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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

The calibration of the absolute sensitivity of photomultiplier tubes in the High Resolution Fly's Eye Detector

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The High Resolution Fly's Eye Experiment (HiRes) measures cosmic rays from 10^{17} eV to beyond 10^{20} eV by the atmospheric fluorescence light produced in their cascade showers. The light is detected with photomultiplier tubes (PMTs). The full HiRes project proposes to use about 30000 PMTs in two sites. More than four thousand tubes are already in operation. Accurate calibrations of the absolute sensitivity of the PMTs are essential to this experiment. We have developed at the University of Utah a facility to calibrate the absolute gain and quantum efficiency of the tubes to the accuracy of better than three percent. This facility has proved to be capable of testing a large number of photomultiplier tubes efficiently and economically. In addition, it can be used to map the gain and the quantum efficiency of a PMT as a function of where the incident photons hit the tube's window. Although this facility is developed for HiRes, it is applicable to other experiments that utilise PMTs. We shall describe in this report the operation principles, the apparatus and some typical results.

1. Introduction

The High Resolution Fly's Eye (HiRes) Experiment [1,2], which is under construction in Dugway Utah, USA is a collaboration of the University of Adelaide, Columbia University, the University of Illinois and the University of Utah. It is a second generation Fly's Eye type detector. This detector measures the fluorescence light in the atmosphere produced by extensive air showers of cosmic rays and gamma rays [3]. The fluorescence light is collected and focused by mirrors onto clusters of PMTs in the mirror's image planes. If one knows the number of photons received by individual PMTs, one can reconstruct the longitudinal profile of a shower. The shower profile in turn gives information about the identity and energy of the primary particle. The original Fly's Eyes have been successful in measuring the energy spectrum and composition of cosmic rays up to 10^{19} eV [4,5]. The highest energy event detected is at $\sim 3 \times 10^{20}$ eV. However, much larger aperture is required to study the energy region above 10^{19} eV. This energy region is most interesting because the cosmic rays at these energies will interact with the microwave background to produce a cut-off in the energy spectrum. The cut-off energy depends on the distance traversed by the cosmic rays. The HiRes experiment is designed to have more than 200 times the aperture of the original Fly's Eyes for events above 10^{19} eV. The full HiRes project consists of 112 detector units located at two sites separated by 13 km. Each detector unit is made up of a mirror (diameter ≈ focal length = 2 m) viewed by a detector cluster of 256 PMTs. Each PMT [#1] has a 1 degree by 1 degree field of view of the sky. A prototype consisting of 14 mirrors has been built and has been in operation for about two years. The next stage currently under construction consists of 56 mirrors.

For most high energy experiments, it is sufficient to measure the relative PMT gain in order to set high voltages and match gains. However, for the HiRes experiment, it is necessary to measure the absolute sensitivities. The data analysis requires us to know the absolute PMT sensitivity in units of pico coulombs per incident photon. Systematic errors in the PMT calibration would propagate proportionally to the systematic error in the derived energy of the primary particle. Similarly, uncertainties in the PMT

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[#1] 40 mm diameter, hexagonal face. Philips type XP3062/FL or Thorn EMI type 9974KAFL.

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sensitivity would directly affect the energy resolution. Since the characteristics of PMTs vary significantly even among tubes of the same type from the same manufacturer, calibrations are necessary. The calibrations include the cathode quantum efficiency, the gain as a function of frequency and applied voltages, the dark current, the linearity of response, the spatial variation of quantum efficiency and gain, and the variability with temperature.

The need for a laboratory setup to calibrate HiRes PMTs is underscored by the fact that there is no built-in, in situ calibration in the HiRes experiment. In many high energy physics experiments the PMTs can be calibrated with singly charged, minimum-ionising particles in the scintillators. There is no such intrinsic calibration in the atmospheric fluorescence experiments. It is also not practical to use the single photoelectron signal for PMT calibration in HiRes. The HiRes tubes are run at low gains so that the sky background does not produce a large dc anode current. The gain is set to about one ADC count per 3 photoelectrons. We would need a hundred times more gain to measure the single photoelectron peak accurately. Moreover, the single photoelectron peak only measures the gain of the dynodes but it does not measure the overall tube sensitivity, which includes the cathode efficiency.

It is also important for imaging experiments such as HiRes to select PMTs with uniform sensitivity across the face of the tube. Any significant non-uniformity would distort the image and degrade the resolution. It is not uncommon to find a PMT whose gain is non-uniform and asymmetric at a level of more than 30%. The structure of the first dynode is usually the major factor. If ultraviolet light is used, the thickness of the window also plays an important role. Our capability to perform two dimensional scans of gain and quantum efficiency helps us to select PMT designs with less than 10% non-uniformity.

After the PMTs are tested for their absolute sensitivities, they are installed to the detectors in the field. There we expect that the gain may change with time due to effects such as ageing, variation of temperature and supplied voltages. Therefore we have installed in the field a system to monitor the relative gain changes. The monitor system consists of a central YAG pulse laser (355 nm) and quartz optical fibres that distribute each light pulse simultaneously to all PMTs and to photodiodes which monitor the laser intensity. The relative response of each PMT is measured at each run with the YAG light pulses and with the detectors' data acquisition system. The data, normalised to the laser intensity, allow us to make corrections to account for the gain changes relative to the prior calibration. The performance of the monitor system has been reported in the 23rd International Cosmic Ray Conference and it will be described in detail in our paper to be submitted on the subject of field calibration of HiRes.

In this report, we describe our PMT-testing facility [6] used to test all 4000 PMTs in the HiRes prototype detector. First, we discuss the technical approach of our setup. Then we describe the apparatus and illustrate its performance with some typical results.

2. Description of the PMT calibration system

2.1. Technical approach

Our calibration system exposes the PMTs to continuous laser light and compares their responses with those of accurately calibrated silicon photodiodes. This approach leads to a calibration system that is very stable, easy to set up and easy to operate. The following describes some of its main features.

Multiple monochromatic UV sources: The sensitivity of PMTs depends on the wavelength, especially near the UV region where the absorption of the glass window becomes important. We use an argon laser and a He/Cd laser to provide monochromatic sources of light at 325, 351, and 364 nms. The wavelengths are chosen to match the nitrogen fluorescence and the window of the UV-pass filter used in the HiRes experiment. The lasers also provide well-defined beams for the spatial scan.

DC measurements: Continuous light sources are used to produce dc signals from cathodes and anodes. This allows us to use simple shutters, amplifiers, ADCs and photodiode monitors without having to worry 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 minimised by taking many data samples.

The illumination a PMT with a continuous light source is similar to the illumination with pulses at a high rate. In both cases, caution must be taken to keep the average current across the electrodes small compared with the standing current in the resistor chain. This sets an upper limit on the source intensity of our setup. The typical light intensity we use is around 10 photons/cm^2/μs. For the PMT diameter of 40 mm and at a gain of 2×10^5, the typical PMT anode current is about 1 μA. This anode current produces 5 mV across a 5 kΩ resistor. It is big enough to be measured accurately but still small compared with the typical 200 μA in the resistor chain of the HiRes tubes.

Another concern about continuous light sources is the effect of space charge. If the space charge near an electrode is too large, it may significantly decrease the electric field and thus lower the gain. In our tests the current from the last dynode is about 1 μA. Assuming conservatively that the transit time between electrodes is about 4 ns, the

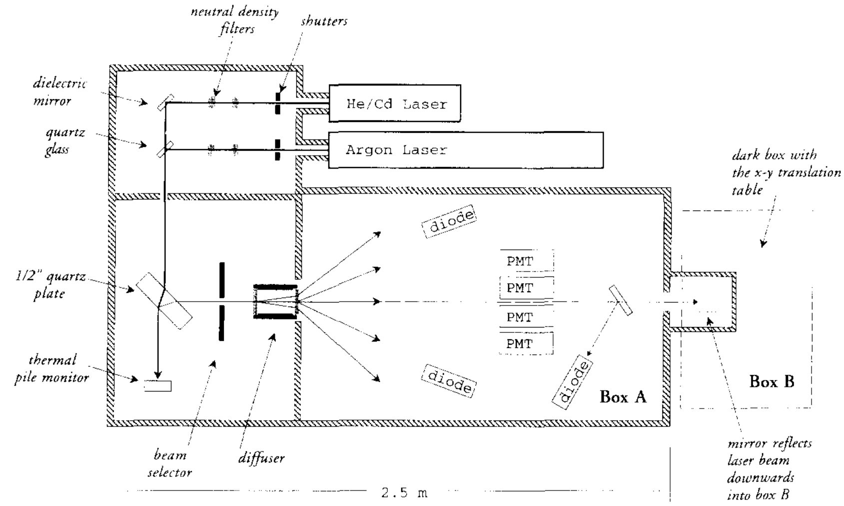

Fig. 1. Schematic view of the PMT calibration setup. The shaded boundaries indicate the walls of a dark box (box-A). The diffuser and the PMTs in box-A are removed when box-B, denoted by the dashed lines, is used for two-dimensional scanning.

total charge Q near the last dynode is about 4×10^{-15} C. The effect of this space charge can be estimated with Poisson's equation for ΔE, the change in the electric field:

$$\Delta E = \int \frac{4\pi\rho}{\varepsilon_0} \, \mathrm{d}l \approx \int \frac{4\pi}{\varepsilon_0} \frac{Q}{LA} \, \mathrm{d}l \approx \frac{4\pi}{\varepsilon_0} \frac{Q}{A},$$

where A is the area of an electrode and L is the characteristic thickness of the space charge. Since the area A is about 1 cm^2 and $\varepsilon_0 = 8.9 \times 10^{-10}$ F/cm, we get $\Delta E = 1.4 \times 10^{-5}$ V/cm. This is much smaller than the typical electric field of 100 V/cm between electrodes. Therefore, the space charge caused by 1 μA of anode current is insignificant and does not affect the amplification of the PMT.

In the cathode quantum efficiency measurements, there is no problem with space charge or high voltage sagging because we measure only the cathode current with no electron multiplication at the PMT. We have therefore increase the light intensity by a factor of 10 to improve the signal to noise ratio in quantum efficiency tests.

Photodiodes as the secondary standard: Silicon photodiodes are very stable light detectors. Their disadvantage compared with PMTs are their small detector area and the lack of amplification, which makes them impractical to use to measure light pulses of very low intensity. However, with continuous light sources it becomes possible to use silicon photodiodes with high gain amplifiers. It has been shown that photodiodes respond linearly to dc light signals for a large range of light intensity [7]. Photodiodes can be used at low dc light intensities as in our PMT calibrations, as well as at higher light intensities when they can be easily calibrated. We have sent four photodiodes, assembled with the amplifiers and power supply, to the National Institute of Standards and Technology (NIST, formerly NBS) to be calibrated. We then use them as standards to calibrate the PMTs. Each PMT calibration is accompanied by a simultaneous measurement of a photodiode looking at the same diffuse light source. Comparison of the PMT signal with that of the monitoring photodiode yields the absolute PMT sensitivity.

2.2. Apparatus

2.2.1. Light source and optics

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 a 2.5 m × 1 m × 0.5 m anodised aluminium table top. Box A in Fig. 1 is where the PMTs are placed to calibrate their overall anode sensitivity and cathode quantum efficiency. Box B is for scanning the face of a PMT with a laser beam to measure the spatial uniformity of gain and quantum efficiency. The dark box is partitioned and baffled to reduce stray light. We currently use as light sources a He/Cd laser [#2] and an Argon [#3]. The lasers are mounted outside the box for ease of access. In the first chamber, shutters, dielectric mirrors, quartz plates and neutral density filters are used to select and to attenuate the light beam. In the second chamber, the laser beam is split by a half inch thick quartz plate. The transmitted beam goes to a thermal pile detector [#4] for monitoring. One of the reflected beams from the quartz plate is selected with a collimator. A light diffuser, which is made of two pieces of Teflon separated by 5 cm, produces uniform illumination in the next chamber where

[#2] Omnichrome 356XM
[#3] Coherent Innova 90
[#4] series 310, Gentec USA.

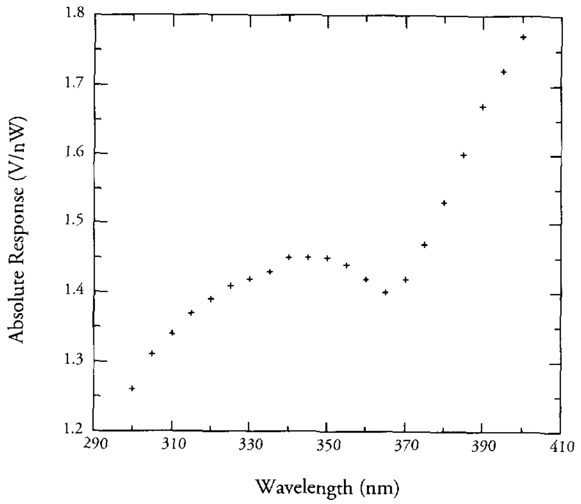

Fig. 2. The absolute light sensitivity as a function of wavelength of one of the silicon photodiode monitors. These data are measured by National Institute of Standards and Technology.

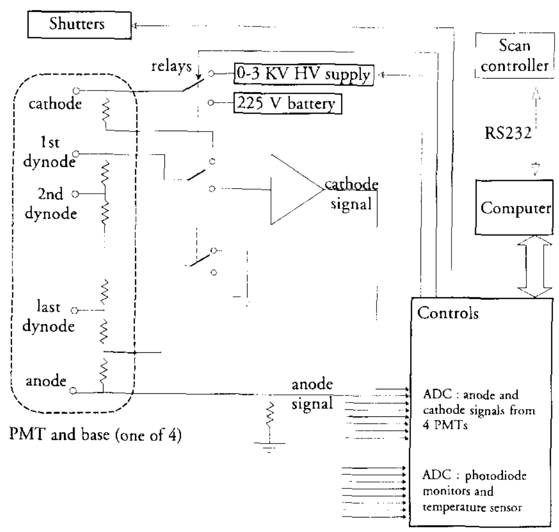

Fig. 3. Block diagram of the control and data acquisition system.

four PMTs are located for testing. Photodiodes mounted at fixed locations monitor the intensity as well as the uniformity of the diffuse light. When we use the scanner in a separate dark Box B, the diffuser is removed and the beam is reflected by a mirror downward into Box B.

2.2.2. Photodiode monitors

The signal from each silicon photodiode [#5] monitor is amplified by a transimpedance amplifier [#6] with a gain of 1 GV per ampere. The output is a few mv for the typical light intensity used. Four of our photodiodes and circuits have been calibrated by the National Institute of Standards and Technology [#7]. This calibration is based on their 100% quantum efficient silicon detectors [8,9]. The three sigma uncertainty is ±1.0%. Fig. 2 shows the spectral response of one of the diodes measured by NIST.

2.2.3. PMT circuit

Four PMTs are measured simultaneously in one batch. The schematic connection to each PMT is shown in Fig. 3. High voltage relays are used to switch between measurements of anode current and cathode current. For the anode tests, the positions of the relays are as shown in Fig. 3. A negative high voltage set by the computer is applied to the cathodes of the PMTs. This high voltage goes through the resistor chain bases. The anode is grounded through a 5.1 kΩ resistor where the signal voltage is measured. In the quantum efficiency calibration, the relays are switched to the other positions. A 225 V battery is used to provide the potential difference across the cathode and the first dynode. The first dynode is disconnected from the cathode and then connected to a high gain transimpedance amplifier. This amplifier, similar to the ones used with the photodiode monitors, measures the cathode to dynode current. Feedback resistors of one giga-ohm are used. The amplifiers are calibrated with a pico-ammeter [#8], and the results are within 1% of what one expects from the values of the feedback resistors.

2.2.4. Control and data recording procedure

The voltage outputs from the amplifiers and the anodes are measured with an analog-to-digital converter (ADC) in the computer [#9]. They can also be analysed with a nanovoltmeter [#10], which communicates with the computer through a IEEE488 interface. The latter provides a cross check on the accuracy of the digitisation. Electronic shutters are used to switch light sources on and off during the calibration. A typical sequence in the measurement is illustrated in Fig. 4, which plots the cathode current against time. When the high voltage is first applied to the cathode with the shutter closed, a transient current is detected. The transient decays exponentially. Then measurements are made by opening and closing the shutter in an alternating sequence. After each shutter switch, the control program waits a few seconds for photodiode circuits to settle before it digitises the PMT and diode signals. A net signal is

[#5] S1126-8BQ, Hamamatsu

[#6] OP128A, Burr Brown.

[#7] National Institute of Standards and Technology, United States Department of Commerce, Gaithersburg, Maryland 20899-0001.

[#8] Keithley 485.

[#9] National Instrument, NB-MIO-16 I/O and 16-bit ADC card, installed to a Macintosh Computer. The single bit precision is 305 nV.

[#10] Keithley 195A.

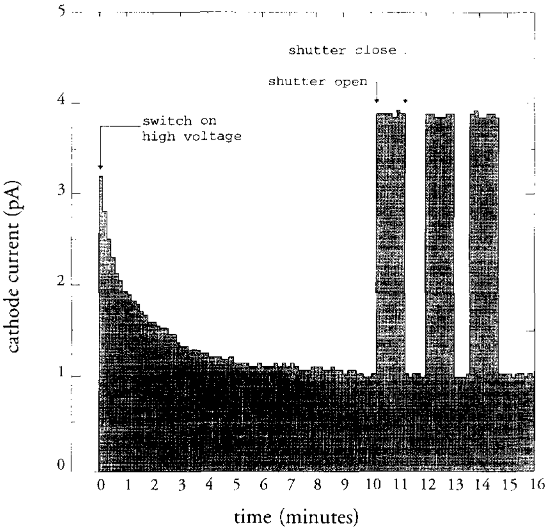

Fig. 4. Cathode current versus time, illustrating the procedure to measure quantum efficiency. When the transient current has subsided and the shutter is closed, the baseline is caused by the non-zero offset of the amplifier. This baseline is subtracted from the "shutter-on" signal to obtain the net response to light.

obtained from each pair of "on/off" measurements. Averages and standard deviations are computed.

The test procedure is automated with the computer. The facility is operated by one technician. Four PMTs are tested in a batch. They are first positioned in a tray where the signal and power connections are made. While four tubes in one tray are being tested in the dark box, the operator prepares another tray of PMTs. The computer will execute the entire test procedure, record the data and notify the operator of PMTs with problems or defect. The test for overall gain as function of high voltage requires an average of 5 min per PMT, including time for tube preparation and test. Every tube in the HiRes experiment is tagged with bar codes, tested for its gain characteristics and the data stored electronically. Ten percents of the PMTs also undergo the quantum efficiency test, which requires somewhat longer test time of about 10 min per tube. Allowing time for regular system checks, we process about 300 PMTs per week and easily meet our construction schedule.

2.2.5. Two-dimensional scan

The computer controls the X–Y scanning platform, which is made of two slide tables driven by stepper motors [#11]. The controller communicates with the computer through a RS-232 interface. During the scanning test, a PMT is mounted on the platform and illuminated by a laser beam. A neutral density filter attenuates the laser beam and at the same time reflects part of the beam to a diode monitor. The anode or cathode current at the PMT is measured in the same manner as described above. After each measurement, the computer changes the position of the PMT with respect to the laser beam.

[#11] Techno Co. USA, controller model 3345.

3. Results and performance

3.1. Anode and cathode sensitivity calibrations

Our goal is to perform absolute calibrations. We base our standards on calibrated silicon photodiodes. We also check that our calibrations are in good agreement with data provided by PMT manufacturers. Fig. 5 shows the quantum efficiencies for twelve tubes made by two different manufacturers. The data denoted by open and solid diamonds are the manufacturers' measurements made at 337 nm. They are very consistent with our measurements at 351 and 325 nm, denoted respectively by circles and squares with one-sigma error bars. Our calibrations also show that the PMTs behave as expected with regard to their linearity and dependence on high voltage. Fig. 6 shows the dependence of the anode sensitivities of two PMTs on the high voltage. They fit a power law very well: gain $\propto$ voltage$^{\alpha}$, where α is found to be about 6 for the 8-stage tubes and 8 for the 10-stage tubes. The linearity of response is illustrated in Fig. 7 where the anode outputs of two PMTs are plotted against the light intensity. The responses are liner for anode currents smaller than ~ 6 μA. For brighter illumination resulting in larger anode currents, the last datum on each curve indicates a slight deviation from linearity. This is expected when the anode current is large enough to affect the high voltage distribution in the PMT base. The base current of a HiRes PMT is about 200 μA. Fig. 7 also shows that there is no residual

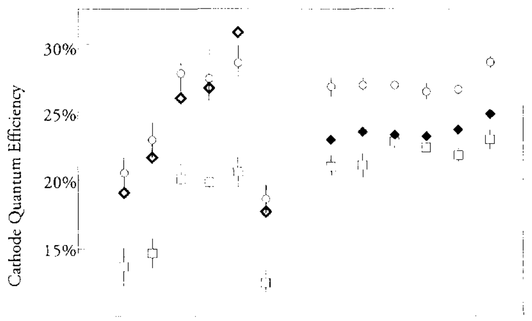

Fig. 5. Comparison of our quantum efficiency measurements at 325 nm (squares) and 351 nm (circles) with the data (open and solid diamonds) supplied by two PMT manufacturers. Data of 12 different tubes, six from each manufacturer, are shown here. The manufacturers' measurements are made around 337 nm, so we expect them to be bracketed by our measurements at 325 and 351 nm.

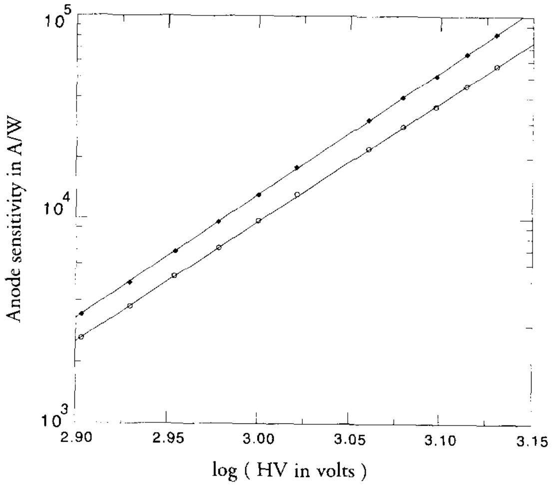

Fig. 6. Dependence of anode sensitivities on the applied high voltage. Data of two tubes are shown. The lines are fits to a power law.

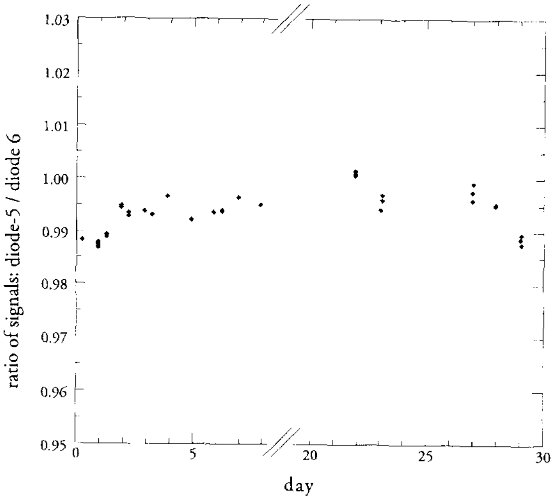

Fig. 8. Ratio of signals from two photodiodes monitoring the diffuse light. The light distribution is found to be stable to better than 1% over a one-month period.

zero offset in the measurements of the net anode signal and the measurements of the light intensity.

3.3. Stability

It is important to ensure long term stability of the calibration system. The stability of the light diffusion and the sensitivity of the photodiodes can be checked readily because we have four photodiodes monitoring the diffuse light. While the output of each diode varies with the source intensity, we expect the ratios of any two diodes to remain constant. Fig. 8 is a plot of such a ratio recorded over a one month period. It is found to be constant with a standard deviation of 0.4%. We also check the overall stability and reproducibility of our system by setting aside 8 PMTs which we denote as "standard" tubes. We test these tubes regularly, typically at the beginning of each day's production run. This test gives the combined stability of the calibration system plus the stability of the PMTs themselves. The former includes all possible contributions from high voltage, temperature, humidity, electronics, etc. The latter may include effects such as PMT ageing or short term exposure to ambient light. Fig. 9 shows the anode sensitivity of a typical "standard" tube over a period of two months, normalised to the average. The standard deviation is about 2%. Some of the variations may be attributed to the fact that the ambient temperature, which is recorded during the calibrations, is only regulated to a few

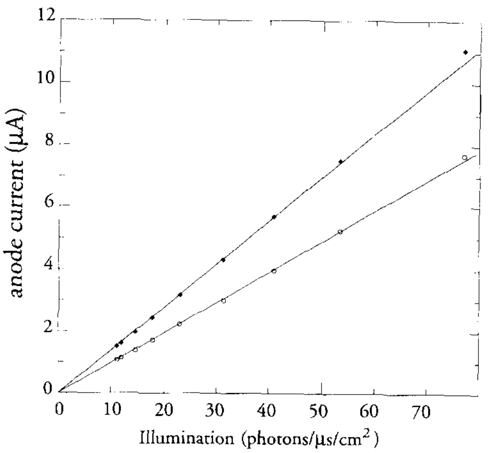

Fig. 7. The linear dependence of anode sensitivities on the intensity of the illumination. Data of two tubes are plotted.

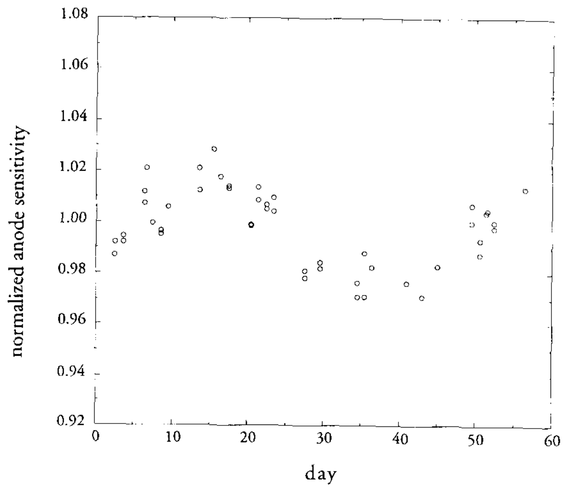

Fig. 9. Anode sensitivity of a PMT monitored for two months. The data has been normalized to the overall average.

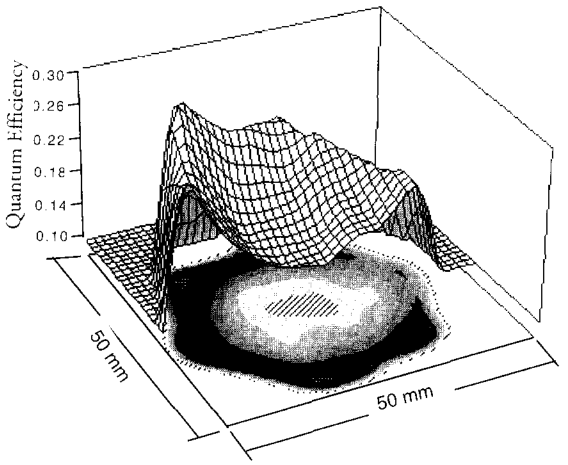

Fig. 10. Quantum efficiency scan at 325 nm of a PMT. The window of this tube has a window that is much thicker in the middle. The scan shows the effect of the attenuation due to the glass.

degrees Celsius. A preliminary study shows that the gains of our PMTs have a temperature coefficient of about 0.5% per°C.

3.4. Two dimensional scan

Detailed analysis of the spatial response of a PMT can be made with the scanning setup. This is illustrated with the following examples. Fig. 10 shows the quantum efficiency map of a PMT that we rejected because of its low quantum efficiency at the centre. The inefficiency is caused by the attenuation of the ultraviolet light by a window that is much thicker in the middle. Fig. 11 shows a map of the anode sensitivity of another tube. The features in the map correspond to the orientation of the structure of the first dynode. This tube is among the first samples we obtained

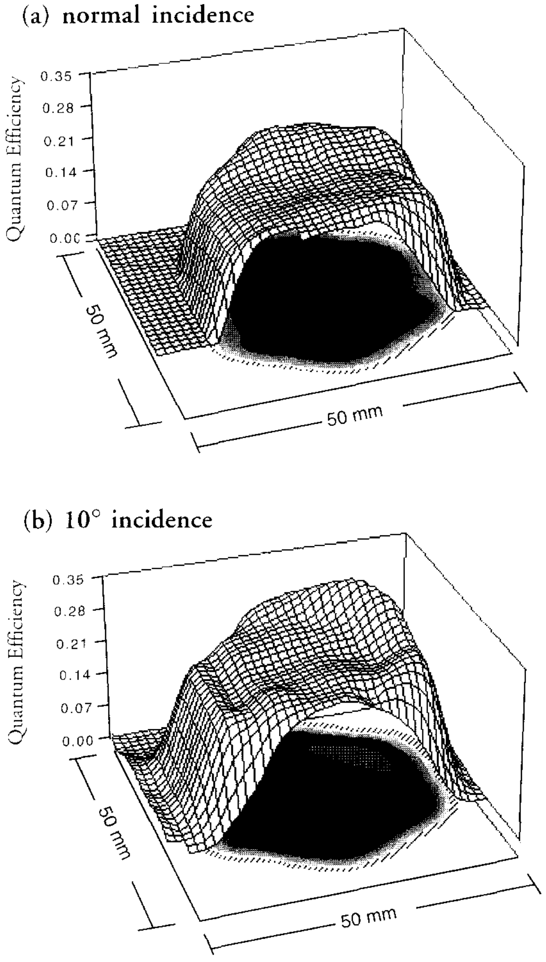

Fig. 12. Dependence of the quantum efficiency map on the light incident angle. Case (a) is for normal incidence and case (b) is obtained with a light beam inclined by 10° to the normal. In the case (b), the quantum efficiency is increased when the light beam hits the interior side wall of the cathode cavity.

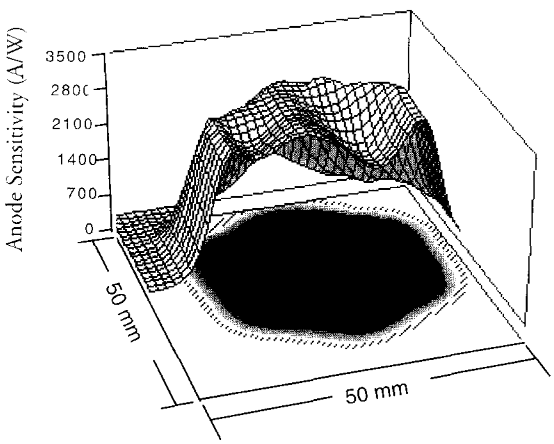

Fig. 11. Anode sensitivity scan of a PMT showing features that correlate with the structure of the first dynode.

from a manufacturer. Since then, the manufacturer has modified the configuration of the electrodes to improve the spatial uniformity. Figs. 12a and 12b show the quantum efficiency map of a PMT at two different orientations to the laser beam. Fig. 12a is obtained with the beam perpendicular to the tube face and figure 12b is obtained when the tube is tilted by 10°. Fig. 12b shows that the signal is enhanced from the photons that hit the inner side wall in the cathode cavity.

4. Conclusion

The facility we developed to calibrate photomultiplier tubes meets the accuracy and efficiency requirement of the HiRes experiment. The uncertainty of the calibration is about three percent or less. We have shown that continuous light sources provide valid calibrations even though the PMTs are employed in an experiment to detect pulsed signals. The dc light source greatly simplifies the instrumentation, and improves the accuracy and stability. With our photodiodes calibrated by NIST, an absolute standard is established. Our results are consistent with those from the PMT manufacturers. The facility has been operated for about two years and we have streamlined our operation. We have identified, eliminated or reduced systematic uncertainties. We shall calibrate all the tubes used in the HiRes project with this setup. We shall use the scanner to study the imaging PMTs designed for the Telescope Array Project [10]. Those are 8×8 multi-anode photomultiplier tubes being developed by Hamamatsu. This calibration facility or a similar setup may also be useful for other experiments that require absolute calibrations or experiments that use PMTs in large quantities.

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