ELSEVIER
Nuclear Instruments and Methods in Physics Research A 450 (2000) 253–269

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.nl/locate/nima

The prototype high-resolution Fly's Eye cosmic ray detector

T. Abu-Zayyad[a], M. Al-Seady[a], K. Belov[a], D.J. Bird[b,1], J. Boyer[c], G. Chen[a], R.W. Clay[b], H.Y. Dai[a,2], B.R. Dawson[b], Y. Ho[c], M.A. Huang[a,3], C.C.H. Jui[a], M.J. Kidd[d,2], D.B. Kieda[a], B.C. Knapp[c], W. Lee[c], E.C. Loh[a], E.J. Mannel[c], J.N. Matthews[a], T.A. O'Halloran[d], A. Salman[a], K.M. Simpson[b], J.D. Smith[a], P. Sokolsky[a], P. Sommers[a], S.B. Thomas[a], L.R. Wiencke[a], C.R. Wilkinson[b,*], N.R. Wild[b]

[a]*Department of Physics and the High Energy Astrophysics Institute, University of Utah, UT 84112, USA*
[b]*Department of Physics and Mathematical Physics, The University of Adelaide, SA 5005, Australia*
[c]*Columbia University, Nevis Laboratories, Irvington, NY 10533, USA*
[d]*Department of Physics, University of Illinois at Urbana-Champaign, IL 61801, USA*

Received 13 August 1999; received in revised form 21 January 2000; accepted 2 February 2000

Abstract

The High-Resolution Fly's Eye (HiRes) is an observatory for the highest energy cosmic rays. It detects the nitrogen fluorescence light induced by the passage of giant cosmic ray extensive air showers through the atmosphere. A two-site prototype of the observatory was operated from September 1994 to November 1996. In this paper we describe the components of that detector, and the procedures used to calibrate the detector and characterise the atmosphere. Data collected by the HiRes prototype are being used for physics studies, including an analysis of the cosmic ray mass composition in the energy range from 10^{17} to 10^{18} eV. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 96.40

Keywords: Cosmic ray detectors; Air fluorescence detection

---

1. Introduction

The High-Resolution Fly's Eye cosmic ray detector (HiRes) has been developed to detect significant number of cosmic rays at energies around the Greisen–Zatsepin–Kuzmin (GZK) cutoff [1,2] using the atmospheric fluorescence technique. Cosmic ray initiated extensive air showers (EAS) cause atmospheric nitrogen to fluoresce in the near-ultraviolet. HiRes builds on the experience

---

[*] Correspondence address: Defence Science Technology Organisation, P.O. Box 1500, Salisbury, SA 5108, Australia.

E-mail address: christopher.wilkinson@dsto.defence.gov.au (C.R. Wilkinson).

[1] Now at Defence Science Technology Organisation, P.O. Box 1500, Salisbury, SA 5108, Australia.

[2] Now at Rosetta Inpharmatics, 12040 115th Ave NE, Kirkland, WA 98034, USA.

[3] Now at Institute of Physics, Academia Sinica, 11529 Nankong, Taiwan, ROC.

PII: S0168-9002(00)00307-7

gained with the Fly's Eye detector [3] and has been designed with the specific goals of:

- increasing the data rate above 10^{19} eV by an order of magnitude over the Fly's Eye to >200 events per year,
- improving the depth of shower maximum ($X_{\max}$) resolution to 20–30 g cm^{-2} from 45 g cm^{-2} for the stereo Fly's Eye, and
- improving the angular resolution and acceptance in the EeV (10^{18} eV) range to increase sensitivity to point sources.

These goals will be achieved through the construction of a two-site detector utilising improved optics, electronics and analysis techniques [4]. This paper describes the design and operation of the HiRes prototype detectors.

The Fly's Eye detector was the first successful air fluorescence detector, beginning operation in 1981 and collecting data up until July 1992 [5]. Thorough reviews may be found in Baltrusaitis et al. [3] and Cassiday [6]. The HiRes detector is the successor to the Fly's Eye, achieving a sevenfold increase in signal-to-noise ratio by decreasing the field of view of each photomultiplier (PMT) from 5.5° to 1° in diameter, and increasing the mirror diameter from 1.5 to 2 m. The improved signal-to-noise ratio significantly increases the triggering aperture of the detector, since light signals can travel further through the atmosphere before being attenuated to the noise level [4,7]. The smaller pixel size also allows finer sampling of the extensive air showers (EAS) longitudinal profile, improving energy and depth of shower maximum ($X_{\max}$) resolution. Simulations [4] indicate that 90% of showers viewed by HiRes will have tracks which bracket shower maximum, which will allow excellent mass composition studies. Further improvements in sensitivity and resolution will be achieved through the operation of two separated detectors to simultaneously observe cosmic ray EAS (known as stereo observing).

The HiRes detector is being constructed in stages through the use of modular mirror detector units. Each mirror unit has a field of view of 16° in azimuth and 13.5° in zenith with independent electronics to allow progressive integration into detector operation. The HiRes detector began operating as a 2-mirror prototype in 1991 at the site of the original Fly's Eye experiment [8]. The two mirrors were orientated to overlook the Fly's Eye II detector, the Chicago Air Shower Array (CASA) and the Michigan Muon Array (MIA). A further 12 mirrors were gradually added with the HiRes 1 prototype becoming fully operational in March 1993 [9]. The 14 detectors were arranged in five elevation bands, covering elevation angles from 3° to 70° overlooking CASA/MIA. The HiRes 2 site was then developed, with a 4-mirror prototype becoming operational in September 1994 [10]. The HiRes 2 site is located 12.6 km to the southwest of HiRes 1, with the four mirrors of the prototype arranged within two elevation bands to overlap the field of view of HiRes 1 and CASA/MIA. The geometry of the two HiRes sites and the fields of view of the prototype detectors are illustrated in Fig. 1.

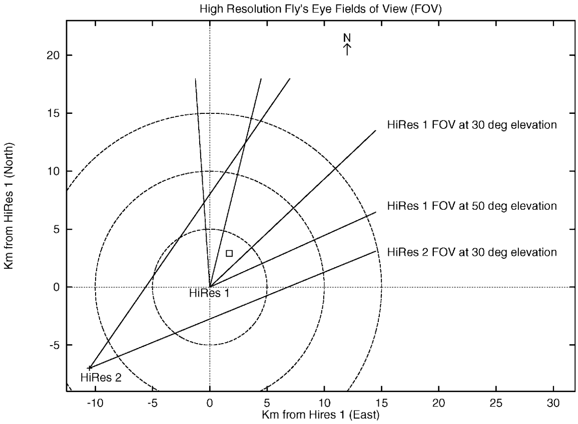

Fig. 1. A plan view of the location of HiRes-1 and HiRes-2 at Dugway Proving Ground and their fields of view. The dashed circles represent distances of 5, 10 and 15 km from HiRes 1, and the square denotes the site of the CASA/MIA arrays. The increase in scale between Fly's Eye and HiRes can be appreciated by noting that Fly's Eye I was located at HiRes 1 and Fly's Eye II was located at the centre of the CASA/MIA arrays.

Data were collected from the two-site prototype for a period of just over two years, with the prototype being shutdown in November 1996 to allow reorganisation of mirrors and electronics for the stage 1.0 HiRes detector.

1.1. Layout of the prototype detectors

The HiRes 1 prototype detector was situated on the Five Mile Hill site of the original Fly's Eye detector within the US Army's Dugway Proving Grounds in Utah, USA. The GPS-determined coordinates are a longitude of 112°50′08.8764″ W, latitude of 40°11′42.6156″ N and an altitude of 1597 m above mean sea level. This is a mean atmospheric depth of 860 g cm^{-2}. The 14 mirrors of the prototype were arranged in five elevation rings with a total 0.81 sr field of view that overlooks the CASA/MIA detectors. Fig. 2 illustrates the fields of view of the mirrors. Mirrors are housed in prefabricated steel buildings with electronically controlled roller doors. The experiment is run from a central trailer, which houses the central computing facilities (computers, hard disks, network routers), central timing electronics, YAG laser (used for calibration purposes) and operator quarters. A single ethernet line is used for communication between the control software and the mirrors.

HiRes 2 is the second site of the detector. It is located on Camels Back Ridge, 12.6 km to the southwest of HiRes 1 (see Fig. 1). The GPS-determined coordinates are a longitude of 112°57′32.292″ W, latitude of 40°07′55.452″ N, and an altitude of 1553 m above mean sea level. The four mirrors of the prototype were arranged in two elevation rings with a field of view that overlaps the HiRes 1 field of view and the CASA/MIA detectors as is illustrated in Fig. 1. Fig. 3 indicates the specific fields of view of the mirrors. This particular arrangement of the prototype mirrors at the two sites is not optimal for reconstruction of the shower axis using the stereo technique, because coincident EAS are seen by both detectors in almost the same direction. Despite this the stereo techniques have been shown to work well [11].

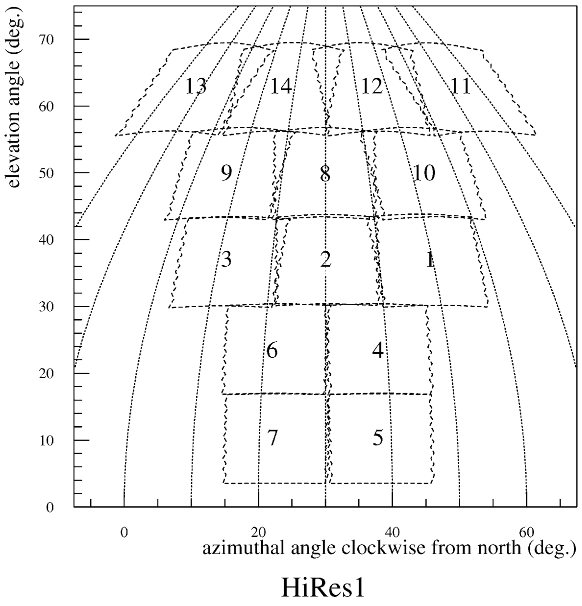

Fig. 2. Fields of view on the sky of the HiRes 1 prototype mirrors. Each of the 14 mirrors images the sky onto a cluster of 256 photomultipliers.

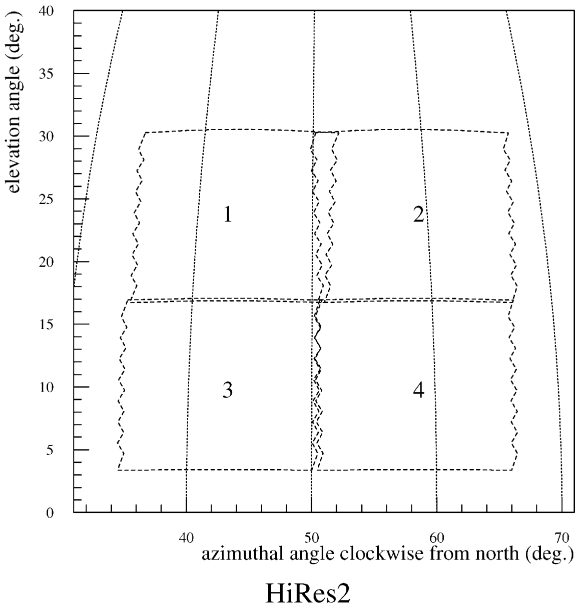

Fig. 3. Fields of view on the sky of the HiRes 2 prototype mirrors.

2. Detector components

Each mirror unit consists of an optical system, photomultiplier tube cluster and data-readout electronics, all of which is housed in a mirror building (with two mirror units per building). The remainder of the data acquisition system is housed in a central

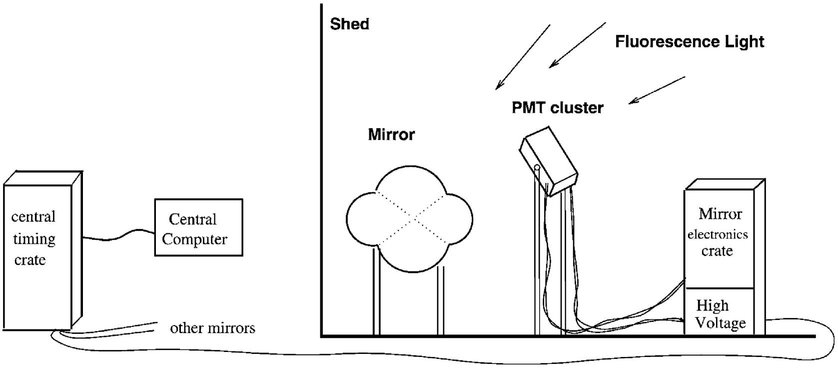

Fig. 4. A schematic of the basic HiRes data acquisition system [19]. Each mirror is serviced by a local electronics crate and high-voltage supply. Data is transmitted via ethernet to a central computer, which also hosts the Central Timing system.

facility. The basic system is illustrated in Fig. 4 – fluorescence light is collected by the mirror, focused onto the PMT cluster and digitised by the electronics. The absolute triggering time is recorded by the central timing crate, and the control software collects the information via ethernet and stores it to disk.

The data acquisition system is almost identical at each HiRes site and a detailed block diagram of the detector components is presented in Fig. 5. These components will now be discussed in detail with the improvements between HiRes 1 and HiRes 2 noted.

2.1. Mirror unit

The mirror unit is the basic component of the data acquisition system. Each mirror unit consists of a 2 m diameter mirror which focuses light onto a cluster of 256 photomultiplier tubes (PMTs) placed behind a UV bandpass (300–400 nm) filter. Each hexagonal PMT has a fixed field of view of approximately 1° diameter, with each mirror having a total field of view of 16° in azimuth and 13.5° in zenith.

A photograph of a mirror unit is shown in Fig. 6, including the rack containing the data acquisition crate, power supplies and high-voltage distribution. Fig. 7 shows a cluster of 256 photomultipliers with the UV bandpass window folded down.

The mirror electronics are housed in a VME crate within the mirror buildings to minimise cable lengths to less than 10 m/channel. The VME crate contains a 68030-based processor board, 16 data acquisition boards (known as 'ommatidial' boards), a trigger board, a programmable pulse generator board (PPG) and a sensor/relay board (known as a 'garbage' board). The mirror electronics also include a power supply for the PMT preamps, the PMT high-voltage supply and the high-voltage distribution system.

Each ommatidial board processes the individual signals of a subcluster of 16 PMTs. A sample and hold system is used to measure the total integrated signal within a fixed time window, along with the relative PMT triggering time. The mirror CPU is the primary interface between the central computer and the ommatidial board with data being sent between the crate and the central computer over an ethernet line. The mirror trigger board determines when triggering criteria have been met, and has a direct (twisted pair) line to the central timing electronics to allow recording of the absolute mirror triggering time. The PPG is used to generate calibration pulses, and the garbage board performs a variety of different tasks such as monitoring the high-voltage system and opening/closing the building door. Each component of the system will now be discussed.

2.1.1. Optics

The mirrors have an effective area of 3.75 m^2, a radius of curvature (R) of 4.74 m and an f-stop of 1.16. For ease of fabrication each mirror is composed of four segments in a clover leaf pattern.

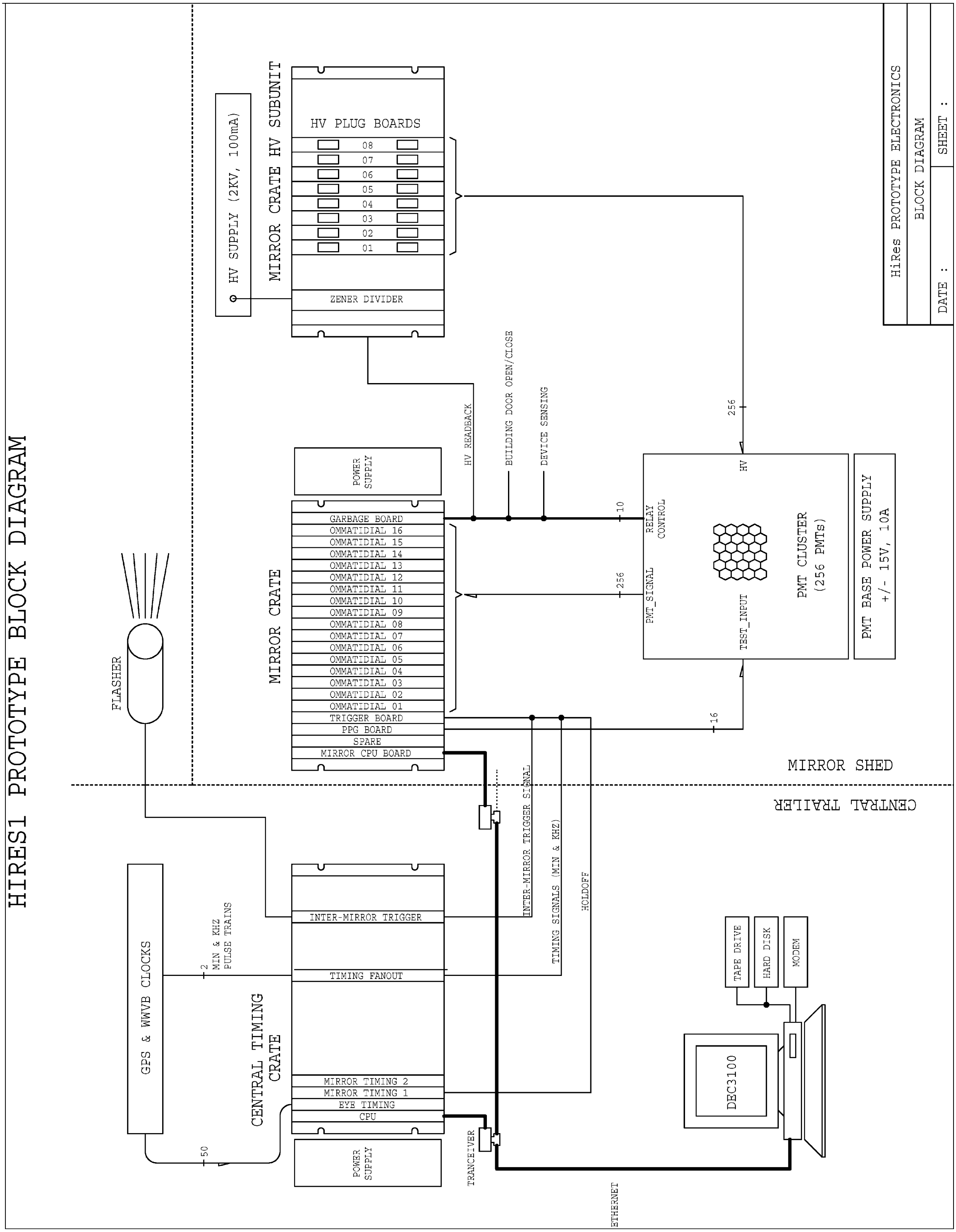

Fig. 5. Block diagram of HiRes 1 prototype components [19]. HiRes 2 is essentially identical.

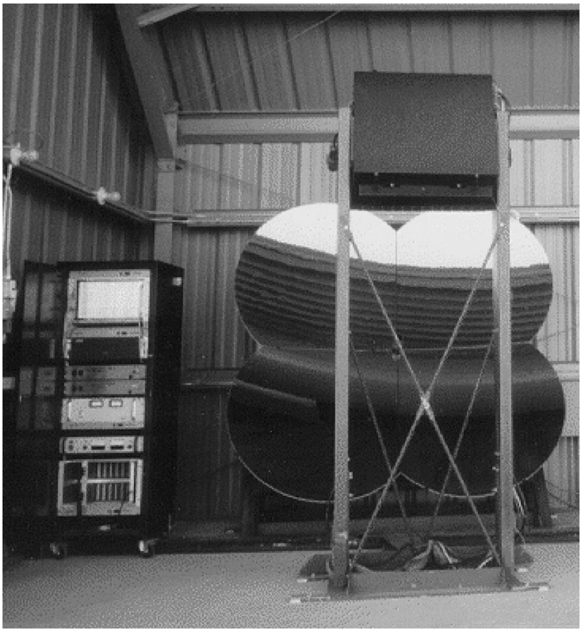

Fig. 6. A prototype mirror unit at HiRes 2. The 2 m diameter mirror is viewed by a cluster of 256 photomultiplier tubes. The rack shown contains the mirror data acquisition crate, power supplies and high-voltage distribution.

Fig. 7. One of the photomultiplier clusters used to image the night sky. Each cluster consists of 256 40 mm diameter hexagonal photomultiplier tubes each having a 1° field of view. The UV bandpass filter (bottom of picture) has been swung down to reveal the photomultipliers.

Each mirror segment was slumped from a 9.5 mm thick glass blank which was cut to size, aluminised and then anodised. Details of the fabrication process may be found in Ref. [12].

The mirrors have been deliberately designed to have a finite spot size. A finite spot size reduces the variation in PMT response along the track caused by dead space between PMTs and gain variations across the face of PMTs. Mirrors were accepted if more than 70% of light was focused down to spot with a diameter of less than 1 cm. Initial average reflectivity was measured as 85% at 355 nm.

Mechanical support for the prototype mirrors used an aluminium hexcell honey-comb structure glued to the backs of mirrors. Unfortunately, this support structure was found to have a large thermal expansion coefficient, resulting in the radius of curvature decreasing with temperature by as much as 3 mm/°C [13]. All HiRes 1 mirrors, and HiRes 2 mirrors 2 and 4 were affected. The remaining two HiRes 2 mirrors utilised a simple three-point mechanical support structure that overcame this problem. The honeycomb structure was replaced after the prototype was shutdown to prevent this problem affecting the full HiRes detector.

The mirror focuses light onto the photomultiplier tube cluster which is situated behind a UV filter used to reduce background light and so improve the signal-to-noise ratio. The face of the PMT cluster was placed at a distance of $0.97(R/2)$ (where R is the radius of curvature of the mirror), a distance which minimised the spot size variation across the field of view. The filter is a single sheet of UG-1 glass which passes light in the 300–400 nm range with a transmission factor of 80% [4]. The measured transmission curve is shown in Fig. 8 together with the nitrogen fluorescence spectrum

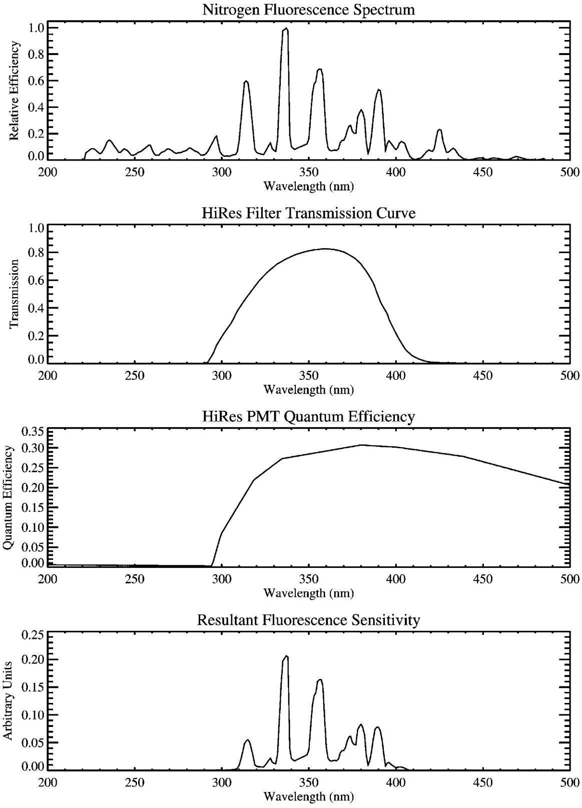

Fig. 8. Resultant fluorescence spectrum after taking into account HiRes filter and PMT quantum efficiency.

and the PMT quantum efficiency curve. The filter was found to enhance the signal-to-noise ratio by a factor of 1.7 [14], a cost-effective improvement.

The pointing directions of the mirrors and clusters are important parameters in reconstructing EAS events. During installation the mirror and cluster were carefully surveyed into position, and the location and pointing directions were then recorded [15]. These directions change slightly as building foundations settle and equipment is accidentally knocked. Thus prior to decommissioning the prototype the positions were resurveyed to determine the amount of movement experienced.

Surveying is conducted using a theodolite which is levelled and referenced to a common distant point with a well-known position. A target is placed in the centre of the cluster, and the location of the reflected image on the surface of the mirror is found. The angle between the reflected image on the mirror surface and the reference point is recorded, as is the distance from the theodolite to the mirror and the position of the image on the mirror. The theodolite is moved, and the process is repeated so that four points on each mirror segment are surveyed. The measured distances and angles can then be used to determine the average pointing direction of the mirror.

The surveying process is a difficult and time-consuming process, with the difficulty increasing with the elevation angle of the mirror. Comparison of surveys done two years apart found that some of the mirrors, and in some cases the entire buildings, had undergone shifts of up to 0.1°. Alternative surveying methods such as the use of precision laser shots are being investigated [15,16].

2.1.2. Photomultiplier tube cluster

The photomultiplier tube cluster is held in the focal plane by a structure designed to minimise obscuration of the mirror field of view. The cluster consists of 256 closely packed 40 mm diameter hexagonal photomultiplier tubes each having a 1° field of view. Half of the mirrors (1,3,9,10,11,12,14) at HiRes 1 used Philips XP3062/FL PMTs and the other half used EMI 9974KAFL PMTs. At HiRes 2, mirror 4 used EMI PMTs and the other three mirrors used Philips PMTs. The Philips PMTs will be used in all future mirrors. A test facility [17] was constructed to measure the absolute gain and quantum efficiency for all PMTs. The facility was able to perform two-dimensional scans across the face of the PMTs, so that PMTs with greater than 10% non-uniformity could be rejected.

Each PMT is soldered to a high-voltage bleeder chain and a preamp circuit. The preamp provides a gain of 100 and generates an AC-coupled signal which removes the mean night sky background. This ensures that only fluctuations in the night sky background contribute to the noise signal. The preamp circuit has an identification chip (used to keep track of PMTs in the clusters) and an external test input. Test pulses from the PPG board are injected via this input and are used to calibrate the data acquisition electronics without high voltage applied to the PMT.

The PMTs are arranged in 16 subclusters of 16 PMTs each, with a single ommatidial board servicing one subcluster. The entire PMT/circuit board assembly mounts in the cluster frame with a 256 socket backplane. The backplane distributes high voltage (HV) and test signals, and transmits PMT pulses from the preamp to the data acquisition boards. At HiRes 1 high voltage is supplied to each PMT through 256 high-voltage cables. At HiRes 2 the PMTs were pre-sorted into groups of 16 with similar gains. Each group of 16 tubes formed a subcluster which could be operated at the same high voltage, simplifying the HV distribution system.

The PMTs are wrapped in magnetic shielding metal and closely packed within the cluster. To prevent a buildup of heat, a cooling fan is located at the top of the cluster. The sides of the cluster box are bonded with a heat-conducting paste, and an aluminium sheet runs vertically through the centre of the cluster. A temperature sensor is located in the centre of the cluster to allow monitoring of the effectiveness of these measures.

2.1.3. Mirror electronics

High-voltage supply and distribution. The high-voltage distribution system provides power for the PMTs in the cluster. Each mirror is powered by a single 2 kV 100 mA supply which is fed into a simple zener voltage divider chain providing twenty-five voltages in 20 V steps to cover a 500 V range. The voltage range was individually set for each mirror (as different PMTs had different optimal high-voltage values), with the middle of the range generally around 1100 V. The zener taps are fed into a matrix plug board which allows each PMT (HiRes 1) or subcluster (HiRes 2) to be tapped to within 10 V of the optimal voltage. PMT gains have been found to be very stable, generally requiring adjustment less than once per year. A VME crate controlled high-voltage readback system is also incorporated to allow checking of the voltage on each PMT/subcluster.

Ommatidial board. The ommatidial boards handle triggering of PMTs and the digitisation of their signals. Each ommatidial board records and stores the integrated charge and the time at which the waveform's leading edge rises above threshold for the 16 PMTs in each subcluster [10,18,19]. The sample and hold electronics used at HiRes 1 and HiRes 2 are presented as block diagrams in Figs. 9 and 10.

The goal is to maximise the sensitivity to cosmic ray EAS signals whilst minimising the effects of the night sky background noise. The pulses generated by EAS have the property that the pulse time width is roughly proportional to the distance from the shower to the detector. Thus two channels are

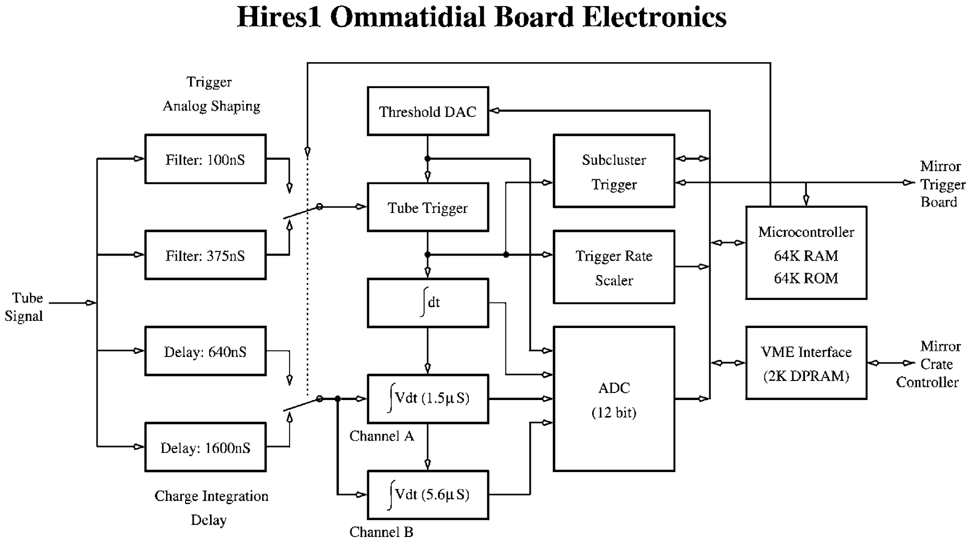

Fig. 9. HiRes 1 data acquisition 'ommatidial' board. After Kidd [19].

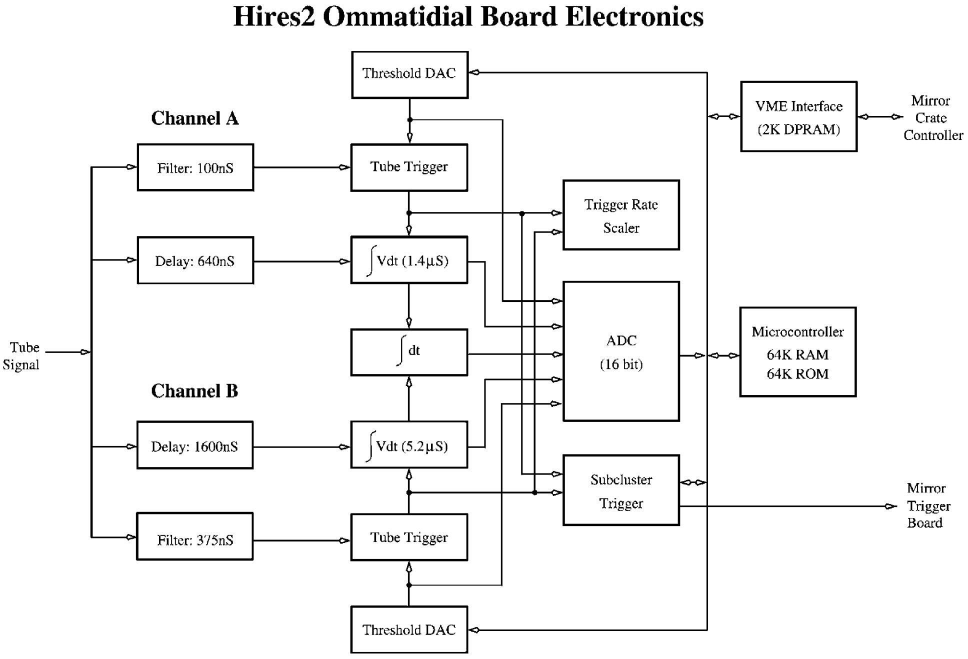

Fig. 10. HiRes 2 data acquisition 'ommatidial' board.

available for each PMT – channel A is optimised for integrating fast, close pulses and channel B for integrating more distant wider pulses. The night sky background has a power law pulse height spectrum, so triggering thresholds can be reduced by including low-pass filters to remove pulses with widths shorter than the expected signal pulse widths. A 100 ns single-pole RC filter is used in channel A and a 375 ns 3-pole LC Bessel filter is used in channel B for this purpose. At HiRes 1 only one filter may be selected for both channels (this is software controllable) whilst at HiRes 2, channels A and B each have their own filter and can trigger independently of each other (see Figs. 9 and 10). HiRes 1 almost exclusively used the 100 ns filter so that the detector would be sensitive to close showers that might trigger CASA/MIA.

The triggering rate of each PMT is measured using a 16 bit scaler and is monitored by an 80188 microcontroller chip. The microcontroller maintains a constant PMT triggering rate through the use of a digital-to-analogue converter (DAC) to dynamically adjust the trigger threshold every 4 s. The choice of triggering rate is a compromise between sensitivity and PMT trigger dead time. At HiRes 1 a trigger rate of 200 Hz was chosen and at HiRes 2, rates of 50 Hz for channel A and 300 Hz for channel B were chosen.

Once a PMT has triggered, the triggering time and the integrated charge of the signal is measured. PMT timing is measured using a time-to-digital converter (TDC). The TDC consists of a capacitor which is charged with a constant current source from the time the PMT triggers until a common stop signal is issued, approximately 10 μs after a full mirror trigger has occurred. The charge is then measured by a 12 bit (HiRes 1) or 16 bit (HiRes 2) analogue-to-digital converter (ADC) and cleared. If no mirror trigger occurs the charge is cleared after 25 μs. The HiRes 1 TDCs had a resolution of approximately 5 ns giving a dynamic range of 2000 (10–20 000 ns). The HiRes 2 TDCs initially had a resolution of 0.65 ns/count which was increased to 2 ns/count in March 1995. This increased the dynamic range from 2000 to 6000 (the maximum time increased from 20 to 60 μs). The linearity of the TDCs is better than 0.2%.

To ensure that the full waveform is integrated, the PMT signals are sent through delay lines while triggering is determined. A delay line of 640 ns was used for the 100 ns filter and 1600 ns for the 375 ns filter. Channels A and B have different integration periods, with charge-to-digital converters (QDCs) being used to measure the integrated charge in each channel. The linearity of the integrators is better than 1%. At HiRes 1, channel A uses a 1.5 μs integration period, and channel B uses a 5.6 μs period. HiRes 2 uses 1.4 μs for channel A, and 5.2 μs for channel B. The different integrate gate lengths correspond to crossing times optimised for near and far showers, providing a compromise between skynoise contamination of short pulses (close EAS) and clipping of long pulses (distant EAS). At HiRes 2 the triggering of each channel is done independently so that it is possible for only one channel to trigger, and thus only one charge integral to be stored. At HiRes 1, the triggering channel is fixed, and both charge integrals are stored. As with the TDCs, QDCs are cleared after 25 μs if no mirror level trigger occurs. An analogue multiplexor fans the 48 storage capacitors (QDCA, QDCB and TDC for the 16 PMTs in a subcluster) into an ADC for readout by the 80188 microcontroller chip.

Trigger board. The ommatidial boards store the time and charge integrals for each PMT in each of the 16 subclusters. When a PMT signal rises above threshold, the PMT trigger flag is set for at least 25 μs. During this time the integrated charge is saved and the PMT may not retrigger. A subcluster trigger is formed when a pattern of PMT triggers within a subcluster matches a pattern in a trigger lookup table. The 16 PMT trigger flags (25 μs pulses) form an input address for a 64 K, 8 bit EPROM. Each bit of the address corresponds to a given trigger flag pattern, thus indicating when a subcluster has triggered according to one of the preprogrammed patterns. The specific bit used is software selectable with different patterns being specified for data collection, diagnostics and testing purposes. Normal operation defines a subcluster trigger as three triggering PMTs, with at least two hexagonally adjacent. Other patterns include any one tube, any two tubes, any three tubes, any two hexagonally adjacent tubes and all tubes.

The output of the subcluster trigger lookup table is reshaped into a 25 μs pulse and is used as an input to a second lookup table to generate a mirror trigger. Normal operation requires at least two subclusters to trigger within the 25 μs window to generate a mirror trigger (a minimum of 6 PMTs). A mirror trigger is also sent to adjacent mirrors. This allows adjacent mirrors to reduce their triggering requirements to a single subcluster, so that an EAS which clips the edge or corner of a mirror may still trigger.

A mirror trigger generates a mirror save condition, which prevents PMT charge integrals from being cleared. New PMT triggers may continue to save integrals for a further 10 μs after a mirror trigger to allow the EAS to finish crossing the mirror. At the end of this period, a holdoff condition is set to prevent any new PMT triggers and stop the TDC integrators. At HiRes 2 the 10 μs period was found to be insufficient and in March 1995 it was increased to 25 μs. When holdoff is set, a signal is sent to the central timing crate to record the absolute mirror holdoff time, and then the PMT charge and time integrals are digitised and saved as a mirror event. The mirror holdoff time is also recorded locally at the mirror by latching scalers which count the 1 kHz and 1 min pulsetrains from the central GPS clock. The latched minute and millisecond values are used to match the mirror event data to the central holdoff time for a much more precise mirror event time. Event processing takes ~ 8 ms, after which the mirror save and holdoff conditions are cleared, resetting the mirror electronics for the next EAS event.

Mirror CPU. The mirror CPU is the primary interface between the central computer and the mirror electronics (the 16 ommatidial boards, the trigger board, the PPG board and the garbage board). The central computer sends commands to set up the mirror for tasks such as calibration and data collection, and the mirror CPU sends back event and mirror status data. An ethernet link using UDP protocol is used for communications between mirrors and the central computer.

The mirror CPU is a Force computers 680303 CPU card using the Wind Rivers System's VxWorks real time operating system. VxWorks provides a fast operating system with Unix-like function libraries and multitasking. The HiRes-specific software is maintained on the central computer and is downloaded to each board when it is rebooted. This allows global changes to the operating software to be made and easily propagated to each mirror unit. The system also allows logins, so operators can login to individual mirrors to check the status and diagnose any problems that arise.

The main task of the mirror CPU is to collect the TDC and QDC information from PMTs in a mirror event. It attaches an event number (using a scaler) and the min/s/ms time using scalers synchronised by the master clock at the start of the night. The information is placed in an event packet, and several mirror events are collected before they are sent to the main computer for storage. The mirror CPU also gathers information on trigger rates, thresholds, network performance and deadtime and checks local time scalers. These monitoring data are packaged every minute and sent to the main computer to be incorporated into the data stream. The CPU also receives control packets from the central computer, which are then sent to the relevant boards. The ommatidial boards can be instructed to set thresholds or disable/enable triggering for individual tubes (useful when stars enter a PMTs field of view), triggering requirements may be set on the trigger board, and the PPG board can be instructed to fire pulses with specified shapes and rates.

2.2. Central timing

The central timing crate houses the master clock used to record mirror triggering times, and to provide timing pulse trains to the mirrors. The basis of the timing system is a 24 bit, 40 MHz scaler (25 ns resolution) which is synchronised to absolute UTC to within 340 ns (2σ) by a global position system (GPS) clock [20]. Relative timing between the two HiRes sites is better, and is of the order of 50 ns for the majority of the time. The GPS receivers at the two sites track at least five common satellites (each receiver can track up to six satellites), 99.9% of the time. In the rare cases when only four common satellites are tracked, relative timing accuracy only degrades to 100 ns [21].

The GPS clocks produce a synchronisation pulse at the start of the UTC second. This is used to latch the 40 MHz scaler, so that the scaler value at the start of each second can be recorded. This allows a measurement of the scaler drift, which can then be corrected for later in the analysis stream. The GPS clock is also used to fan out minute and millisecond pulse trains to each mirror, which are used to assign event times (to the millisecond level) in event packets.

The 40 MHz scaler is used to provide sub-second times with a resolution of 25 ns. When a mirror trigger holdoff is raised, a signal is sent from a mirror down a dedicated line to latch the value of the 40 MHz scaler. The tens and ones of the absolute millisecond time are also recorded from the GPS. The id-number of the triggering mirror, the scaler value and lower digits of the millisecond time are packaged together and placed in a timing packet. If additional mirrors trigger within 50 ms of the first mirror, their triggering information is added to the timing packet, up to a maximum of 128 triggers. The timing packet is then sent to the central computer via ethernet and added to the data stream. Event and timing packets are matched later in software.

The prototype detector initially used WWVB clocks which only had a resolution of 1 ms. These WWVB clocks were replaced with GPS clocks in November 1994. At HiRes 1, the central timing crate is also used to produce a pulse to fire a xenon flasher (flashers are described in Section 3.4.1) which is used to alert CASA/MIA of a HiRes 1 trigger [19].

2.3. Control software

The central computer at each site is a DECStation 3100 workstation. This is used to control data collection for the entire detector site [22]. This computer makes network connections to each mirror and handles the initialisation of each mirror for data collection. The control software includes a user interface so an operator can issue commands and view the detector response (such as PMT count rates, trigger rates, and any warnings or alarms). The operator issues diagnostic calibration and detector operation instructions, which are then sent via the ethernet to each mirror. Event, timing and status packets from the mirrors and the control program are collated and written to a local hard disk.

3. Calibration

Calibration is an important component of data collection. To extract useful information from EAS we must understand how the different detector components function (such as response of individual PMTs) and how we can convert this to useful information. HiRes calibration can be broken into five areas: PMT response, mirror behaviour, filter response, electronics response, and the atmosphere. Calibration parameters are obtained for the different components (some occasionally, some nightly), and are combined to enable us to calibrate data from normal detector operation.

3.1. Photomultiplier tube response

A computer-controlled testing station to measure the response of PMTs was built at the University of Utah and is described in Ref. [17]. The test bed was designed to measure the PMT quantum efficiency, the gain as a function of voltage and the uniformity across the PMT face. Here we will concentrate on PMT calibrations at the detector site.

3.1.1. Temperature dependence

The PMT gain temperature dependence is roughly 0.5%/°C, a significant figure given that the detector operates in ambient temperatures from $-15°C$ to 40°C. The PMT clusters are cooled with a fan in an attempt to maintain a uniform cluster temperature, but the actual temperature is allowed to vary. A temperature sensor is located in the centre of each cluster and two additional sensors record the building and crate temperature. Measurements are recorded using the garbage board.

3.1.2. UV light delivery systems

The response of the PMTs to UV light is monitored each night using a YAG laser system at HiRes 1, and a similar system using a xenon flash bulb system [23] at HiRes 2. These systems are used in nightly calibrations and mirror reflectivity measurements (to be discussed in Section 3.2).

The system consists of a light source and optics located in the central trailer, which focus light into one of two bundles of fibre optic cables that then pipe the light out to each mirror. Fibres in the first bundle terminate in the centre of each mirror, so that light from the fibre will illuminate the PMT cluster. Fibres in the second bundle are attached to the cluster, so that their light must first reflect off the mirror before arriving at the cluster. Each fibre terminates at the base of a cup where it encounters eflon sheets which diffuse the light so that it will uniformly illuminate the mirror or the cluster. The light entering the fibre bundles is monitored with silicon photodiodes. A solenoid is used to select the bundle that the light source fires into. A Macintosh computer is used to trigger the light source, operate the solenoid, calibrate the monitor photodiodes and record the diode measurements which are then sent to the central computer for recording in the data stream. Pulse-to-pulse intensity variations at the fibre bundles are approximately 1% at HiRes 1 and 5% at HiRes 2.

Two sets of calibration data, each consisting of 50 laser pulses, are taken each night. The calibration systems at HiRes 1 and HiRes 2 are slightly different with the information being used differently at each site. At HiRes 1 the relative response of each PMT to the average response of the cluster is measured, and is used to weight the electronics gain which is measured nightly using the PPGs (to be discussed in Section 3.3). This calibration is done on the assumption that the response of PMTs will not vary significantly between absolute calibrations.

At HiRes 2, the average QDCs and the average intensity measured by the photodiodes are used with measurements of the electronics constants (determined using the PPGs). Constants obtained from the absolute calibration are used to convert the diode measurements into numbers of photons, which can then be used to determine the total gain of the electronics and PMTs.

3.1.3. Intermirror and absolute calibration

The intermirror and absolute calibration is performed using four standard tubes which are moved from mirror to mirror [15,24]. The four PMTs were selected to have similar gains and uniform response across their faces. They were calibrated in an absolute sense against US National Institute of Science and Technology (NIST) photodiodes [24]. A portable calibration system consisting of an ommatidial board, PPG board, a high-voltage supply and monitor was constructed so that the standard tubes could be operated with standard electronics in the field. The standard tubes are placed in a subcluster of a mirror and illuminated with the resident mirror UV light source (a YAG laser at HiRes 1, a xenon flasher at HiRes 2). The response of the standard PMTs and the PMTs in all other subclusters are compared. The sensitivity of the full cluster was then calculated using the gains of the standard tubes, the filter transmission and the PMT response to the UV light. The mean sensitivity for PMTs in all clusters was found to be 12 160 AW^{-1} at 325 nm, or a gain of approximately 2×10^5 electrons per photoelectron.

3.2. *Mirror reflectivity*

The relative night-to-night variation in the mirror reflectivity is measured by comparing the average PMT response to directly viewed and reflected UV light. The light monitoring system previously discussed (YAG laser/xenon flash bulb) is used to provide a light source. Unfortunately a series of tests conducted just before the prototype was disassembled revealed that small flexing of the Teflon diffusers within the cups could affect output on a nightly basis by 10% or more, thus affecting the accuracy of the tracking of mirror reflectivity.

The absolute mirror reflectivity starts at $\sim 90\%$ when the mirrors are washed, a twice yearly occurrence. Experience with the Fly's Eye mirrors indicated that dust accumulation occurs rapidly in the first month or two after washing reducing the reflectivity to $\sim 80\%$. After this time, the rate of accumulation drops off and reflectivity only decreases slowly [19].

3.3. *Electronics response*

A programmable pulse generator (PPG) board in each crate allows a square pulse of varying width and amplitude to be injected into the input of the preamp of each PMT. Software is used to vary the pulse width and amplitude so that the electronics constants can be calculated. For QDCs the task is to relate the PPG pulses with QDC charge, and for TDCs it involves fitting TDC values to known length holdoff times. Electronics calibration is done at the start and end of each night.

3.3.1. *PMT pedestals, electronic noise and sky noise*

Part of the calibration process is the taking of 'snapshots' of the signals seen by the detector. For a period of a minute, PMTs are forced to repeatedly trigger in order to measure PMT pedestals, electronics noise and sky noise. The mean value of the QDC readout gives the electronics pedestal for the channel, and the rms variation provides a measure of the electronics and sky noise. Because of the AC-coupled PMT signal, pedestal values should be the same whether taken in a dark building with the doors closed, or taken when viewing the night sky. This has been observed to be true to within 0.2 QDC counts at HiRes 1. However, the noise contribution will differ depending upon whether the building doors are open or closed. Snapshot data taken with building doors closed are used to indicate electronics noise. Snapshot data taken with building doors open indicate the electronics noise combined (in quadrature) with the night sky noise. At HiRes 1, the combined electronics and sky noise was found to be 40 photoelectrons in channel A and 200 photoelectrons in channel B. Unfortunately, problems with the HiRes 2 electronics have prevented snapshot measurements from being used. However, the similar integration times imply that skynoise in each channel is probably similar.

3.3.2. *TDC calibration*

The TDC calibration is performed by using noise snapshots to start the TDCs and the holdoff counter. When the counter reaches a specified value it issues a signal to stop TDC integration. At HiRes 1 the holdoff times used range from 500 to 18 000 ns in 500 ns steps, with 20 TDC integrations performed at each step so that the mean and standard deviation of the TDC counts can be determined.

A linear function is then fitted to relate TDC values to the physical times.

A similar calibration range was initially used at HiRes 2, where the 15 bit TDCs were set at 0.65 ns per TDC count. In March 1995, the length of holdoff during data collection was increased from 10 to 25 μs, and the TDCs were changed from 0.65 to 1.5 ns/TDC count, giving a full-scale TDC range of 49 μs. In December 1995, the maximum holdoff time in TDC calibrations was extended from 18 μs to the hardware limit of 25 μs, so as to calibrate as much of the TDC range as possible. The hardware was then modified in February 1996 allowing calibration over the full range from 1 to 50 μs in 1 μs steps. Thus for data taken between March 1995 and February 1996, the calibration of the last half of the TDC range must be an extrapolation of the first 18 μs of data. The best functional fit to the HiRes 2 calibration data was also explored. A least-squares fit to a straight line was initially used, but investigations showed non-linearities in the TDC and thus a more suitable quadratic function was chosen instead.

3.4. *Atmospheric monitoring*

Effective monitoring of the atmosphere is a difficult and important challenge for the HiRes detector. The effective aperture, EAS light production and light propagation are affected by clouds, temperature variations, pressure variations and by the distribution of aerosols. With the prototype detector, atmospheric monitoring was performed through operator observations, an array of collimated UV light sources known as flashers, a permanent YAG laser system, and a portable telescope-mounted laser known as the Laserscope. Meteorological data were also available from the Dugway meteorological department, and a basic weather station measuring temperature and wind velocity was located at HiRes 2.

Within the 300–400 nm band, the predominant atmospheric attenuation processes are Rayleigh (molecular) and aerosol scattering [25]. Calculation of the Rayleigh attenuation of a light beam is straightforward, especially if a recent radiosonde sounding of the vertical density profile of the atmosphere is available. The aerosol attenuation is a more challenging problem, given the varying aerosol content of a typical atmosphere.

An array of flashers, the fixed YAG laser and the Laserscope are all used to monitor the aerosol content so as to estimate the extinction length on a nightly basis. All systems are used to generate a collimated beam of UV light into the atmosphere. Light will be scattered out of the beam and then be viewed by the HiRes detector at a variety of scattering angles. Light viewed at small angles is dominated by aerosol scattering whilst light viewed at large angles is dominated by Rayleigh scattering. Hence by knowing the orientation of the original beam, the scattering angles of the observed light can be determined, and thus it is possible to characterise the state of the atmosphere. Clouds and fog that cause large amounts of scattering can also be detected.

3.4.1. *Xenon flashers*

Xenon flashers consist of a xenon flash bulb located at the focal point of a 20 cm spherical mirror contained in a hermetically sealed cylindrical steel housing [23]. Flashers act as reverse telescopes with light from the flash bulb being collimated by the mirror to produce a beam that travels into the atmosphere through a pyrex window. The flashbulb produces a 1 μs 0.8 J light pulse with approximately 10% of energy falling in the 300–400 nm range. After taking into account geometrical effects and reflection and transmission losses, the pulse energy exiting the flasher is 0.2 mJ. Shot-to-shot variation is 5% (1σ).

The flasher units are designed to operate independently with power and electronics located in an adjacent box. Solar panels are used to charge the batteries that supply the power. A heater unit prevents the buildup of frost or snow on the window. The original flashers have circuits that will trigger the flasher to fire at a rate of ~ 1 Hz for 10 s, every ~ 7 min. Radio-controlled flashers have recently been developed and allow much greater flexibility in the use of flashers, allowing computer or operator control of triggering and heating [23].

Vertical flashers were originally developed for use by the Fly's Eye experiment and several flashers located around CASA and in the HiRes 1 field of view were retained. An array of vertical flashers was placed in the HiRes 2 field of view specifically for atmospheric monitoring [23,26]. Flashers are aligned along two 'legs' at distances of 1, 2, 4, 8 and 10 km from the detector, and along a given leg all flashers are viewed by the same set of PMTs (covering elevation angles from 3° to 30°).

Light from vertical flashers must scatter at angles close to 90° to be viewed by HiRes 2. Since the aerosol phase function is relatively independent of the details of the aerosol size distribution in this angular region, the received light intensity is primarily sensitive to the horizontal extinction length. Signals from flashers at different distances but the same emission angles are compared with reference nights and results from models to allow a measurement of the extinction length and aerosol content [23,25].

An inclined flasher, known as the intersite flasher (ISF), is located at the centre of CASA and aligned so that scattered light is visible by both detectors [27,28]. PMTs view light with scattering angles from 30° to 70°. Around 30° the intensity of the scattered light is strongly dependent on the density of aerosols whilst at viewing angles of 70° the intensity is mostly sensitive to Rayleigh scattering. Thus a quality ratio (QR) has been defined that compares the intensity in the first 5° of the track with the last 5°. Atmospheric models are used to interpret the QR results.

Quality ratio measurements are made every 7 min and measurements are available for all stereo data. The majority of nights have good atmospheric conditions (a selection effect given that the detector is only operated on reasonable nights) with 90% of the nights having horizontal extinction lengths between 18 km (purely Rayleigh) and 7 km (aerosol extinction length of 13 km). The variation over the night has also been studied and was generally found to be small (generally less than 1%). Not surprisingly, nights with higher aerosol content tend to be more unstable. The data from the intersite flasher have also been compared with those from the HiRes 2 flasher array. The two independent measurements of extinction length are well correlated [27].

3.4.2. Fixed YAG laser system

A steerable YAG laser system has been constructed at the centre of the Fly's Eye II/CASA site and is used in nightly atmospheric monitoring [25,29]. The system consists of a YAG laser which is frequency tripled to 355 nm. The YAG fires 10 ns pulses with energies up to 50 mJ, at a rate of 1 Hz. The beam is well collimated with a divergence of 10 mrad, and is directed to the atmosphere using a series of mirrors. Mirror directions are controlled by stepper motors which allow pointing to any azimuth or zenith angle to within 0.1°. A personal computer is used to control and monitor the system, and is set up so that it may be operated remotely by the HiRes operators. Each hour, the laser fires 0.4 mJ shots in a pattern of eight equispaced azimuthal directions at zenith angles of 0°, 30°, 45° and 60°. The laser is powerful enough that the scattered light is visible by both detectors.

3.4.3. Laserscope

In addition to the fixed YAG laser system, a portable laser system known as the Laserscope has been developed [16]. The Laserscope consists of a commercial YAG laser (frequency tripled to 355 nm) mounted on a commercial Meade LX-200 telescope. The laser produces a 5 ns pulse with a nominal energy of 4 mJ, with the direction given by the telescope which has a pointing accuracy of 5 min of arc. An energy probe and a radiometer are used to measure the energy of each pulse.

The head of the laser, the optics and energy probe are contained in a custom-made box mounted on the telescope. The laser is aligned with the telescope at the start and end of each night, and the telescope is aligned with several stars to check its absolute pointing accuracy. A personal computer is used to control and log telescope pointing, laser triggering and energy monitoring. Triggering time is recorded to the nearest second. A GPS system has been developed to trigger the laser on the start of each UTC second.

The Laserscope was designed with several applications in mind. In addition to atmospheric monitoring, it can be used to generate a set of reference events for testing reconstruction resolution [11] and for checking PMT/mirror pointing directions [16].

4. Conclusion

The two-site HiRes prototype detector was operational for just over two years. It has been succeeded by the full detector, with the HiRes 1 site being completed in 1998 and the HiRes 2 site in 1999. Both sites now view the full 360° of azimuth. HiRes 1 consists of 22 mirror units viewing the elevation range from 3° to 17°, while HiRes 2 views elevations from 3° to 30° with a total of 43 mirror units. The sample and hold electronics used in the prototype detectors has been implemented at HiRes 1. At HiRes 2, new flash ADC electronics has been installed to measure the pulse shapes with 10 MHz sampling.

The HiRes prototype has been an invaluable instrument for investigating the design and performance of this next-generation cosmic ray observatory. At the same time, a physics study has been underway, using the prototype in coincidence with the MIA muon array to investigate the mass composition of cosmic rays at the lower end of the energy range to be covered by HiRes, from 10^{17} to 10^{18} eV [19,30].

Acknowledgements

We are indebted to the staff of Dugway Proving Grounds for their continued cooperation and assistance. It is also a pleasure to acknowledge the support of the technical staff at our institutions. This work is funded in part by the National Science Foundation under grant numbers PHY 95-12810, 93-22298, 93-21949, 92-15987 and the Australian Research Council.

References

[1] K. Greisen, Phys. Rev. Lett. 16 (1966) 748.
[2] G.T. Zatsepin, V.A. Kuzmin, JETP Lett. 4 (1966) 78.
[3] R.M. Baltrusaitis et al., Nucl. Instr. and Meth. A 240 (1985) 410.
[4] University of Utah, Staged construction proposal for the high resolution Fly's Eye (HiRes) detector, NSF Proposal, 1993.
[5] D.J. Bird et al., Phys. Rev. Lett. 71 (1993) 3401.
[6] G.L. Cassiday, Ann. Rev. Nucl. Part. Sci. 35 (1985) 321.
[7] B.R. Dawson, Fluorescence detector techniques, Proceedings of the Auger Meeting on Nitrogen Fluorescence Cosmic Ray Detectors, Salt Lake City, Pierre Auger Project Technical Paper GAP-96-017, 1996. (www.auger.org/admin/GAP_Notes/).
[8] W. Au et al., Proceedings of 22nd International Cosmic Ray Conference, Dublin, vol. 2, 1991, p. 692.
[9] D.J. Bird et al., Proceedings of 23rd International Cosmic Ray Conference, Calgary, vol. 2, 1993, p. 462.
[10] D.J. Bird et al., Proceedings of 24th International Cosmic Ray Conference, Rome, vol. 3, 1995, p. 548.
[11] C.R. Wilkinson et al., Geometrical reconstruction with the high resolution Fly's Eye prototype cosmic ray detector, Astropart. Phys. 12 (1999) 121.
[12] E.C. Loh, in: M. Nagano (Ed.), Proceedings of Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays, ICRR, University of Tokyo, 1993, p. 219.
[13] S. Thomas, University of Utah, Personal communication, 1996.
[14] J.W. Elbert, in: M. Nagano (Ed.), Proceedings of Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays, ICRR, University of Tokyo, 1993, p. 232.
[15] T. Abu-Zayyad et al., Proceedings of 25th International Cosmic Ray Conference, Durban, vol. 5, 1997, p. 333.
[16] T. Abu-Zayyad et al., Proceedings of 25th International Cosmic Ray Conference, Durban, vol. 5, 1997, p. 349.
[17] D.J. Bird et al., Nucl. Instr. and Meth. A 349 (1994) 592.
[18] J. Smith, in: M. Nagano (Ed.), Proceedings of Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays, ICRR, University of Tokyo, 1993, p. 250.
[19] M.J. Kidd, Properties of extensive air showers around 10^{17} eV, Ph.D. Thesis, University of Illinois, 1997.
[20] D.J. Bird et al., Proceedings of 24th International Cosmic Ray Conference, Rome, vol. 3, 1995, p. 746.
[21] C.R. Wilkinson, The application of high precision timing in the high resolution Fly's Eye cosmic ray detector, Ph.D. Thesis, University of Adelaide, 1998.
[22] J. Smith, in: M. Nagano (Ed.), Proceedings of Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays, ICRR, University of Tokyo, 1993, p. 265.
[23] L.R. Wiencke et al., Nucl. Instr. and Meth. A 428 (1999) 593.
[24] J.N. Matthews et al., The absolute calibration of HiRes 1, Internal Note, University of Utah, 1997.
[25] P. Sokolsky, in: M. Nagano (Ed.), Proceedings of International Symposium on Extremely High Energy Cosmic Rays: Astrophysics and Future Observatories, ICRR, University of Tokyo, 1996, p. 253.
[26] T. Abu-Zayyad et al., Proceedings of 25th International Cosmic Ray Conference, Durban, vol. 5, 1997, p. 361.
[27] D.J. Bird et al., Atmospheric scattering studies using the high resolution Fly's Eye cosmic ray detector, in preparation.

[28] T. Abu-Zayyad et al., Proceedings of 25th International Cosmic Ray Conference, Durban, vol. 5, 1997, p. 345.
[29] T. Abu-Zayyad et al., Proceedings of 25th International Cosmic Ray Conference, Durban, vol. 5, 1997, p. 365.
[30] T. Abu-Zayyad et al., HiRes/MIA measurements of EAS development between 10^{17} and 10^{18} eV, Proceedings of 26th International Cosmic Ray Conference, Salt Lake City, vol. 5, 1999, p. 365.