BaBar Note # **000**
October 27, 1998

Comparison of PMT and PD Measurements for BaBar Barrel Calorimeter Crystals

J. M. Bauer
University of Mississippi

Abstract

During the quality control process, the CsI(Tl) crystals of the barrel calorimeter were measured with a photo multiplier tube (PMT) in one of three different light yield scanners. After gluing the photo diodes (PD) on the crystals, the light yield was again measured in another setup suitable for the photo diodes. In this note, the measurements via PMT and via PD are compared, time dependencies identified, the overall error of the measurement discussed, and history of the measurements recorded.

1 Introduction

From August 1996 to April 1998, nearly 6000 CsI(Tl) crystals arrived at SLAC and were prepared for installation in the BaBar barrel calorimeter. This report is focusing on the following elements of the quality control and assembly procedures: The light yield of the crystals was measured with a photo multiplier tube (PMT) equipment shortly after the crystals arrived at SLAC. Once they passed this stage, photo diodes (PD) were glued onto their back end and the light yield measured again. This note is making comparisons of the PMT light yield measurements and the PD light yield measurements to assess the quality and consistencies of the measurements.

2 The Quality Control and Photo Diode Gluing Procedure

The first step in the quality control procedure was the light yield measurement via photo multiplier tubes (PMT). The tube collected the scintillator light created by a radioactive source (^{22}Na or ^{137}Cs), which was moved along the side of the crystal by a stepping motor.

Besides examining the uniformity of the light yield along the crystal length, the scanner also returned an absolute measure of the light output by comparison with the light output of an encapsulated CsI standard crystal (1 inch tall, 1 inch diameter). By being encapsulated, the standard crystal was not able to degrade *e.g.*, due to humidity. All standard crystals were produced by the French company Crismatec to have the same light output.

The amount of light output of a given crystal was then noted as the percentage of the light output of the standard crystal. This percentage usually ranged from 20% to 50%. The crystals were required to have a light yield of at least ~25% to be accepted in the quality control process. If the crystals did not meet the uniformity criteria, they were "tuned" by polishing or roughening up the crystal surfaces at selected places. Also, if the a crystal was too large and polished to the right size, tuning was subsequently necessary.

Scanner 1 was the only scanner ready at the beginning. Scanner 2 joined in soon. In Fall 1997, two more scanners were added. Scanner 3 continuously had problems and was later used as a source of spare parts, while Scanner 4 was functional until the last crystals arrived. No measurements by Scanner 3 were final measurements, and this note therefore only deals with measurements of Scanners 1, 2, and 4. Usually, Scanners 1 and 2 did the initial scans of the crystals, while Scanner 4 was often used for the tuning the crystals.

If passing the quality control criteria, the crystals were passed on for gluing photo diodes (PD) to the rear face of the crystals. Details of this procedure are described in BaBar Note 452[1]. Each crystal received one set of two independent photo diodes. Once the epoxy had cured, the crystals were measured again in another setup. Here scintillation light was created by a radioactive source (^{77}Y) placed on the front face of the crystal. The charge in the photo diodes was then picked up and measured. For each of the two photo diodes, one light yield measurement was obtained. For this analysis, we use the sum of the two photo diode measurements.

3 Difficulties in Comparing PMT and PD Measurements

Many factors were able to influence the outcome of the PMT and PD measurements, but the main reason for discrepancies between the PMT and the PD measurements is considered to be the following: For the PMT measurment, the light from the crystal was collected through the round opening of the photo multiplier tube. White Tyvek covered the remaining part of the back end of the crystal to simulate the reflector plate mentioned below. For the PD measurement, less light is collected since the photo diode had a smaller surface area than the photo tube. The area of the PD is a square, and not round, and around the PD area, a white reflector plate is glued on the crystal to reflect any light back into the crystals.

During the process of gluing the photo diodes onto the crystal, the rear surface of the crystal had to be polished. All this, the quality of the glue joint as well as the exact details of where the photodiode and the surrounding reflector plate was placed on the crystal had an impact on the overall light output. Even if the PMT and the PD measurements would be completely accurate, the two measurements might not agree with each other too well due to changes introduced in the gluing process.

4 The Data for the Analysis

The numbers used in this analysis were all extracted from the Oracle database, into which all final and official results were entered. We may assume that the photodiode measurements carry no error. The measurements were in fact pretty stable. In addition, only one single measurement setup was used for the PD measurement, while three setups were used for the PMT measurement. The numbers carry no correction factors, not for the PMT measurements, but also not for the PD measurements. The PD measurements of the barrel crystals are considered to be overestimates by a factor 1.25, but this overall factor does not have an impact on the conclusions of this report.

This report does not look at the uniformity measurements of the crystals. The correction[1]to the PD measurements based on uniformity measurements of close to 100 crystals therefore is also not of any importance for this report.

Several crystals had their diodes glued on, but were not used in the calorimeter. These crystals were also included for the analysis of this report.

5 Choosing the correct fitting algorithm

The report is looking at the correlation between the PMT and the PD measurements. For each crystal exists therefore a pair of PMT and PD measurements. For this analysis, we choose the PD measurement as x, the PMT measurement as y, and fit to a straight line, $y = A + Bx$. We assume here that the PD measurements have no measurement error associated with, and that the PMT measurements all have the same measurement error. This should be a quite good approximation, since a standard crystal was daily measured with the PD system[1], averaging a light yield of 7400 ± 60 e$^-$/MeV.

Remember that choosing the PMT measurement as x and the PD measurement as y does not lead to the same fitting line as choosing the PMT measurement as y and the PD measurement as x (See [2] Page 203, Problem 8.17). The differece can be considerable, since in the first case, the fit extrapolates to a positive PMT value for PD = 0, in the second case to a negative PMT value for PD = 0.

6 PMT vs. PD

The first three plots (Figure 1) show the PMT measurements plotted with the PD measurements on the horizontal axis. The correlation between the two measurements can clearly be seen. For each of the three sets of data (Scanner 1, Scanner 2, Scanner 4), an independent least square fit was obtained for the function:

$$M_{\mathrm{PMT}} = A + BM_{\mathrm{PD}} \tag{1}$$

Here M_{PMT} is the light yield measured with the PMT (in percent), and M_{PD} is the light yield measured with the photo diodes (in photo electrons per MeV, or pe^-/MeV). All three lines are shown in each of the three figures for easier comparison. The results of the fits are listed in Table 1. Note that none of the fits cross the origin.[1]

Scanner	A (%)	B (% / (pe^-/MeV))
1	9.15	0.00365
2	10.41	0.00401
4	6.86	0.00457

Table 1: Fit results for the least square fit of type $A + xB$ for the three scanners.

7 Deviation from Fit

Next let us plot the difference between the fits and each of the measurements normalized to the fit value. This means that for each crystal, we take the measurement M_{PMT} and M_{PD} as well as the fit values A and B for the given scanner. We first calculate the PMT value estimated from the fit:

$$F_{\mathrm{PMT}} = A + BM_{\mathrm{PD}} \tag{2}$$

and then the quantity:

$$\Delta = \frac{M_{\mathrm{PMT}} - F_{\mathrm{PMT}}}{F_{\mathrm{PMT}}} \tag{3}$$

The quantity Δ is then binned into histograms (Figure 2), and a Gaussian fit over the center region is performed (from -10% to $+10\%$). The standard deviation of the three Gaussians is found to be around 5% (Table 2). The value is slightly lower for Scanner 4, possibly because it was only for a few months in service and therefore did not have as much opportunity to drift as Scanners 1 and 2. (See later.)

The width of 5% tells us that for any given crystal the (PMT,PD) measurement combination has a standard deviation of (relative) 5% to the mean for the given scanner. For a crystal with about 40% light yield (relative to standard crystal), the standard deviation is then in absolute terms around 2%, which gives a range of 38 to 42% light yield (with respect to the standard crystal).

[1] The fits to the Scanner 1 and Scanner 2 data look perhaps not quite correct, but a cross-check revealed, as expected, a minimum at the factors A and B. Also, no points are extremely far away which could have skewed the fit. See also Figure 2.

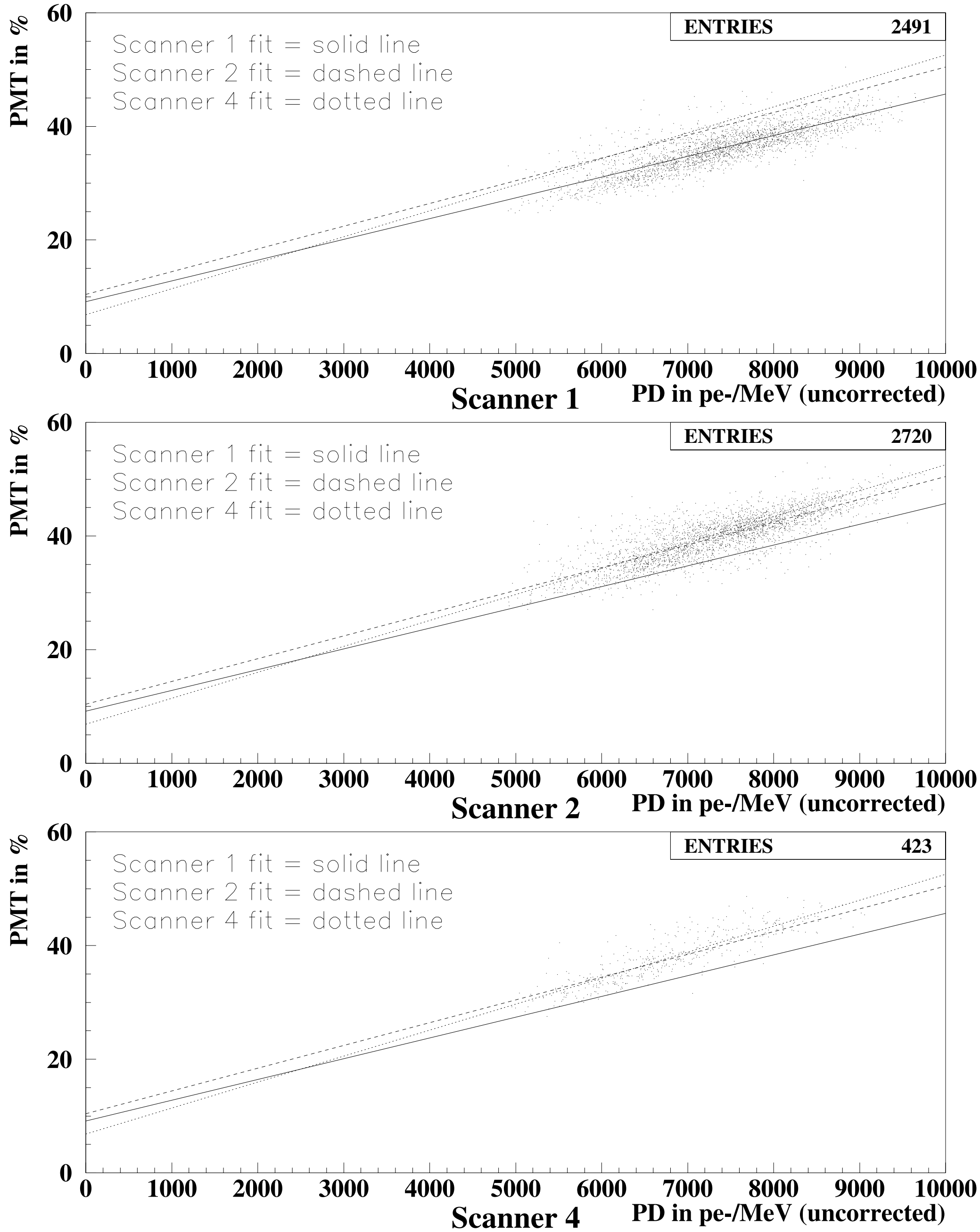

Figure 1: Phototube (PMT) measurements plotted versus their corresponding photodiode (PD) measurements for Scanners 1, 2, and 4. To facilitate comparison, the straight-line fits to the three data sets are shows in all three plots. The parameters of the straight line fits are listed in Table 1.

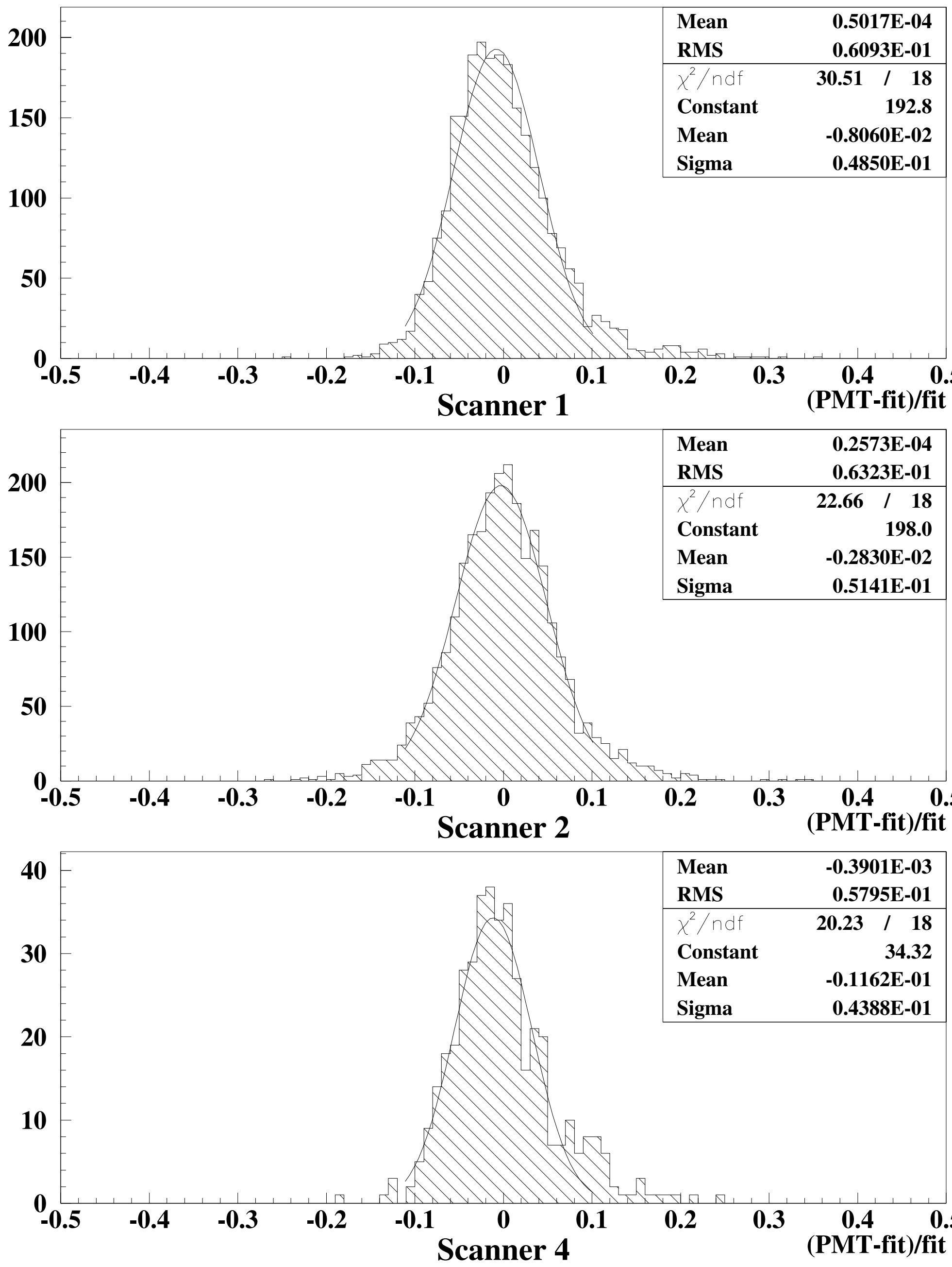

Figure 2: Distributions of $\Delta = (M_{\rm PMT} - F_{\rm PMT})/F_{\rm PMT}$ and results from Gaussian fit to the center of the distribution. No points are outside the shown x-range.

Scanner	σ of fit (%)
1	4.9
2	5.1
4	4.4

Table 2: Standard deviations of the Gaussian fits for Scanner 1, 2, and 4. See Figure 2.

Note that we are looking here at the pair of the PMT and PD measurement. Any change in the crystal during the gluing process can move the PD measurement up or down, which then affects F_{PMT} and Δ.

8 Drifts

Measurements were taken for about 20 months. During this time, changes might have been introduced that systematically might have shifted the measurements. To examine this, we plot the Δ of each crystal versus the days since August 15, 1996. In Figure 3, the plots show the Δ of all crystals measured with a given scanner, using the fit results for the same scanner. No obvious trend can be seen for Scanner 4. Scanner 1 tends to have higher numbers early on, and lower numbers later, while for Scanner 2 the early numbers rather tend to be lower. Note that these numbers are all with respect to the fit of the given scanner, and that we cannot conclude that the numbers are "too high" or "too low" in any absolute terms. Trends are visible, but still small compared to the normal spread of the (PMT,PD) measurement sets.

Since the fits for the three scanners noticeably differ, it is of interest to repeat the same plots using the fit result of one single scanner. Since Scanner 4 seemed to agree more with Scanner 2 than with Scanner 1, we select the fit result of Scanner 2. The plots are shown in Figure 4. One clearly sees how much lower the results of Scanner 1 are. The plots also seem to indicate that initially Scanner 1 and Scanner 2 gave in the average identical results, and that later Scanner 2's results rose in the average.

Does the trend depend on the light output? To answer this question, the data sets for each scanner were split into three equal-sized parts and plotted versus time (Figure 5). The exact limits within the data sets are listed in the figure description. From looking at the plots, we can conclude that there is no obvious difference in the trend between the high, medium, and low PD measurements. Only the scatter is larger for the low PD measurements than for the other parts.

9 The Scanner 1/Scanner 2 Discrepancy

When Scanner 2 was installed, its results were compared with Scanner 1's results. An entry in the log book from December 1996 indicates that the comparison between Scanner 1 and Scanner 2 via measurements of a prototype crystal resulted in a light yield of 29.57% for Scanner 1 and 28.24% for Scanner 2. Note that here (with statistics of one measurement) the Scanner 1 result is higher than the Scanner 2 result.

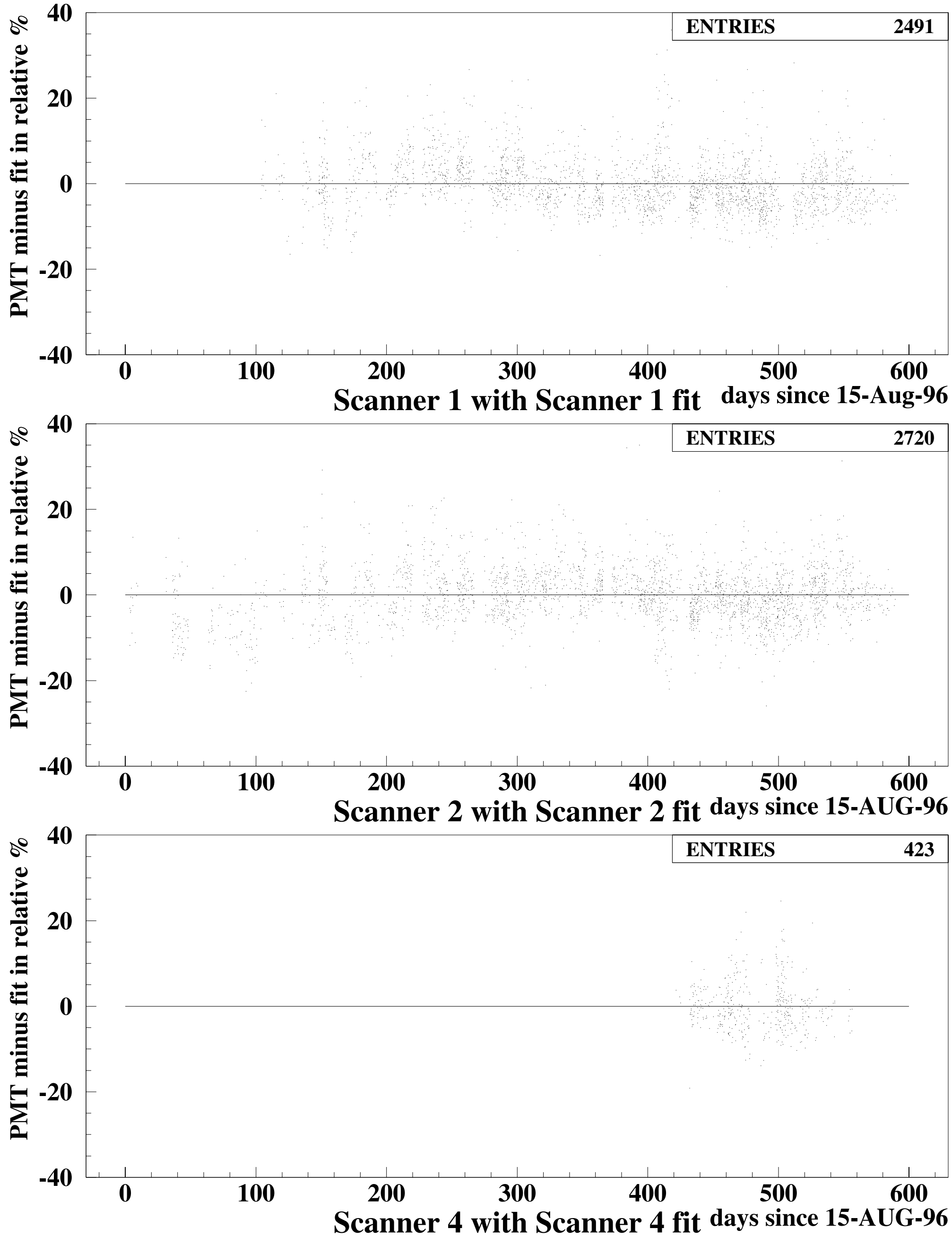

Figure 3: Trend of $\Delta = (M_{\rm PMT} - F_{\rm PMT})/F_{\rm PMT}$ over time. The time is given in days starting August 15, 1996.

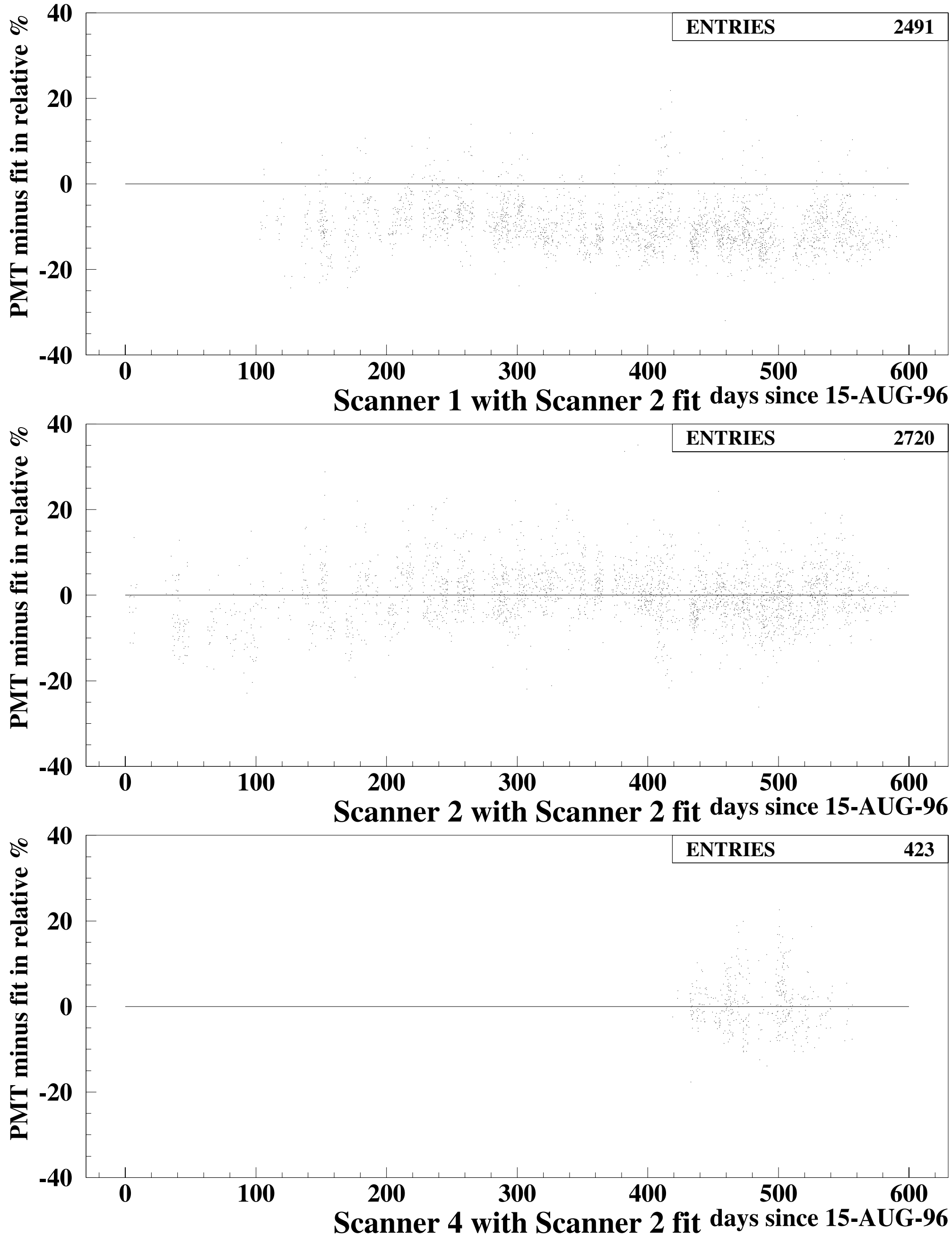

Figure 4: Trend of $\Delta = (M_{\mathrm{PMT}} - F_{\mathrm{PMT}})/F_{\mathrm{PMT}}$ over time. The time is given in days starting August 15, 1996. For the plots in this figure, F_{PMT} was always calculated with the fit parameters from Scanner 2, even for measurements in Scanner 1 or Scanner 4.

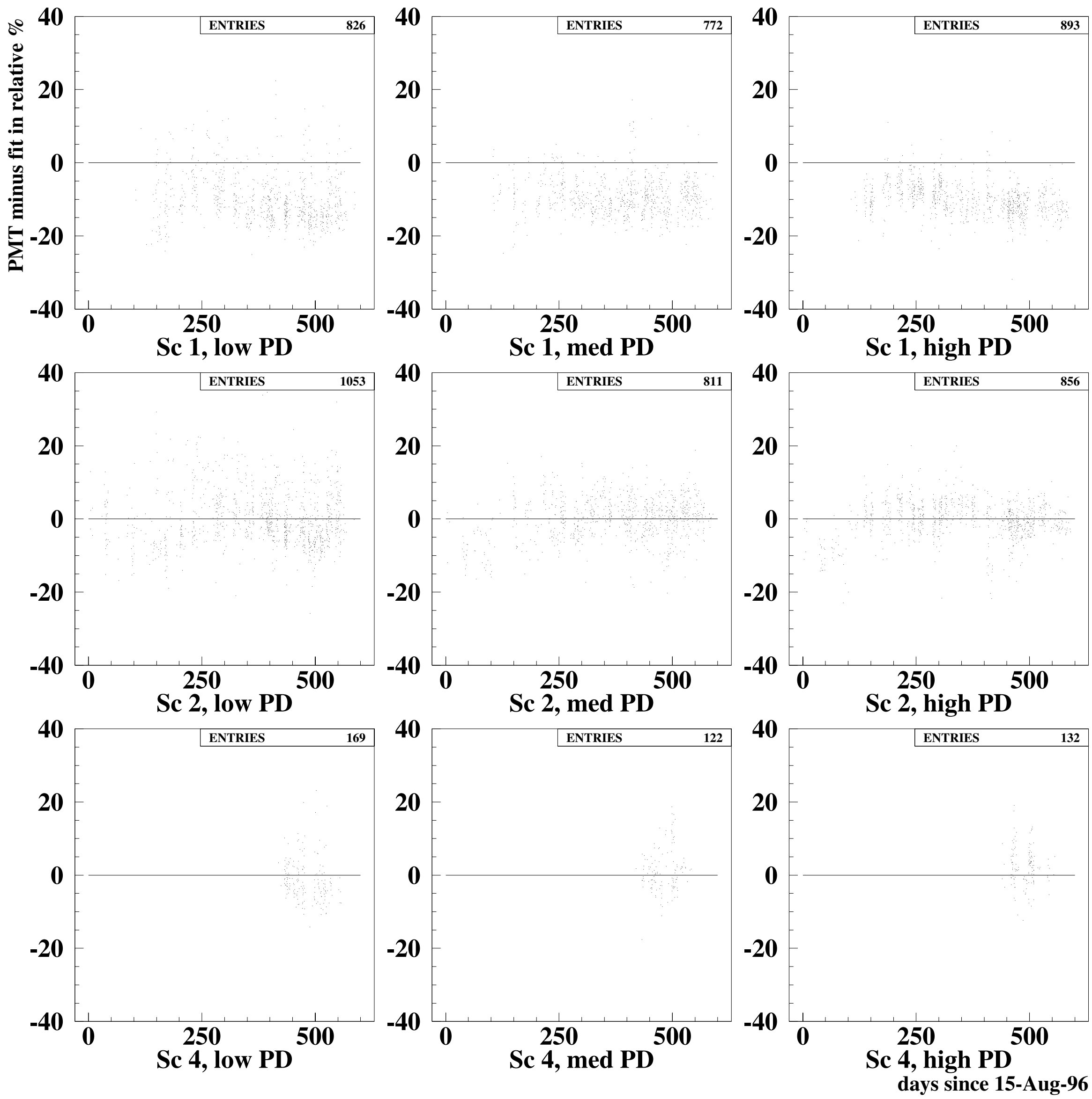

Figure 5: Like Figure 4, trend of $\Delta = (M_{\mathrm{PMT}} - F_{\mathrm{PMT}})/F_{\mathrm{PMT}}$ over time for different scanners. This time, however, the data sets are split into different PD light yield ranges. For this plot, each scanner's data set was divided into three roughly equal-sized parts. The borders for Scanner 1 are at 7000 and 7700 pe^{-}/MeV, for Scanner 2 at 7100 and 7800 pe^{-}/MeV, and for Scanner 4 at 6500 and 7200 pe^{-}/MeV.

The existence of a discrepancy between measurements in Scanner 1 and Scanner 2 was known at least by March 1997. Some effort was made to understand its origin, but any check short of exchanging photo multiplier tubes was negative. The result of such a check performed July 14, 1997 is listed in Table 3. Here two crystals, BCAL 2115 and BCAL 2116, were measured in both Scanner 1 and Scanner 2. The two standards with serial numbers 3367 (usually used in Scanner 1) and 7380 (usually used in Scanner 2) were also measured in both scanners. Crystal BCAL 2116 was measured twice in Scanner 1 and once in Scanner 2, while crystal BCAL 2115 was measured once in Scanner 1 and twice in Scanner 2. As one can see, using different standards or different crystals made no difference to the fact that Scanner 2 resulted in a light yield 15% (relative) higher than in Scanner 1.[2]

Scanner	Standard	LY in % BCAL 2115		LY in % BCAL 2116	
1	3367	34.07		35.35	35.52
1	7380	34.47		35.77	35.94
2	3367	40.16	39.85	42.15	
2	7380	39.61	39.30	41.58	

Table 3: Result of PMT measurements of two crystals in Scanner 1 and Scanner 2 with interchange of the two standards of serial numbers 3367 and 7380. This set of measurements demonstrates that the higher results in Scanner 2 are not due to the standards or the crystals, but are due to some property of the scanners. The measurements are from July 14, 1997.

Another check was done September 28, 1997 with crystal BCAL 2223 (Table 4). Here Scanner 2's results are again higher by 5.5% absolute or 15% relative. The previous light yield for the crystal was 37.10% with respect to the standard crystal measured in Scanner 1 on July 25, 1997, which means that the light yield as measured in Scanner 1 went down by about 1.3% absolute or 3.5% relative.

Scanner	Standard	LY in % BCAL 2223
1	3367	35.80
1	7380	35.84
2	3367	41.42
2	7380	41.30

Table 4: Another result of PMT measurements of crystal BCAL 2223 in Scanner 1 and Scanner 2 with interchange of the two standards of serial numbers 3367 and 7380. The measurements are from September 28, 1997.

[2]Table 3 also provides some estimate for the consistency of the PMT measurements itself. Repeating the same measurement of a crystal again, leads to results of about $\pm 0.5\%$ in absolute light yield, or less than 2% relative. This, of course, does not imply anything about a repeat of the same measurement at another day.

The last documented check was done with a crystal provided by Hilger (Vendor ID 120B). This crystal was later returned to Hilger. The crystal was measured in both Scanner 1 and Scanner 2 beginning of November 1997. Crystal standard 3367 was used in Scanner 1, and crystals standard 7380 in Scanner 2. In Scanner 1, the crystal gave a light yield of 31.61%, in Scanner 2 of 38.59%. This is a 7% absolute difference, and about 20% relative change.

From Tables 3 and 4 it is clear that the discrepancy was not caused by the crystals themselves or the crystal standards. Since it was considered more important to keep the scanners in working and stable condition, the photo tubes were not exchanged.

It is possible that the photo tube of one or more of the scanners exhibits non-linearity. The standard crystal usually resulted in ADC counts around 600, while a normal crystal (with 20% to 50% of the standard crystal output) only showed ADC counts around 120 to 300. What if the phototube's response were non-linear, for example lower by 10% below 300 ADC counts, while normal around 600 ADC counts? Then the ADC counts for normal crystals would be 111 to 270. This would give a light yield of 18.5% to 45% with respect to the standard instead of 20% to 50%.

Scanner 1 did not have an automatic high-voltage shut-off on accidental opening of the door to the scanner. Scanner 2, on the other hand, had such an automatic shutoff installed, making it virtually impossible to run the tube at high voltage with open door. It might be possible that once or more often the door of Scanner 1 was opened with the high voltage still applied, and that this might have damaged the photo tube. No sharp drop is, however, seen in Figure 3 or Figure 4 which could indicate when such an accident might have occurred.

Compared to the results of Scanners 1 and 2, Scanner 4's results were found to be even higher during the crystal quality control process, although not as far from Scanner 2 as Scanner 2 was from Scanner 1. Figures 1, 3, or 4 do not show this difference clearly. Unfortunately, dedicated scanner-by-scanner comparisons are not available for Scanner 4.

10 Conclusion

By comparing the photo tube and the photo diode measurements for the crystals, we obtain an estimate of how well these two measurements agree. For each scanner alone, we find a standard deviation of about 5% relative. This value is affected by the internal consistency of the PMT measurements ("How much do repeated measurements of the same crystal on the same scanner differ?") and of the PD measurements ("How much do repeated PD measurements of the same crystal differ?"). It also depends on the changes to the actual light output due to the gluing process: "How much does the gluing process push the light yield randomly up or down?" Note the word "randomly". Any systematic shift would be taken care by the fit parameters A and B and would go into the inter-calibration of the PMT and PD measurements.

Scanner 1 tends to have lower results than Scanner 2, as already observed during the time of quality control. Trends are noticeable over time, but small compared to the overall deviation. The discrepancy between Scanner 4 compared to Scanner 2, which was observed during the measurement period, is not noticeable in Figure 3 or 4.

The PMT measurements of the overall light output were important for the acceptance or rejection of the crystals after their arrival at SLAC. Currently, their accuracy is not as important. The calibration of the detector will start with the PD measurements, which better represents the current condition of the crystals in the calorimeter. The uniformity of each crystal was measured with the PMT measurement and is expected to be used during the analysis of the data, but all uniformity results are normalized to 1, making the absolute light output of the crystal unimportant. No noticeable difference in the measurement of the uniformity was observed between any of the scanners.

11 Acknowledgments

Thanks to the Bill Wisniewski, Giuliana Manzin, and Paul Va'vra for reading the manuscript and providing input from their own experiences during the crystal quality control process. And of course thanks to them and all the other members of the crystal quality control group and the crystal gluing group under Jens Brose for working over a period of nearly 600 days on all the measurements of the crystals.

References

[1] J. Brose *et al.*, *The Performance of the Photodiode Readout of the Barrel Calorimenter Crystals*, BaBar Note 452).

[2] J.R. Taylor, *An Introduction to Error Analysis*, 2nd edition (University Science Books, Sausalito, CA, 1997).