additional procedures required at the tank level, and no interference with the data taking.

2 Conversion factors

It is therefore instructive to investigate the entire conversion process of the readout chain, starting from the number of photoelectrons, n_{PE}, to the signal produced. In this procedure, we will show the calculation step-by-step, with an explanation of all of the factors involved leading to the final conversion.

The first step is the amplification of n_{PE} by the PMT gain, G, to produce the total number of electrons at the anode. At this step, the charge at the anode is

$$Q_{anode} = eGn_{PE}$$

However, the readout chain reads both the total number of electrons at the anode and the total number of electrons at the last dynode. For the purposes of measuring Q_{VEM}, the dynode signal is more useful. Therefore, we must take into account the gain of the last dynode, α.The charge at the last dynode is then

$$Q_{dynode} = e\left(\frac{\alpha - 1}{\alpha}\right)Gn_{PE}$$

The dynode signal is then amplified via a two-stage amplifier on the base to give a sufficient dynamic range to cover the total signal span in cosmic ray showers.

The charge after this amplifier, with gain $G_{elect.}$, therefore, is

$$Q_{base} = e\left(\frac{\alpha-1}{\alpha}\right)G_{elect.}Gn_{PE}$$

At this point, however, it is important to realize that while $G_{elect.}$ cannot be measured directly (since the signal before amplification is not measured) as the station is running, the quantity $\left(\frac{\alpha-1}{\alpha}\right)G_{elect.}$can be - it is the dynode-anode ratio, R_{DA}. Therefore, the charge at the base can be written as

$$Q_{base} = eR_{DA}Gn_{PE}$$

After the base, the signal is again amplified (and filtered) at the front end electronics. The nominal gain of the front end, G_{FE}, is 0.5, which matches the full scale of the base $(0-2\text{V})$ to the full scale of the FADC $(0-1\text{V})$. Therefore the charge present at the input of the FADC is

$$Q_{FADC} = eG_{FE}R_{DA}Gn_{PE}$$

The charge is digitized at 40 MHz ($t_s = 25$ ns) through a 50Ω load (Z_{load}). The FADC is 10 bit, and therefore has a range of 0-1023 channels ($G_D = \frac{1\text{V}}{1023\text{ ch}}$). The charge measured, therefore, is

$$Q_{meas} = \frac{G_D\left(\sum_i x_i\right)t_s}{Z_{load}}$$

Equating Q_{FADC} with Q_{meas}, and solving for n_{PE}, we get

$$n_{PE} = \frac{G_D\left(\sum_i x_i\right)t_s}{eZ_{load}R_{DA}G_{FE}G}$$

where $x_i$is the FADC value of the ith sample, and the sum runs over the width of the pulse. Z_{load}, G_D, and t_s are fixed by design and have negligible variation from detector to detector. Thus, substituting and evaluating all constants,

$$n_{PE} = 3.0\times10^6\frac{\left(\sum_i x_i\right)}{R_{DA}G_{FE}G}$$

The remaining three conversion factors, R_{DA},G_{FE}, and G must be determined to convert the signal into total number of electrons. R_{DA} is measured constantly by the station electronics and is present in the monitoring data. G can be computed based on the high voltage values present in the monitoring data and the PMT test data, though that requires special care and will be discussed in Sec. 3.

G_{FE} is not measured accurately for each front end, though a rough measurement is taken to ensure that it is approximately 0.5 during front end testing. As it is not possible to measure this value directly, it suffices to use the nominal value of 0.5, assuming a 10% variation, which from testing results is certainly sufficient and likely to be an overestimate of the total variation.

3 Computing the PMT gain G from HV values

3.1 Computing the PMT HV

There are two measurements of the PMT high voltage present in the monitoring data. The first is the DAC value that produces the control voltage given to the PMT. The second is a readback of the high voltage from a sense output of the HV supply present on the base. While the readback is a "true" measure of the output voltage of the supply, the value very likely contains pedestal and gain variations from station to station which are unknown. The output of the DAC (a Burr-Brown DAC7625U) is accurate to ±4 LSBs at full-scale, which for a 12-bit DAC is an accuracy of ±0.1%. The conversion from input voltage to output high voltage is measured very accurately during PMT and base testing, and therefore it is likely to be more accurate to convert the DAC value into the high voltage of the PMT rather than using the readback of the output voltage. The readback of the output voltage is most useful as a diagnostic tool to ensure that the HV module of the base is functioning properly.

The displayed "PMT HV" in the monitoring data is an "estimate" of the high voltage using the *nominal* conversion between the DAC value and the output high voltage (2000V/4095 ch). To calculate the true PMT HV, the DAC value must be converted to input voltage, and the base-specific conversion between input voltage and output high voltage must be applied. Thus, the true PMT HV is

$$\mathrm{HV} = \frac{2500\mathrm{mV}}{4095\mathrm{ch}} \times \mathrm{DAC} \times R_{base}$$

where R_{base} is the base-specific conversion factor between input voltage (in millivolts) and output voltage (in volts) in the PMT database. It is located in the Photonis shipping sheet, and specified as HV_RATIO.

3.2 Computing the PMT gain G

The PMT gain, G, can be obtained from the PMT test data using the values given in the log-log plot of Gain vs. Voltage. The plot is

$$\log G = m \log HV + b$$

where m is the second number listed on the plot, and b is the first, and is typically negative. An example plot is shown in Fig. 1. Thus, solving for G,

$$G = 10^b HV^m$$

and substituting for HV from the previous expression and evaluating the constants,

$$G = 10^b \left(0.61\ \mathrm{DAC}\ R_{base}\right)^m$$

The final conversion from integrated signal to number of photoelectrons, then, is

$$n_{PE} = 3.0 \times 10^6 \frac{1}{R_{DA} G_{FE}} \frac{10^{-b}}{\left(0.61\ \mathrm{DAC}\ R_{base}\right)^m} \sum_i x_i$$

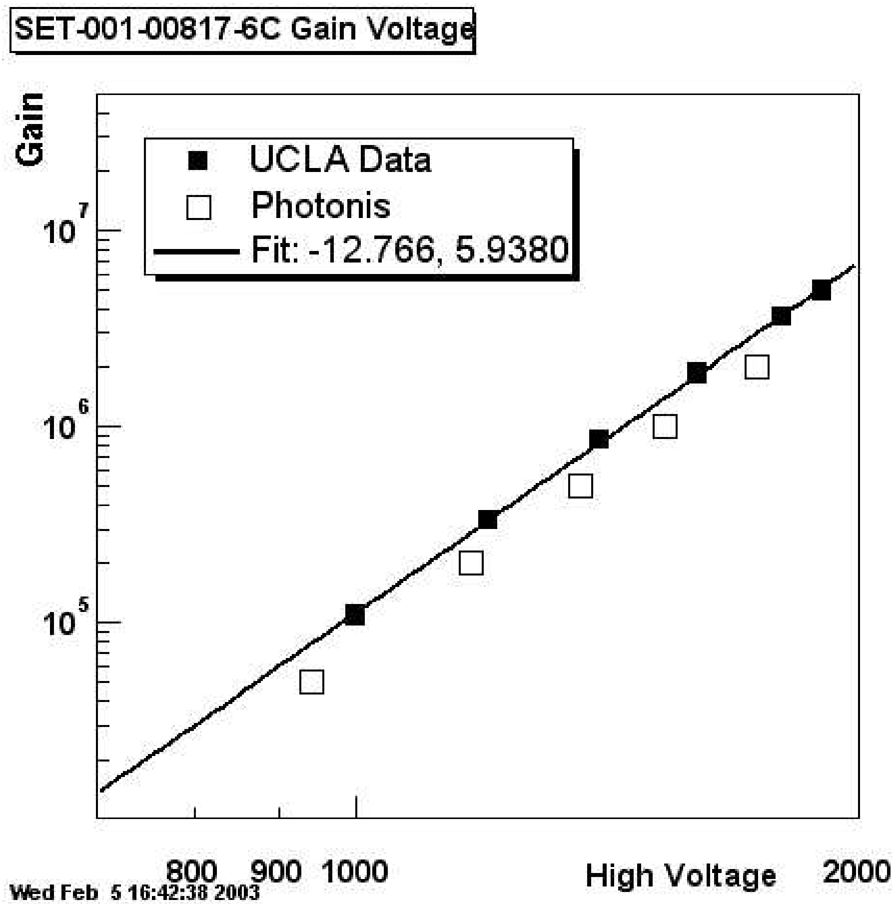

Figure 1: A sample gain vs. voltage plot in the PMT test data. The numbers listed for the fit are the offset and slope, respectively, for a log-log plot of gain vs. voltage. The relation between gain and voltage for this plot would be $\log G = 5.9380 \log HV - 12.766$.

or, substituting the nominal value of G_{FE}assuming a 10% variation,

$$n_{PE} = 6.0 \pm 0.6 \times 10^6 \frac{1}{R_{DA}} \frac{10^{-b}}{(0.61 \text{ DAC } R_{base})^m} \sum_i x_i$$

4 Obtaining the integrated VEM signal

The last piece to determining $n_{PE}\,(VEM)$ now that we know how to calculate the number of photoelectrons for an integrated signal, is to obtain the integrated signal of a VEM. Thankfully, this is already done for us by the local station as part of its monitoring, and given as the "VEM area". Thus, the calculation of $n_{PE}\,(VEM)$ is just

$$n_{PE}\,(VEM) = 6.0 \pm 0.6 \times 10^6 \frac{1}{R_{DA}} \frac{10^{-b}}{(0.61 \text{ DAC } R_{base})^m} A_{VEM}$$

Thus, from the monitoring data, we obtain A_{VEM}, the VEM area, R_{DA}, the dynode-anode ratio, and the HV DAC value. From the PMT test data, we obtain R_{base}, the conversion from input voltage in millivolts to high voltage, and m and b, the slope and offset of the log-log plot of gain vs. high voltage. The most significant sources of error in this calculation come from the front end gain uncertainty, which is likely overestimated, and R_{DA}. The systematic uncertainty in the R_{DA} calculation given by the local station could be avoided by using the $G_{elect.}$ given in the PMT test sheet (as the dynode anode ratio), but that would require using α from the PMT test sheet as well, which has much higher error than R_{DA}.

5 Calculating $n_{PE}\,(VEM)$ for Production Tanks

Calculating $n_{PE}\,(VEM)$ is straight forward, however, the main difficulty arises in collecting all the necessary data from different locations. The base slope, R_{base}, is given in a base characterization file, the gain to voltage conversion data is given in the PMT testing database, and the dynode to anode ratio, R_{DA}, DAC input, and VEM area are given in monitoring data.

For the following calculation, we analyzed monitoring data from June 4 to June 6, 2004 to get the DAC input, R_{DA}, and A_{VEM}. We only used tanks with constant high voltage set, or in other words, a constant DAC input value over the time period specified. The distribution of photoelectrons per VEM is presented in Fig. 2.

Once gain and n_{PE} are known, the gain matching of phototubes can be checked. We expect an inverse correlation between n_{PE} and gain. In Fig. 3 we see this relationship. The error for each point is dominated by the uncertainty in the gain of the front end (G_{FE}).

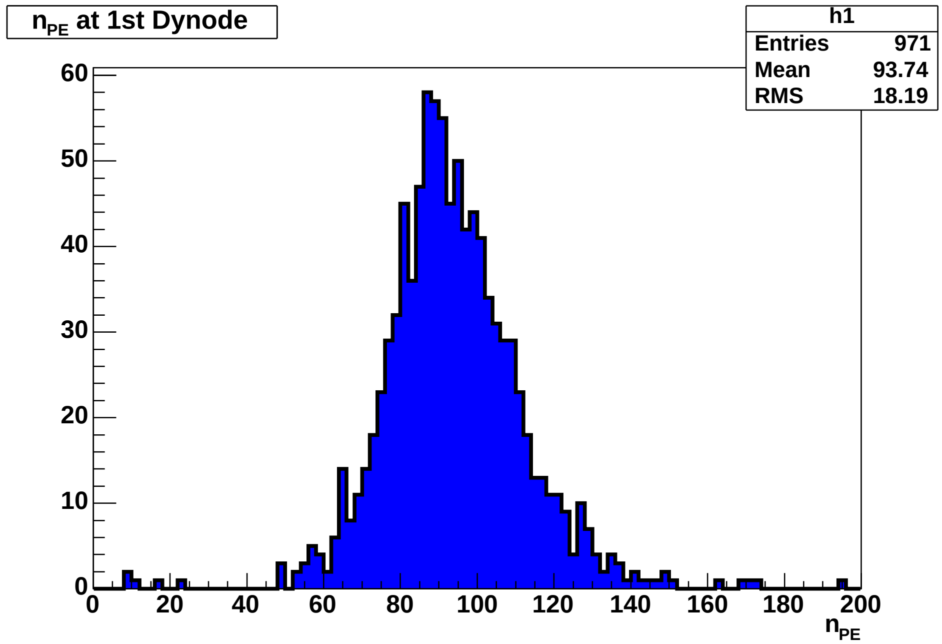

Figure 2: Distribution of photoelectrons at 1st Dynode.

6 Conclusion

A detailed computation of the number of photoelectrons per VEM, $n_{PE}\,(VEM)$, has been performed, taking into account all of the electronic gains and conversion factors required. The final result is

$$n_{PE}\,(VEM) = 6.0 \pm 0.6 \times 10^{6}\frac{1}{R_{DA}}\frac{10^{-b}}{(0.61\ \mathrm{DAC}\ R_{base})^{m}}A_{VEM}$$

where the 10% error systematic comes from the estimation of the front end. This error could easily be improved upon in the future.

In addition, $n_{PE}\,(VEM)$ has been calculated for all tanks with constant high voltage in early June. The results clearly show that the mean $n_{PE}\,(VEM)$ for production surface detectors, per PMT, is 93 ± 18. This, therefore, implies that $n_{PE}\,(VEM)$ per tank is three times this value, or 280 ± 54.

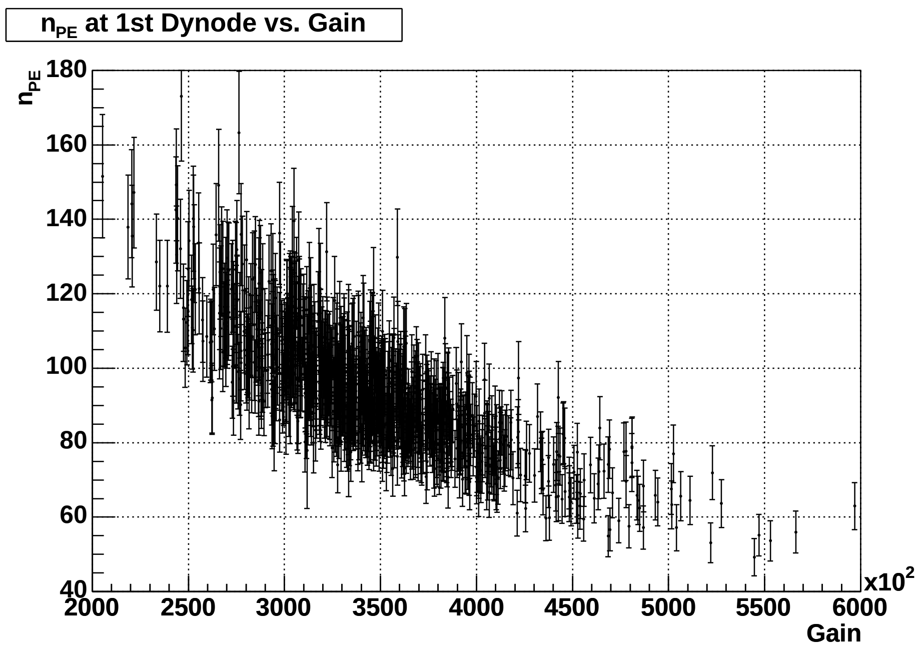

Figure 3: Photoelectrons at 1st Dynode vs. Gain.