Analysis of Gain Monitoring System for UCNA

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1 Introduction

The purpose of this report is to analyze the gain monitoring system and calibration setup for ultra cold neutron decay and categorize possible calibration shifts. An outline of the apparatus, an analysis of possible calibration issues, and a series of tests relevant to the setup will be presented.

2 Gain Monitoring System (GMS)

The GMS is shown schematically in figure 1, it consists of two separate renditions of the following, one for either end of the experiment. The main UCNA β-scintillator consists of a piece of scintillator attached by light guides (LG) to 4 separate photomultiplier tubes (the β-PMTs). An LED box has two fiber optic cables. One cable is glued to the β-scintillator and the other cable is connected to the monitor (M) PMT setup via a clear acrylic cookie. The monitor setup involves a piece of NaI with a Co-60 source attached on one end and on the other the cookie with the fiber optic glued to it and a PMT attached to the cookie. We envision a Bi-207 source to be periodically inserted into the region of the β-scintillator for gain calibration. The experiment involves 4 event types: LED light pulses, Co-60 gamma decays, neutron β-decays and Bi-207 source decays.

3 Analysis of Gain Shifts and Errors in Corrections

The analysis consists of two parts: a mathematical analysis of the GMS corrections, and an analysis of possible failures of the system and our ability to correct them.

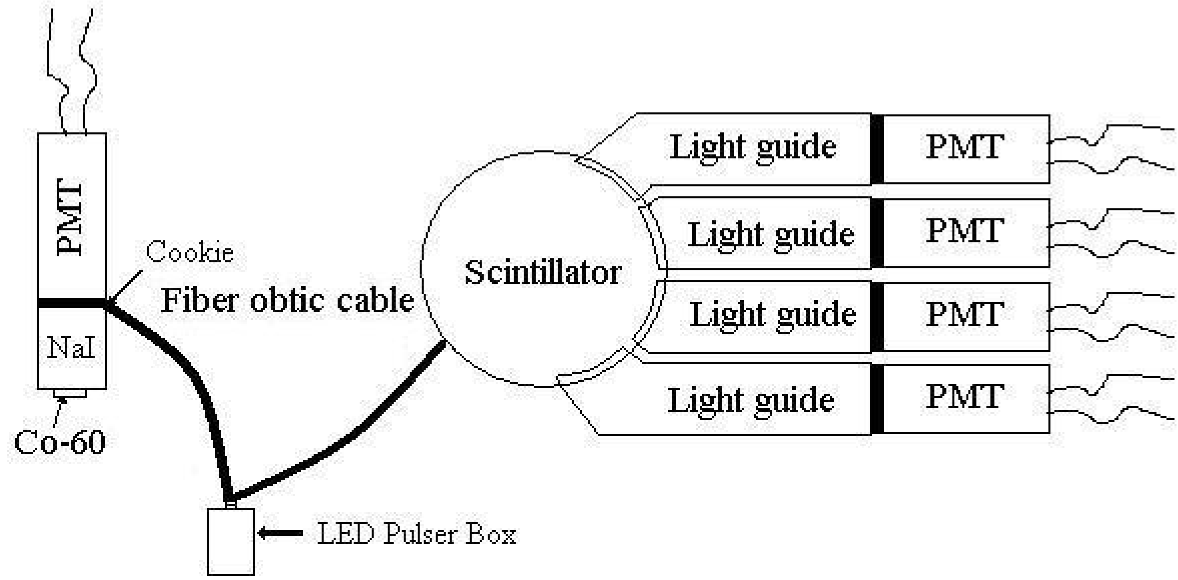

Figure 1: **Setup Schematic**

3.1 Mathematical relations

This section provides formulae for corrections based on the GMS. Table 1 lists the relevant quantities. All peak measurements are in units of ADC channels, energy measurements are in keV and calibration constants are in keV/channel. Peaks may vary as functions of time, where $t = 0$ is the initial calibration and some time $t > 0$ is the time when the calibration adjustment calculations are applied. Also there are 4 separate PMTs involved in the measurement of the β-scintillator light output, this system could be applied to each one in turn since they may all drift independently.

For the monitor setup we define the monitor calibration constant $C_m(t)$ as:

$$C_m(t) = \frac{E_m}{S_m(t)} = \frac{E_{LEDm}(t)}{LED_m(t)} \tag{1}$$

Similarly for the β-scintillator setup we define:

$$C_\beta(t) = \frac{E_\beta}{S_\beta(t)} = \frac{E_{LED\beta}(t)}{LED_\beta(t)} \tag{2}$$

We reference all calibrations relative to the Bi-207 calibration at $t = 0$. Hence for the monitor tube we have:

$$\frac{C_m(t)}{C_m(0)} = \frac{S_m(0)}{S_m(t)} = \frac{LED_m(0)}{LED_m(t)}\left(\frac{E_{LED_m}(t)}{E_{LED_m}(0)}\right) \tag{3}$$

Variable	Designation	Units
Beta Scintillator Bi-207 source peaks	$S_\beta(t)$	channel
Beta Scintillator Bi-207 source energy	E_β	keV
Beta Scintillator LED peak channels	$LED_\beta(t)$	channel
Beta Scintillator apparent LED energy	$E_{LED\beta}(t)$	keV
Calibration of β-PMTs	$C_\beta(t)$	keV/channel
Monitor Co-60 source peaks	$S_m(t)$	channel
Monitor Co-60 source energy	E_m	keV
Monitor LED peak channel	$LED_m(t)$	channel
Monitor apparent LED energy	$E_{LEDm}(\mathrm{t})$	keV
Calibration of m PMT	$C_m(\mathrm{t})$	keV/channel

Table 1: **Variables used in mathematical analysis**

While for the β-PMTs we have:

$$\frac{C_\beta(t)}{C_\beta(0)} = \frac{S_\beta(0)}{S_\beta(t)} = \frac{LED_\beta(0)}{LED_\beta(t)}\Big(\frac{E_{LED_\beta}(t)}{E_{LED_\beta}(0)}\Big) \tag{4}$$

In order to solve the equations the assumption is made that the apparent energy of the LED peaks as a function of time will remain proportional in the β-scintillator relative to the monitor PMT:

$$\frac{E_{LED_\beta}(0)}{E_{LED_m}(0)} = \frac{E_{LED_\beta}(t)}{E_{LED_m}(t)} \tag{5}$$

This implies there are no problems where the fiber-optic cable joins with the monitor PMT or the β-Scintillator. We assume that during runtime no Bi-207 source is available to calibrate the β-PMTs, so we need to determine it from the known factors in the monitor tube and the ratio of equation (3) to equation (4), thus giving:

$$C_\beta(t) = C_\beta(0)\Big(\frac{LED_m(t)}{LED_m(0)}\Big)\Big(\frac{S_m(0)}{S_m(t)}\Big)\Big(\frac{LED_\beta(0)}{LED_\beta(t)}\Big) \tag{6}$$

3.2 Gain system example

We consider a simple example where both considered PMTs have calibration changes causing all peaks to shift. The hypothetical spectra are shown schematically in figure 2. Table 3.2 contains all the information that would be needed to ensure proper calibration. Note only the lower 1173keV Co-60 peak is used for the calibration.

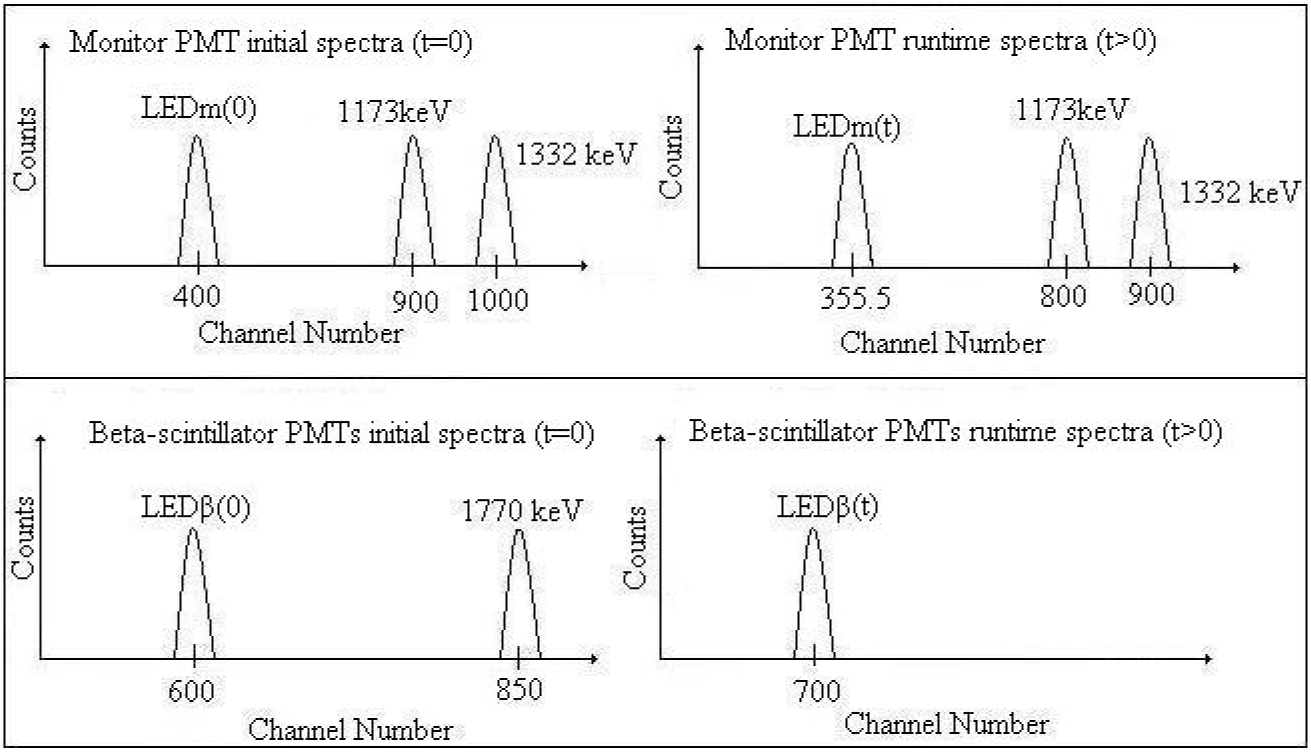

Figure 2: **Hypothetical spectra for the GMS setup**

3.3 Description of considered scenarios

All scenarios we considered are shown in table 3. The scenarios are grouped by color. Group 1 (red) consists of scenarios 1-3 and has to do with real β-scintillator calibration changes. Group 2 (black) consists of scenarios 4-7 and refers to physical changes to the GMS. Group 3 (blue) consists of scenarios 8-10 which represent changes related to the LED. All scenarios will be discussed in the context of equation (6) repeated here for convenience:

$$C_\beta(t) = C_\beta(0)\Big(\frac{LED_m(t)}{LED_m(0)}\Big)\Big(\frac{S_m(0)}{S_m(t)}\Big)\Big(\frac{LED_\beta(0)}{LED_\beta(t)}\Big) \tag{6}$$

1. Scenario 1: Scint degradation means any occurrence which degrades the scintillator's light output. Examples are: yellowing of the scintillator, aging of scintillator and loss of scintillator fluor over time. It is assumed that such degradation would be uniform throughout the scintillator detector. In equation (6) $LED_\beta(t)$ decreases, this causes an increase in the calibration factor for the β-PMTs as expected.

2. Scenario 2: Scint/PMT LG join degradation. This is the degradation of the join between the scintillator detector and any of the 4 LGs leading to the β PMTs and/or the join between those LGs and the 4 PMTs. This degradation could be caused for

Quantity	Value at $t = 0$	Value at $t > 0$	units
LED_m	400	355.5	channel
S_m	900	800	channel
LED_β	600	700	channel
Sβ	850	none	channel
E_m	1173 keV	same	keV
Eβ	1770 keV	same	keV
C_m	1.303	1.466	kev/channel
C_β	2.082	1.78	keV/channel

Table 2: Calibration values for Hypothetical spectra

Group	Scenario	$LED_m(t)$	$LED_\beta(t)$	$S_m(t)$	$S_\beta(t)$	Correctable?
1	1 Scint degradation	Same	Change	Same	Change	yes
1	2 β-Scint/β-PMT LG join degradation	Same	Change	Same	Change	yes
1	3 Temp or HV drift of β-PMT	Same	Change	Same	Change	yes
2	4 Degradation of Fiber S Joint	Same	Change	Same	Same	no
2	5 Temp or HV drift of m PMT	Change	Same	Change	Same	yes
2	6 Distance of Co 60 change	Same	Same	Change	Same	small effect
2	7 Degradation of Fiber m Joint	Change	Same	Same	Same	no
3	8 LED Voltage change	Change	Change	Same	Same	yes
3	9 Degradation of LED	Change	Change	Same	Same	yes
3	10 Temp of LED change	Change	Change	Same	Same	yes

Table 3: **m refers to monitor, LG refers to light guide, β-Scint refers to β-scintillator and LED refers to light emitting diode.**

example by the loss of optical grease or physical detector shift. A degradation of one PMT LG connection will cause changes only to what the PMT attached to that LG views. Those PMTs whose LG are effected will see a decrease in calibration for all peaks. The LED_β(t) peak would decrease in each effected β PMT, this change causes an increase in the corrected calibration from equation (6) as expected. Since each PMT will be affected differently there will be a non-uniform pattern to how each β-PMTs $LED_\beta(t)$ peak shifts. However this scenario would be properly accounted for through equation (6), provided the β-PMTs are calibrated individually.

3. Scenario 3: Temp or High Voltage drift of β-PMT. A decrease in PMT temperature or voltage causes a decrease in PMT calibration. An increase in PMT temperature or voltage causes an increased PMT calibration. In equation (6) the $LED_\beta(t)$ peak either increases or decreases in channel number as appropriate for the temperature/HV change involved, the $LED_m(t)$ peak has the same apparent energy allowing for equation (6) to correct the calibration.

4. Scenario 4: Degradation of the Fiber-S Joint. This scenario occurs when the connection between the scintillator and the fiber optic cable from the LED pulser box degrades. Examples are: the connection moves, the interface becomes blurry or a gap occurs between the cable face and the scintillator. This scenario causes the LED_β(t) peak to decrease but does not effect any other viewed peaks so it is not a real gain change, the result is an erroneous calibration factor $C_{beta}(t)$ in equation (6). Since the change of this peak is not corrected by a corresponding change in another peak this situation is not able to be accounted for. When this scenario occurs a recalibration with the Bi-207 source is necessary .

5. Scenario 5: Temp or HV drift of m PMT. $LED_m(t)$ and $S_m(t)$ both change by a proportionate amount causing the ratio of the two to remain the same. Thus $C_\beta(t)$ remains the same as required.

6. Scenario 6: Distance of Co-60 change. In equation (6) the S_m(t) peak would decrease/increase and exceedingly small amount with a decrease/increase in Co-60 source distance. Due to the exceedingly small energy deposition of γs in the air between the source and the crystal different geometries of crystal for γ-decays viewed from different angles means the width and shape of the γ-peak could be affected. This scenario is assumed to not be a significant factor in the calibration equations. To avoid this problem the Co-60 source should simply be fixed in place.

7. Scenario 7: Degradation of the fiber M joint. This scenario involves the connection between the monitor cookie and the fiber optic cable from the LED pulser box. Examples would be that the connection moves, the interface becomes blurry or a gap occurs between the cable face and the monitor PMT face. This scenario causes a decrease in the $LED_m(t)$ peak. Since a decrease in the $LED_m(t)$ peak causes an unbalanced change to equation 6 making the calibration factor invalid.

8. Scenario 8: LED voltage change. When the voltage pulse to the LED from the power supply increases/decreases in amplitude then the output of light from the LED correspondingly increases/decreases. The LED needs to be pulsed at a voltage such that a small variation in voltage results in a small variation in the intensity of emitted light (approximately 5 V for the LEDs used in the tests). Regardless a change in supplied voltage means that the LED peaks in both the scintillator and the monitor PMTs will increase/decrease in peak channel with increases/decreases in the voltage. Changes in LED light output are incorporated into equation (6), this is because $LED_m(t)$ will change proportionally with $LED_\beta(t)$ causing the ratio of the two values to remain constant.

9. Scenario 9: Degradation of LED. Over time the light emitted by the LED decreases in intensity due to aging. This process might be accelerated by running the LED at higher than the manufaturers suggested voltages, which for GMS purposes is normally done, but for smaller duty factors than considered in the manufacturers specifications. When the LED's output decreases in intensity the peaks in the M and β PMTs decrease in channel number. Accounted for through equation (6) as explained in scenario 8.

10. Scenario 10: Temp of LED change. A change in the temperature of the LED causes a change in output light intensity and a slight shift in wavelength. Only the LED peaks are effected in this scenario with either an increase or decrease in channel number. The LED wavelengths are stated to be 360-370 nm for NSHU590 B and 370-380 for NSHU590 A. Accounted for through equation (6) as explained in scenario 8.

3.4 Summary of scenario effects according to group

This summary is also included in short in the final column of table 3. Group 1 scenarios: Scenarios 1-3 effect solely the LED_β(t). The calibration factor $C_\beta(t)$ however is calculated correctly via equation 6.

Group 2 scenarios: Scenario 4 causes a uniform decrease in all LED_β(t) peaks. This causes $C_\beta(t)$ to erroneously increase. Care must be taken to ensure this does not occur. No measure of how long it takes for this decrease to occur has been performed, this could be characterized online using the Bi-207 source in long term tests. Scenario 5 is covered by correcting the calibration via the Co-60 peak energy and channel. Scenario 6's effect (motion of Co-60 source) is likely to be negligible. Scenario 7 can not be accounted for since it effects the assumptions made in deriving equation 6, namely it effects only one factor the $LED_m(t)$ peak not the real system calibration.

Group 3 scenarios: Scenarios 8,9 and 10 are accounted for in the calibration calculations for the GMS because the ratios for the initial and runtime apparent energy measurements are constant. However the monitor and β-PMTs have slightly different wavelength ranges, this means that when group 3 scenarios occur the wavelength of the LEDs light output varies slightly causing an assumed small error in the ratio of apparent LED energies.

4 Measurements of slopes

4.1 Test Setup

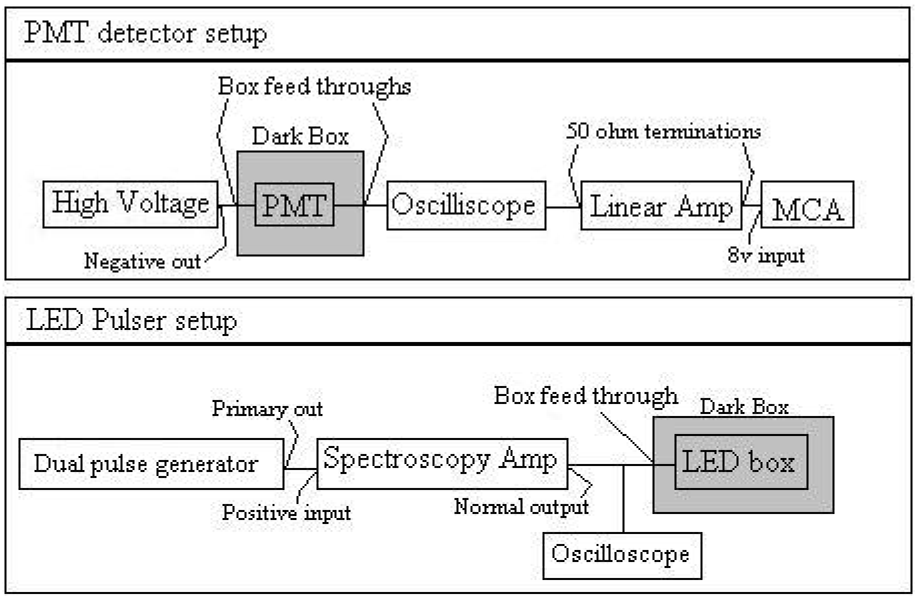

Figure 3: **Block diagrams for the LED drift experimental setup**

Figure 3 shows a block diagram for the setup of the various tests performed. Three setups were tested see figure 4 for schematic. Setup # 3 was found to be the most appropriate and was used for all reported tests.

An LED pulser box (see figure 5 for schematic) was fabricated using a Nichia UV LED of either type NSHU590A or NSHU590B. The LED box and a 1-inch PMT were placed inside a light tight box (see figure 6) of dimensions (39in)x(12in)x(12in) with two SHV feed-throughs and two BNC feed-throughs attached through the box's front. The box's lid is edged with black weatherstripping and the interior is lined with black felt.

1. LED box setup: The dual pulse generator (Canberra model 1407P) was connected through it's primary out port to the specrtoscopy amplifier's (Canberra model 1417B) positive in port. The primary out port on the pulse generator outputs one pulse at a time, not a pulse pair. The pulser was pulsed at 10 kHz frequency. The spectroscopy amplifiers normal output was set to produce positive unipolar pulses and the gain

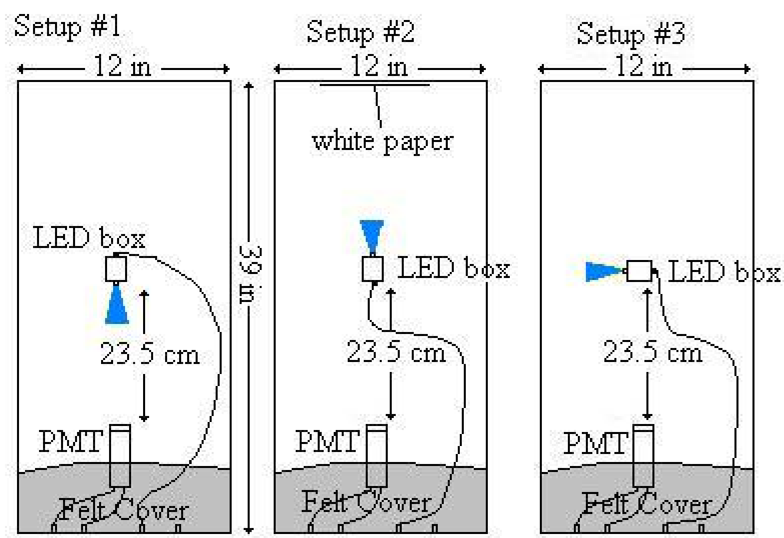

Figure 4: **Setups 1,2 and 3, Setup #1 saturated the PMT, Setup 3 was used for all reported tests**

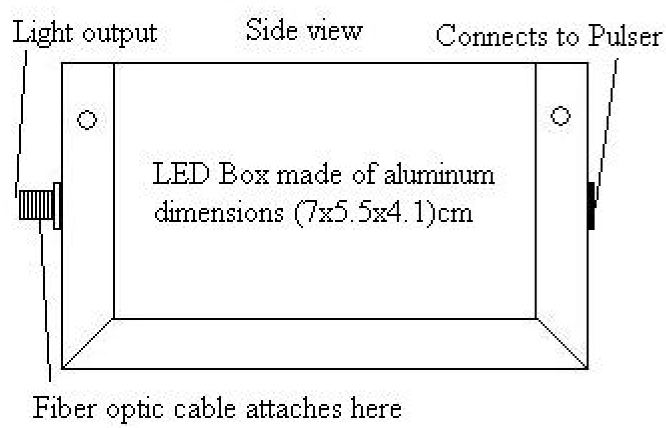

Figure 5: **Diagram of LED Box constructed for UCNA**

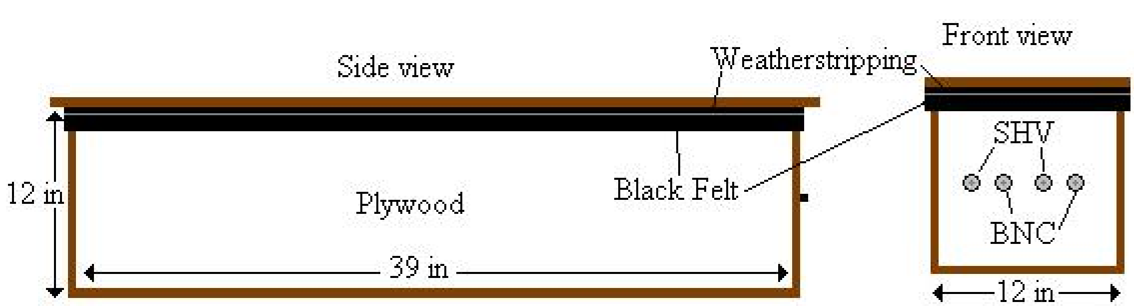

Figure 6: **Diagram of Light tight box**

was set to produce an output voltage pulse of 5 V, the shaping time and impedance were set to their lowest settings. The spectroscopy amplifiers normal output was then connected to the LED pulser box as well as to the input on the oscilloscope.

2. PMT setup: The PMT was connected to a high voltage power supply (Ortec model 556) nominally operated at -0.95 kV. The output from the PMT was connected to the Oscilloscope (Tektronix TDS 2024) to view it's output and was split to also go to the linear amplifier's (Nuclear Enterprises LTD model C115) negative input and terminated with a 50 ohm resistor. The linear amplifier was set so as to produce a fairly well shaped pulse of approximately 8 V which was then sent through the linear amplifiers INT output which is also terminated with a 50 ohm resistor direct to the multi-channel analyzer (MCA)(Tracor Northern model TN-7200). Each MCA spectra was downloaded to the computer via a RS232 adapter and analyzed using ROOT, see figure 7 of appendix for sample analysis.

4.2 PMT output pulse height vs LED Pulse Voltage tests

This test determined the relationship of LED pulse voltage to LED light output. The light output was measured using the PMT's output pulse height as measured on the oscilloscope. The relationship to light output was assumed to be linear. The PMT output pulse height (P_{out}) was plotted against the height of the input voltage pulse (Vin) as measured in another channel of the same ossicilloscope. The slope of this plot is $\Delta P_{out}/\Delta Vin = (24 \pm 0.4) mV/channel$ which at the operating point of 5 V gives a drift of $\frac{24}{50} * 100\% = 48\%/V$. The 48%/V drift was found to be independent of the LED-PMT orientation as long as the PMT was not saturated.

4.3 Tests of Peak position vs PMT High Voltage (HV)

The dependence of LED peak position on the PMT HV was measured. The slope was found to be 3.2 channels/V. At the operating HV of -0.96 kV the peak drift was $\frac{3.2 \text{ channels/V}}{440 \text{ channels}} * 100\% = 0.72\%/\text{V}$. Appendix figure 8 shows the graph of this relation, p1 is the slope p0 is the y-intercept and χ^2_ν is the goodness of fit for the linear fit.

4.4 Tests of drift over time

This series of tests measured the drift of both the type A and type B LEDs over time. For the drift tests analyzed in this report both LEDs were tested with the input LED voltage run at 5 V and frequency 10kHz so that short precise measurement could be made at various points during the day. The protocol for time tests involved use of the MCA timer

LED type	Trial	Slope(channels/s)	Slope (%/s)	χ^2_ν	Δt (s) for ΔLED = 1%
LED A	1	$(-10 \pm 1) * 10^{-5}$	$3.8 * 10^{-5}$	33/8	26000
LED A	2	$(-11 \pm 2) * 10^{-5}$	$4.2 * 10^{-5}$	16/8	24000
LED B	1	$(-645 \pm 2) * 10^{-5}$	$200 * 10^{-5}$	$2.8 * 10^4/8$	662
LED B	2	$(0 \pm 2) * 10^{-5}$	0	83/8	infinity
LED B	3	$(4 \pm 2) * 10^{-5}$	$0.9 * 10^{-5}$	270/8	100000

Table 4: Summary of drift tests

to track measurement time and the use of a stopwatch to track overall experiment time. All measurements were performed for the same measurement time. The appendix contains the pertinent graphs in figures 9-13 for the five trials sumarized in table 4.4. Each value used in the graphs for this test is the peak channel of a gaussian fitted to the MCA output (see figure 7 with the error used being the gaussian's σ. The χ^2_ν value relates to the statistical error in the mean based on the Gaussian fit. The Slope in %/s is calculated based upon the LED peak value at 400 seconds. See table 4.4 for results.

Trial 1 for LED B has a large slope which could be attributed to the fact that is was performed shortly after setup and the PMT and power supply had not settled down. The slope and χ^2_ν for this trial are very different from the other 4. For LED A trials 1 and 2 and LED B trials 2 and 3 the χ^2_ν for the tests were bad due to drifts in the LED peak which do not follow a line.

From the above tests it was decided to use LED A. This is because of seemingly better χ^2_ν values found in the above tests. This is consistent with manufacturers specifications relating to the LED output vs temperature slopes, which peak around room temperature for LEDA while LEDB has a slope around room temperature. It is also consistent with Gray Rybka's logbook.

5 Conclusion

The analysis of the GMS has shown that in most cases it is possible to monitor the gain of the system after an initial calibration is performed. The equation describing the variation of the calibration correction factor with time is:

$$C_\beta(t) = C_\beta(0)\left(\frac{S_m(0)}{S_m(t)}\right)\left(\frac{LED_m(t)}{LED_m(0)}\right)\left(\frac{LED_\beta(0)}{LED_\beta(t)}\right) \tag{6}$$

From an analysis of possible effects on detector and GMS performance we found that recalibration using the insertable Bi-207 is needed in two scenarios:

1. When the fiber optic to β-Scintillator join degrades.
2. When the fiber optic to monitor join degrades.

LED peak position was measured vs: LED pulser voltage, PMT HV and time (combination of effects with slow drift). The resultant slopes were:

1. For LED pulser voltage (V_{in}):
$$\frac{\Delta LED}{\Delta Vin} = \frac{\Delta P_{out}}{\Delta V_{in}} = 46\%/V \text{ at 5 V}$$
2. The PMT HV setting had the effect of:
$$\Delta\text{LED}/\Delta\text{HV} = 0.72\%/V \text{ at -0.96kV}$$
3. The following typical value was found by plotting LED peak channel vs time with the operating parameters specified above and at a typical temperature of 25 degrees Celsius:
$$\frac{\Delta LED}{\Delta t} = 4 * 10^{-5}\%/s$$
This results in a time of 25000 seconds for an LED peak drift of 1%. The worst time to drift by 1% that we observed was 662 seconds.

We now attempt to determine the rate at which the LED must be pulsed in order for the LED peak to be known to within 1% before it drifts by 1%. Assuming the LED peak to be located at the end of the β spectrum producing around 40 photo electrons in the β-Scintillator implies the following relative width of the LED peak:

$$\frac{\sigma}{\bar{c}} = \frac{1}{\sqrt{40}} \tag{7}$$

Supposing we desire to extract the uncertainty in the mean to the 1% level implies the following relation:

$$\frac{\delta_c}{\bar{c}} = \left(\frac{\sigma}{\sqrt{N}}\right)\left(\frac{1}{\bar{c}}\right) = 1\% = \frac{1}{100} \tag{8}$$

Resulting in the following minimum number of pulses to achieve a 1% uncertainty:

$$N = \frac{100^2}{40} = 250 \tag{9}$$

If we assume the worst case time for the peak to drift by 1% to be 662 seconds the following is the minimum rate needed:

$$Rate = \frac{250}{662s} = 0.4Hz \tag{10}$$

We regard this as a worst case time, however there could be other drifts which we were not sensitive to. So the pulse rate for UCNA should be about 1 Hz so that this possible issue is not a factor. The pulse rate should be increased if higher precision is needed, or if the number of photo electrons is lower. For example based on our measurements, to determine the gain to 0.1% in 66 seconds would require an LED pulse frequency of 400 Hz.

Further tests using the actual system would be required to find numbers more applicable to the experiment's setup. It would be necessary to periodically recalibrate the experiment to ensure that none of the peak drifts were caused by physical changes to the equipment which can not be accounted for through the GMS. Long-term in situation data at LANL is needed to find the remaining slopes such as a long term measure of the degradation of fiber connections with time, which will set the time allowed before recalibration is needed.

6 Appendix

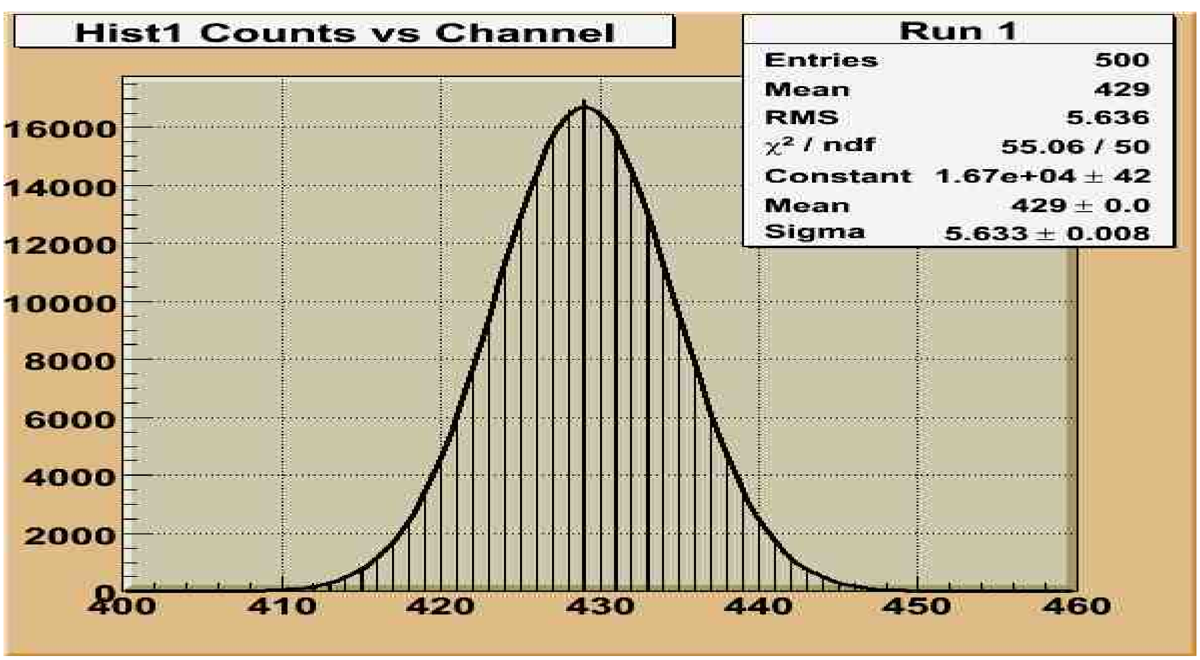

Figure 7: **Typical pulse height spectrum fit with a gaussian (LEDBtrial2run1)**

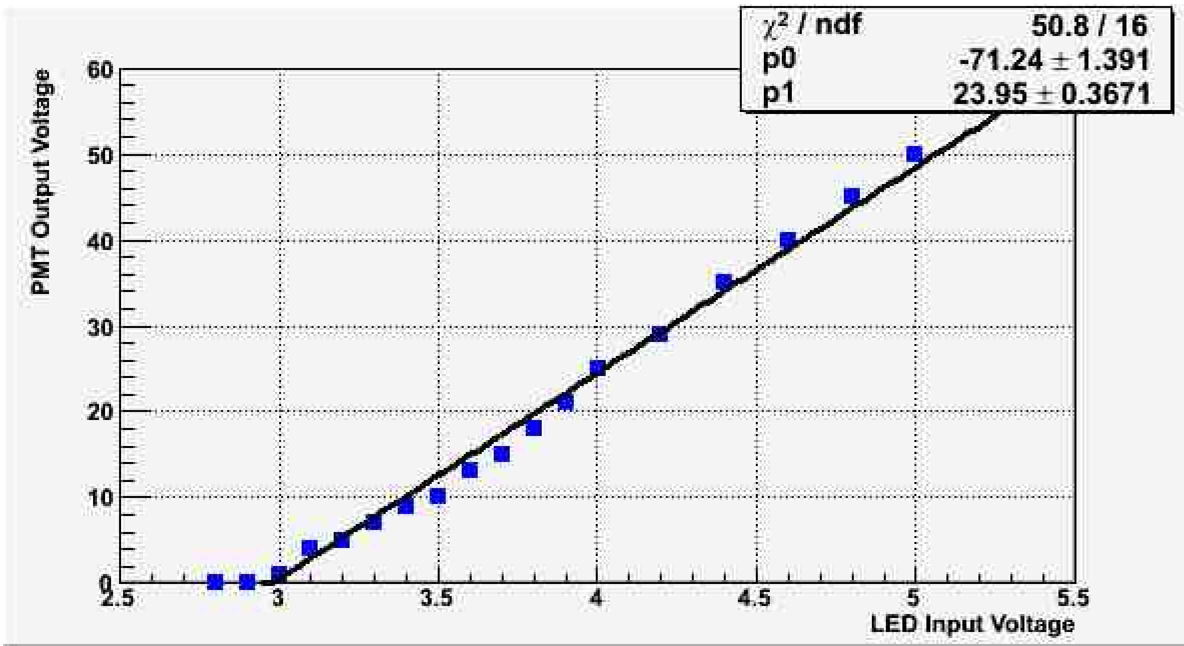

Figure 8: **PMT output pulse heights dependance on LED input voltage**

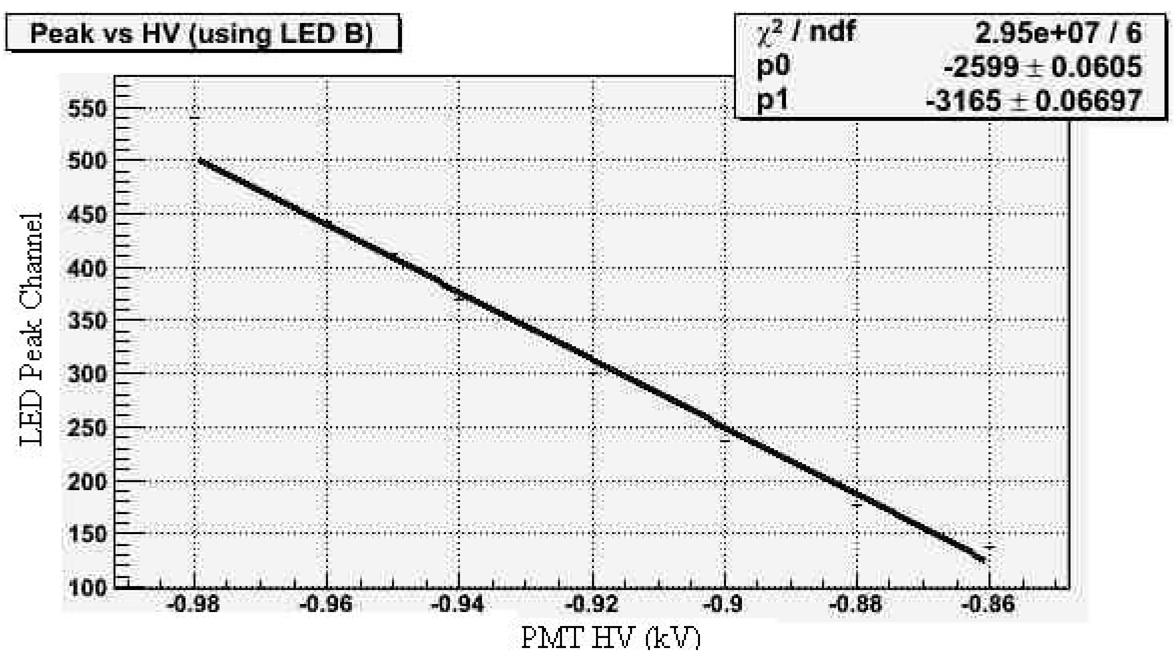

Figure 9: **LED peak vs PMT HV is a linear**

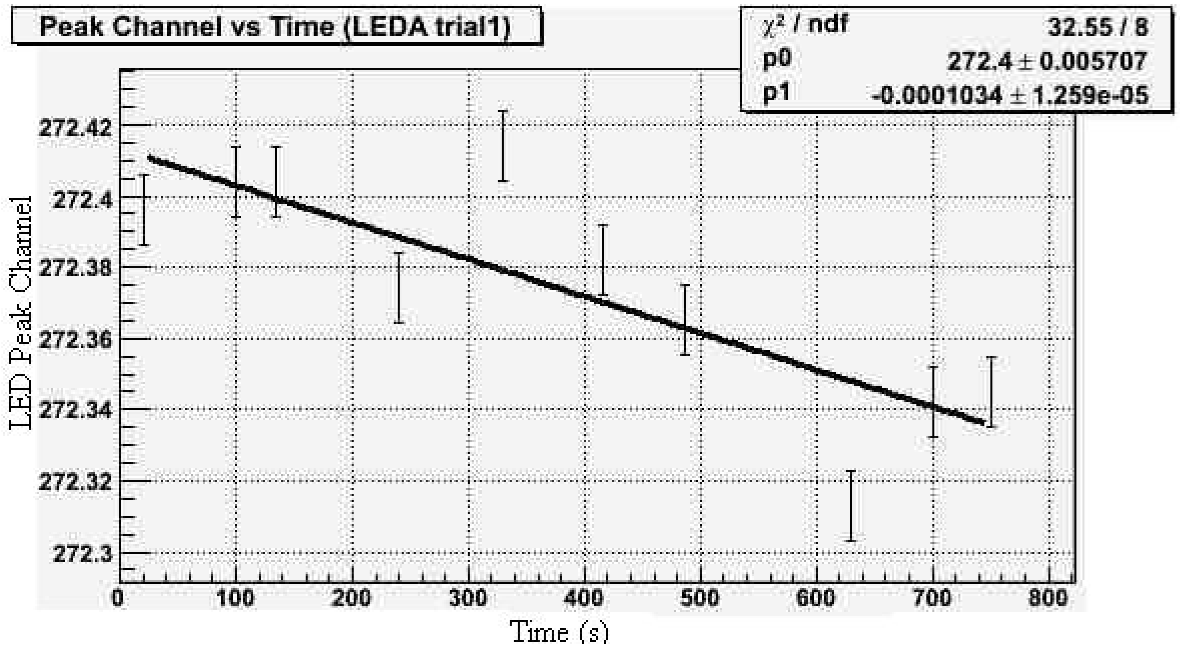

Figure 10: **LED peak vs time. Drift test 1, LED A**

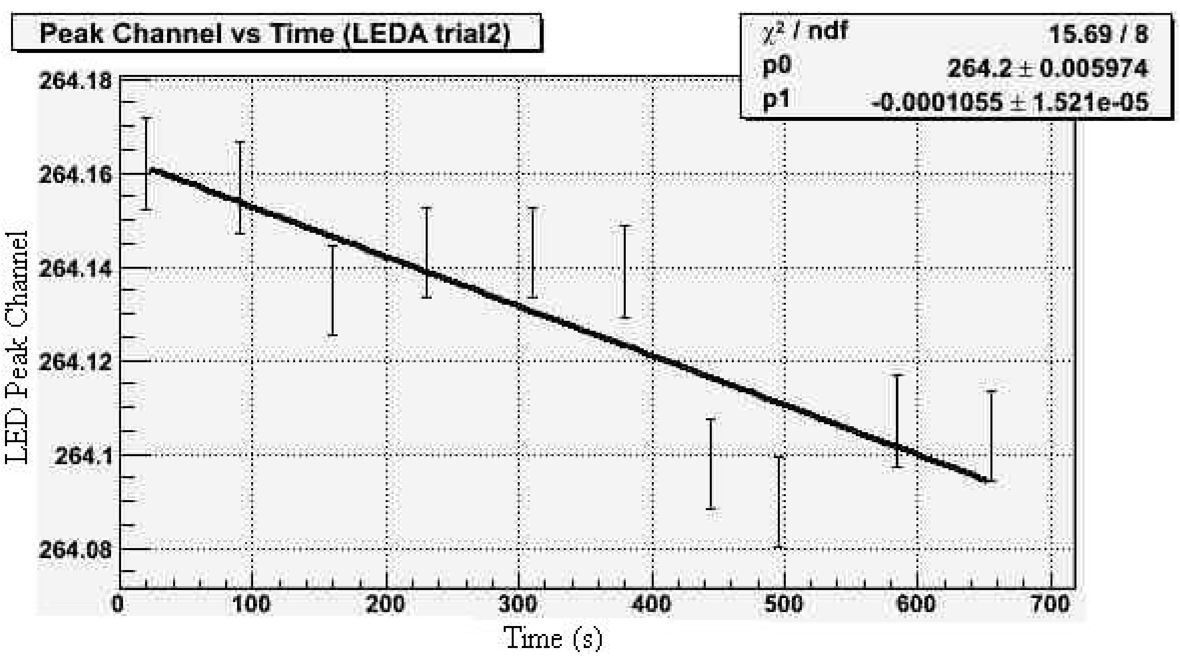

Figure 11: **LED peak vs time. Drift test 2, LED A**

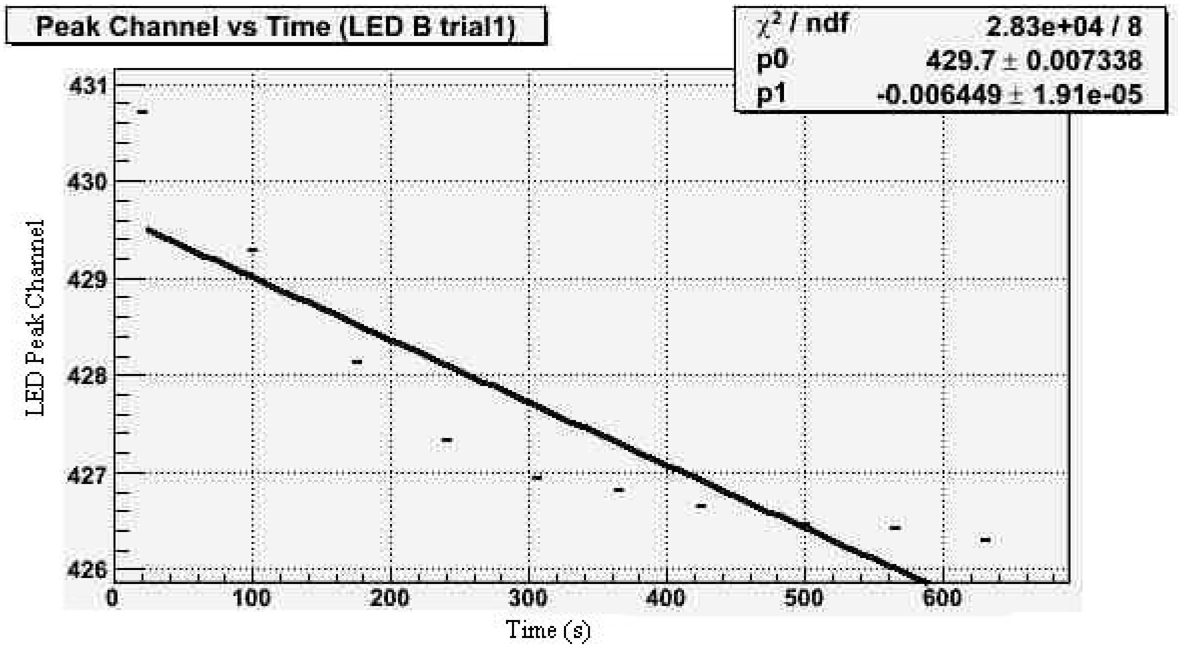

Figure 12: **LED peak vs time. Drift test 1, LED B**

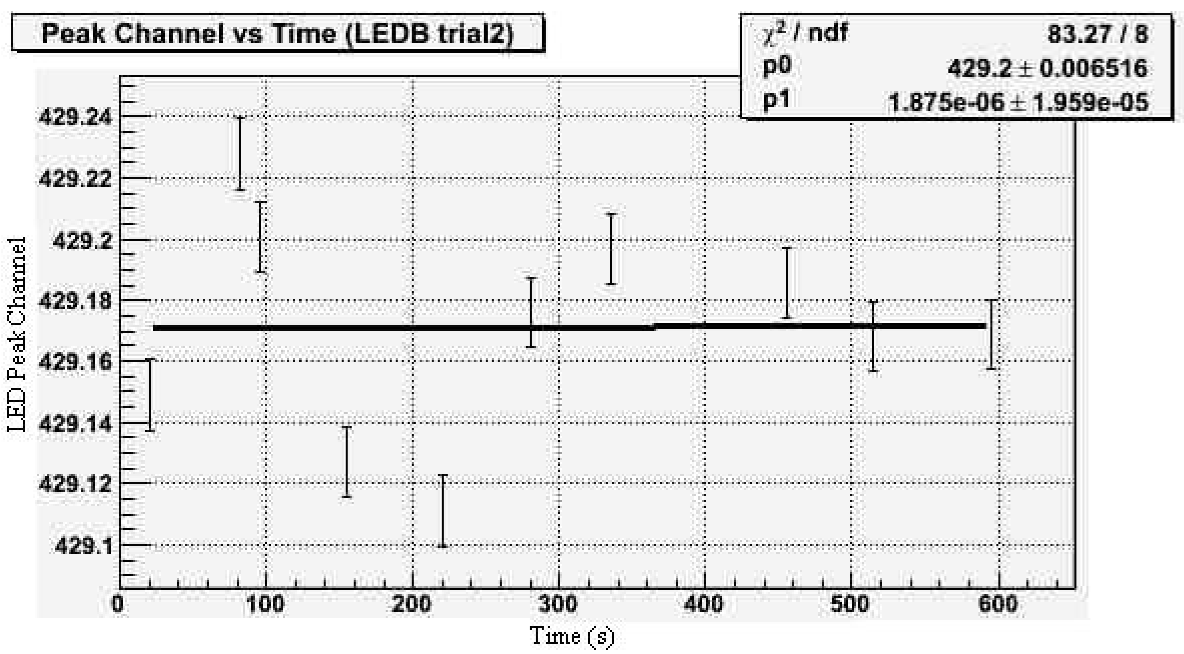

Figure 13: **LED peak vs time. Drift test 2, LED B**

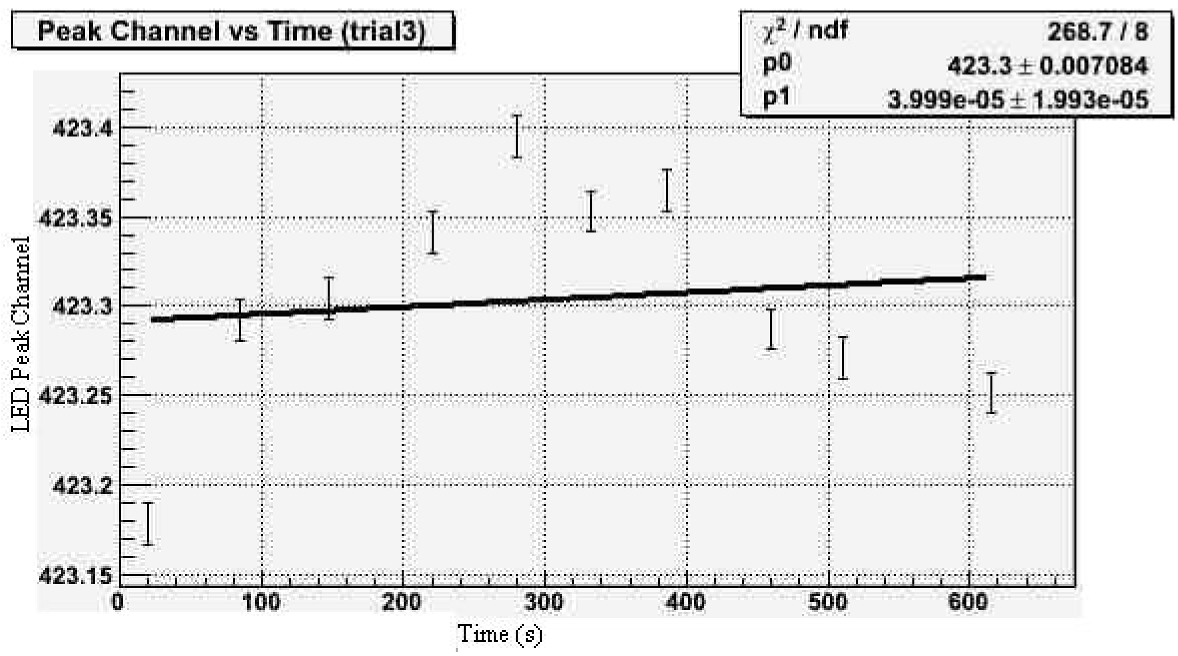

Figure 14: **LED peak vs time. Drift test 3, LED B**