

CALIBRATION OF PHOTOMULTIPLIER TUBES IN THE HIRES EXPERIMENT

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1. INTRODUCTION

Approximately 40,000 Photomultiplier tubes (PMTs) are used in the HiRes experiment (Bird et al 1993). They measure the fluorescent light produced in the atmosphere by extended air showers of high energy cosmic rays and gamma rays. The shower profiles are then derived from the signals of the PMTs. (Baltrusaitis R. M. et al, 1985) The wavelength of the detected fluorescent light ranges from 300 to 400 nm. It is important to know the absolute anode sensitivities of the PMTs at these wavelengths for the applied voltages. In order to better understand the performance of HiRes, one also wants to measure other properties of PMTs such as cathode quantum efficiency as a function of frequency, dark current and spatial variation of sensitivity across the face of the tubes. We need to perform these measurements with an accuracy of a few percent. Furthermore, since the number of tubes involved is very large one full HiRes site employs more than ten thousand tubes the PMT calibration set up needs to be automated to a large degree so that tubes can be processed efficiently.

In this paper, we describe such a PMT,-testing facility (Zhu, 1992) that we developed at the University of Utah. It has been operated to test and to calibrate all 4000 PMTs used in the HiRes prototype at the rate about 300 tubes per week.

2. APPROACH

Our approach to PMT testing has the following features.

(1) *Multiple monochromatic UV sources*: Instead of using a monochromator to select wavelengths, we use an Argon laser (351 or 364nm) and a He/Cd laser (325 nm) as our UV sources. These sources provide monochromatic wavelengths. Multiple sources also permit cross checks for systematic errors.

(2) *DC measurements*: Continuous light sources are used to produce do signals from cathodes and anodes. This allows us to use simple shutters, amplifiers, ADCs and photodiode monitors without worrying about their timing and frequency responses. Each measurement is obtained by taking the average of a series of "light on/light off" measurements. Any drifts in the light intensity, residual background light level or amplifier baseline will not affect the measurements, provided that the time scale of the drifts is either longer than the "light on/light off" time or shorter than the individual sampling time. The variance within each series of measurements provides a quantitative estimate of the random errors, which can be minimized by taking many data samples.

(3) *Photodiodes as the secondary standard*: It has been found that silicon diodes respond linearly to do light signals for a large range of light intensity (Eppledauer and Hardis, 1991). Therefore they can operate at very low light intensities as required for

PMT calibrations, as well as at higher light intensities when they are calibrated with thermal pile detectors. The thermal pile detectors themselves are readily calibrated with an electric current. Each PMT calibration is accompanied by a simultaneous measurement with a photodiode looking at the same light source. Comparison of the PMT cathode or anode outputs with the outputs of the monitoring photodiode provides the absolute PMT sensitivity.

3. APPARATUS

The layout of the PMT test facility is shown schematically in Figure 1. Most components are enclosed in a light-tight metal box built on an anodized aluminum table top of about 8' x 3'. The lasers are mounted outside the box for ease of access. Area A in Figure 1 is where PMTs are placed to calibrate their overall anode sensitivity and cathode quantum efficiency. Four tubes are tested in one batch using a light diffuser. Area B is for scanning the face of a PMT with a laser beam to measure the spatial non-uniformity of gains and quantum efficiencies.

Electronic shutters and optical elements such as dielectric mirrors, quartz plates and neutral density filters are used to attenuate the light, to switch light sources, and to split the light beam. The dark box is partitioned and baffled to reduce stray light.

In our setup, PMT and photodiode output can be measured either with commercial nano-voltmeters or pico-ammeters, which communicate to the computer through a IEEE488 interface. Alternatively, they can be converted to voltages to be measured with a 16 bit analog to digital converter in the computer. The computer also controls the X-Y scanning platform, the electronic shutters, a high voltage supply and the high voltage relays which are required for switching between anode and cathode measurements.

4. RESULTS

The HiRes PMT calibration facility performs well as expected. Figure 2 shows the quantum efficiencies of 6 tubes made by EMI Thorn. The data denoted by crosses are the manufacturer's measurements made at 337nm. They are consistent with our own measurements at 351 and 325 nm, denoted respectively by diamonds and squares. One-sigma error bars are shown for our measurements. Figure 3 shows a scan of the spatial uniformity of the quantum efficiency of a 1.5 inch hexagonal PMT used in HiRes.

We have also compared our PMT calibration with other measurements. For instance, one can obtain the sensitivity of a PMT by measuring the variance of low level signals. We used an LED to produce variable light pulses of low intensity. The PMT signal S in pico-coulombs is given by $S = kN\bar{a}$, where k is the anode sensitivity and $N\bar{a}$ is the number of incident photons. The signal variance ΔS^2 is given by $\Delta S^2 = \sigma_{\text{pmt}}^2 + \sigma_I^2$; the first term is caused by the counting statistics of electrons emitted by the cathode and the dynodes, and the second term includes all other contributions such as electronic noise and LED stability. The first term can be written as

$$\sigma_{\text{pmt}}^2 = k^2(1 + \bar{a}^2)N\bar{a} / \bar{a} = Sk(1 + \bar{a}^2) / \bar{a},$$

where \bar{a} is the quantum efficiency and n is gain / gain of the PMT (\bar{a} is about 0.46 for a 8-stage PMT at a gain of 10^5). Therefore, plotting ΔS^2 versus S should yield a straight line with σ_I^2 as the intercept and $k(1 + \bar{a}^2) / \bar{a}$ as the slope. This value of the slope can be compared with results made by the calibration facility. Figure 4 shows the data of ΔS^2 versus S for a PMT demonstrating the linear relation. The slope from the best fit is 1.03 times the value predicted with independent measurements of k , \bar{a} and \bar{a} . This excellent agreement between two entirely different methods supports our confidence in the accuracy of the PMT calibration.

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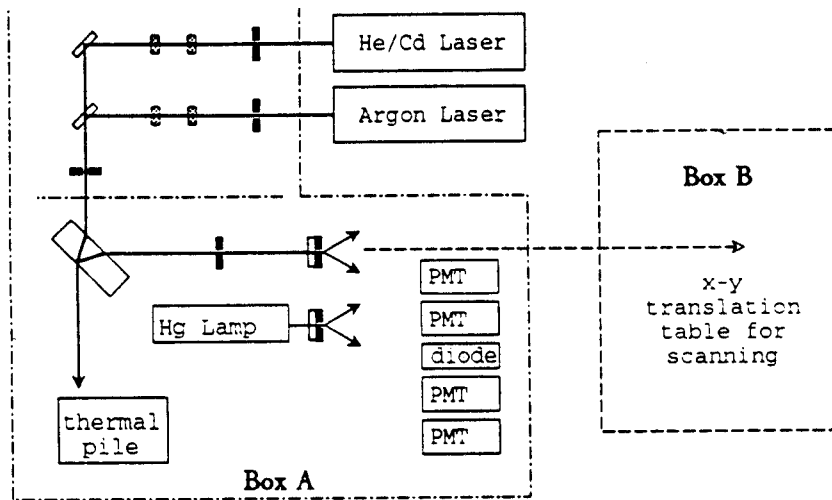


Figure 1. Schematic of the HiRes PMT calibration facility.

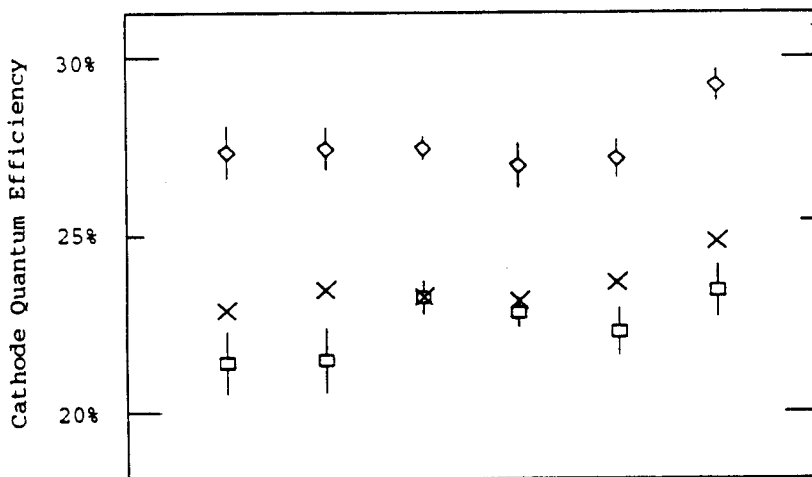


Figure 2. Comparison of our quantum efficiency measurements at 325 nm (squares) and 340 nm (diamonds) with the measurements made by the PMT manufacturer @a 340 nm (crosses) for six PMTs.

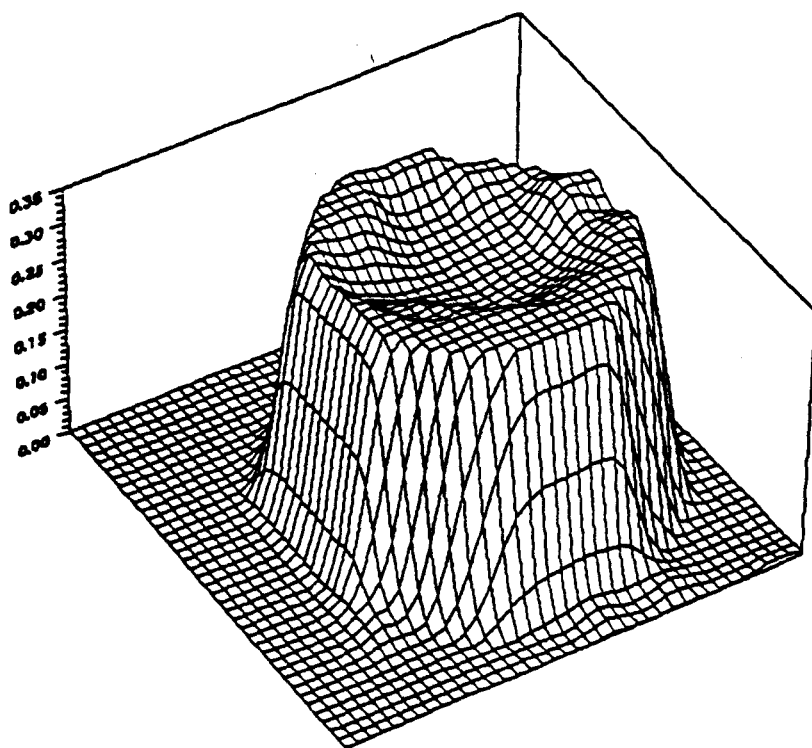


Figure 3. Spatial Map of the quantum efficiency (the Z axis) of a hexagonal PMT, about 40mm in diameter.

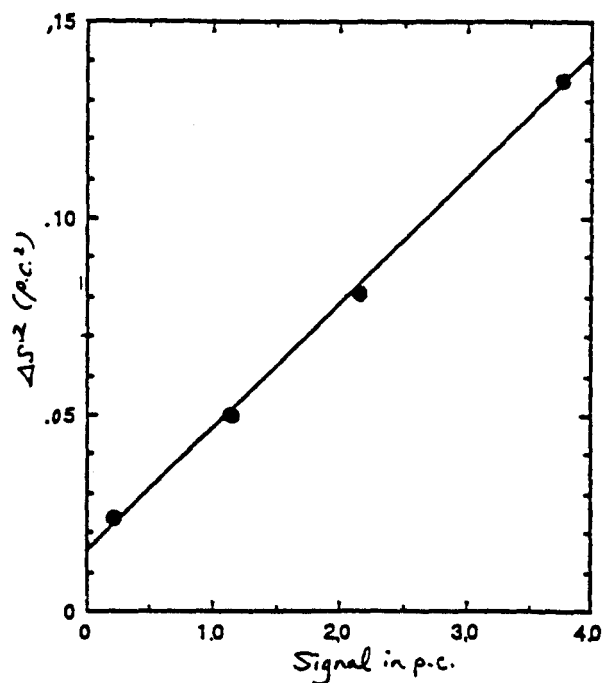


Figure 4. The plot of the variance ΔS^2 vs. signal S for a PMT. It shows the dependence on counting statistics and provides a way to determine the PMT's sensitivity.