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A fiber-optic based calibration system for the HiRes Experiment

G. Archbold, for the HiRes Collaboration

High Energy Astrophysics Institute, Physics Dept, Univ. of Utah

Abstract. This article describes a fiber-optic based calibration system installed at the High Resolution Fly's Eye (HiRes) astro-particle physics observatory. The HiRes detectors measure ultra-violet scintillation light from distant extensive air showers. This automated calibration system delivers light from a frequency-tripled (355nm) YAG laser to the 10,762 photo-multiplier tubes of the 42 HiRes-II detectors. The design, implementation, operation, and use of the system will be reviewed.

1 Introduction

1.1 Air fluorescence measurements

The High Resolution Fly's Eye experiment (HiRes) studies ultra high energy particles that interact in the earth's atmosphere. The interaction of secondary particles traveling through the atmosphere at nearly the speed of light creates an extensive air shower (EAS). The collision of the secondary charged particles with atmospheric nitrogen generates ultra-violet scintillation light. To first order, the amount of light produced is proportional to the energy of the primary particle. A main objective of the HiRes experiment is to find what sources in the universe can accelerate particles above $10^{19}eV$ (Baltrusaitis et al., 1985).

1.2 The HiRes Experiment

Two observatories, HiRes-I and HiRes-II, are operated in the Utah west desert at the US Army Dugway Proving Ground, approximately 160 km southwest of Salt Lake City. The observatories have a total of 64 detectors and 16,384 photo-multiplier tubes (PMTs) that record scintillation light from EASs.

Each detector has a spherical mirror with an effective area of 3.88 m^2 that focuses light onto a cluster of 256 PMTs. Each PMT views a $1^\circ \times 1^\circ$ patch of the sky. The detectors are arranged such that the HiRes-II's 42 detectors view nearly 360° in azimuth and a range from 3° to 31° in elevation. HiRes-I is located 12.6 km away and features 22 similar detectors and has half the angular coverage of HiRes-II (nearly 360° in azimuth and a range from 3° to 17.5° in elevation).

The data acquisition system of HiRes-II observatory uses flash analog/digital converters (FADCs) with a sampling period of 100 $\mathrm{n}s$ to digitize signals from the PMTs (Abu-Zayad et al., 1997). Using the pointing directions and charge distributions of each PMT associated with an EAS, the shower direction, energy and longitudinal profile can be reconstructed.

1.3 Overview of the Hires-II calibration system

The fiber optic calibration system (Girard et al., 2000) was designed to perform a relative calibration of the HiRes-II detectors over the anticipated 5 year observation period and track the response of each detector including changes in PMT gain, electronic response, and reflectivity of each mirror. Hence light from the calibration system must be distributed to all detectors at the HiRes-II site in a uniform and stable manner (compared to the typical 10-30 % combined systematic uncertainties associated with scintillation measurements of air showers).

To obtain this stability, a single light source is located in a clean, temperature-controlled environment and distributed to the detector via fiber-optics. Each fiber runs in a single piece from the source to the detector, decoupling the calibration system from the EAS detectors, which are exposed to the ambient desert climate. The relative intensity of each light pulse is measured and recorded by a monitoring system located in the same controlled environment as the source.

A pulsed source is used because the PMT signal from an EAS crossing the field of view is also pulsed. To perform timing calibration, it is desirable to use pulses that have a fast rise time. To check the linearity of the HiRes detector and check the PMT response over the range of light recorded

Correspondence to: G. Archbold
(archbold@cosmic.utah.edu)

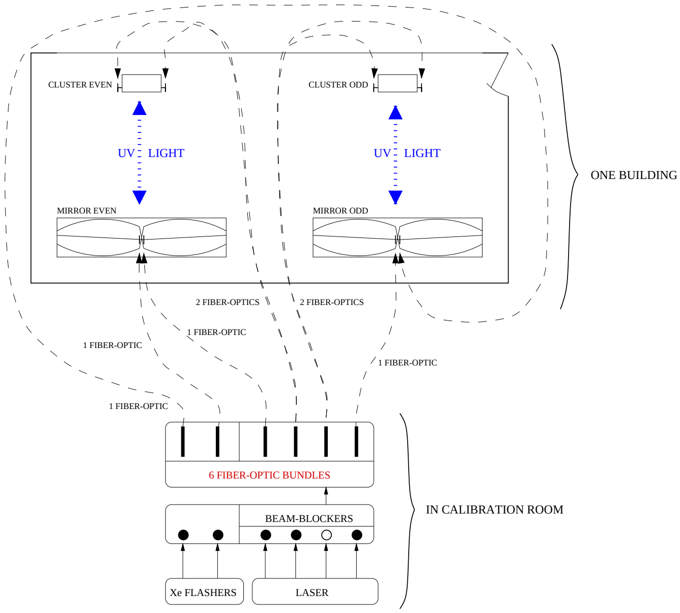

Fig. 1. Routing of the fibers of the HiRes-II calibration system from the light source to the detectors. One of 21 buildings is shown. The diagram is not to scale.

from air showers of different energies and geometries, the amount of calibration light can be varied in a controlled manner. The source wavelength lies within the 300 to 400 nm band of nitrogen scintillation in air.

The system is computer (PC) controlled to ensure routine operation, incorporate diagnostic routines, and allow remote operation. Physical access to hardware is limited to service work only.

Additionally, the design has the flexibility to incorporate light sources with different wavelengths and pulse durations, for example, lasers and broadband xenon flash-bulbs.

2 Delivering the light

The 42 detectors at HiRes-II are distributed in 21 buildings with two detectors per building. The calibration room is located in the middle of the site. Light from the source is transmitted through 168 continuous optical fibers (11 km total length) to each detector. The fibers range in length from approximately 40 to 100 m. Eight fibers are routed to each building (figure 1). Two fibers, dubbed “mirror fibers,” are routed to each building, with one going to the center of each mirror illuminating each PMT cluster directly. A second pair of fibers called, “cluster fibers,” is routed to each PMT cluster, one to each side. These fibers send light that is reflected by the mirrors back to the PMTs. A Teflon disk in front of each fiber diffuses the light to produce a point source.

At the source end the fibers are grouped into 6 bundles. Four “mirror” bundles each contain 21 mirror fibers, one from every building. Likewise, two “cluster” bundles contain 21 pairs of cluster fibers, one pair from a cluster in every building. By illuminating a single bundle at a time, the corresponding detectors (one per building) can be calibrated with no crosstalk of light from other fibers in the same building.

The light source, monitoring system, fiber bundles and associated optics are mounted on an optical table in the calibration room of the central facility (figure 2). The optical table is attached to steel pillars embedded in a concrete foundation. A black-anodized aluminum box covers the table to minimize reflections, light leaks, and contaminants such as dust.

The light source is a frequency tripled Nd:YAG laser (Big Sky Lasers, 2000). It generates 8 mJ pulses of 6 ns duration at a final wavelength of 355 nm. This wavelength lies close to the 357 nm scintillation line produced by EASs and between the two other main lines of 337 nm and 391 nm (Kakimoto et al., 1996).

Since the transmission efficiency of silica optical fibers increases with wavelength, it is important to eliminate the long wavelength components before the beam reaches the fiber bundles. Two 45° mirrors, specially coated to reflect 355 nm light, reduce the 1064 nm and 532 nm components in the beam to much less than 1%. Fibers of 210 μm diameter fused silica were selected for their transmission properties in the UV.

A fraction of the beam is sampled for shot-to-shot monitoring. A beam splitter redirects 1% of the light to a photodiode probe connected to a radiometer. The rest of the beam passes through a motorized eight-position filter wheel that can vary the amount of light transmitted to the EAS detectors by specific amounts. A second filter in front of the filter wheel reduces the final output to better match the dynamic range of the detectors. This filter can be removed temporarily to allow enough light through the system so that the fiber outputs in the detector buildings can be easily measured by a portable radiometer.

Three fixed 50% splitters and two fixed 100% reflecting mirrors divide the laser beam into four equally intense parts. Each is aligned with a different fiber bundle. Using four

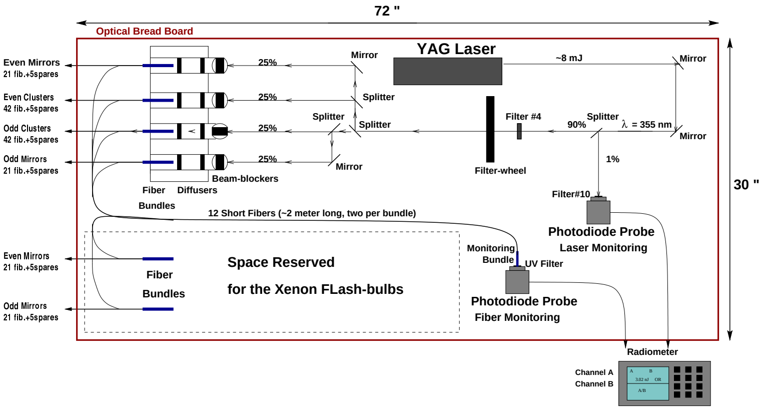

Fig. 2. Layout of the optical table in the calibration room.

computer-controlled, solenoid-actuated "beam-blockers," each beam part can be blocked or passed to illuminate its corresponding fiber bundle.

A diffuser fixed in front of each fiber bundle flattens the beam profile and removes any time varying local peaks. Fused silica windows were chosen for their high damage threshold in the UV range. Each diffuser consist of a pair of these windows, etched on one side and mounted in a threaded black-anodized tube.

At the source end, a bundle of 50 fibers form a close-packed 2 mm diameter circle which is smaller than the 3 mm diameter of the laser beam. To prepare the bundle, the fiber ends were stripped of their nylon jackets and gathered with heat-shrink tubing. This package was glued along the center of a 6.35 mm O.D. stainless steel tube with a UV transparent and resistant epoxy. After curing, the end was cut by a slow cut diamond saw. The resulting surface was smooth enough and did not require polishing.

At the detector end, each fiber end was stripped and cleaved to maximize light emission. A Teflon disk of a nominal thickness was placed in front (figure 3). After removing all filters in the beam path, the energy at all fiber outputs was measured with a portable radiometer and a photo-diode probe. The Teflon disks were exchanged with those of different thickness so that the output energies of all 168 fibers were between 40 and 60 pJ. This adjustment compensated for fiber-to-fiber differences in length and light coupling.

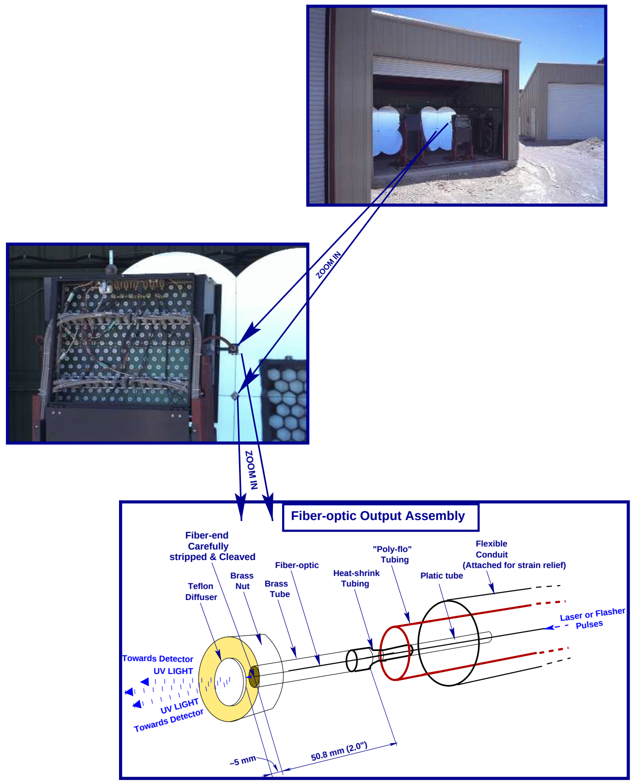

Fig. 3. One fiber output assembly.

3 Monitoring the light pulses

Two photo-diode probes monitor variations in the amount of light delivered to the fibers to normalize the corresponding signals measured by the HiRes detectors. The "laser monitoring" probe measures 1% of the laser beam sampled by a beam splitter. The "fiber monitoring" probe measures the relative amount of light sent through two short fibers in each bundle (figure 2). The two probes are connected to a two-channel radiometer that measures the pulse energies and sends the digitized measurements through a RS232 connection to the PC.

The laser monitoring probe is sensitive to changes in the laser output. The laser varies by about 5% RMS shot to shot. Measurements of this probe were compared to measurements of the remaining beam by a piezo-electric probe. In a lab test of 65,000 laser shots corresponding to several weeks of normal operation at HiRes-II, the RMS of the ratio between the two measurements was less than 1%.

The fiber monitoring probe is sensitive to changes in the laser output and to changes in all the beam line components including splitters, mirrors, filters, diffusers, and fiber bundles. Shot-to-shot measurements from the two monitors were correlated to better than 1% RMS over 150,000 laser shots. This places an upper limit on the contribution of the beam line components to the overall uncertainty of the monitoring

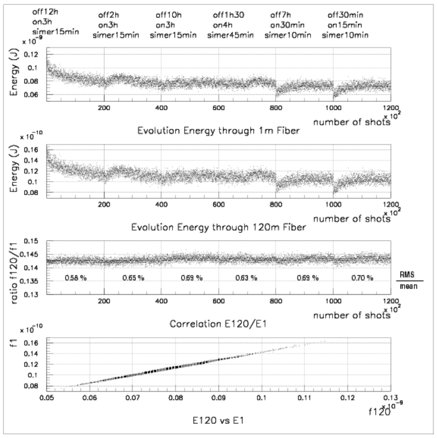

Fig. 4. Long test with interruptions (six trials of 20,000 shots). The measurements performed by two fibers of the test bundle are well correlated despite their difference in length and the laser fluctuations.

system.

Fiber monitoring measurements were found to track the amount of light delivered to other fibers in the same bundle at the level of 1%, even when fluctuations in the laser output were quite large. For these lab tests two photo-diode probes were used, one connected to a short monitor fiber and the second to a single 120 m long fiber. These fibers were separated by 1 mm in the test bundle. Figure 4 displays the results from six successive trials of 20,000 laser shots each. Generally the laser output energy for the six segments showed discontinuities if the laser warm-up time was shorter than an hour. The RMS of the ratio of light transmitted through these two fibers was between 0.58% and 0.70% for each trial. In another test the correlation was found to vary from 0.3% for adjacent fiber pairs to 1.0% for fibers on opposite sides of the test bundle.

Nightly, the laser output and each bundle output is monitored automatically. The laser fluctuates by 3% RMS to mean ratio. The corresponding fluctuation in the global pulse area measured by the 256 PMTs in a cluster is about 6%. This is consistent with an uncertainty of about 5% in the FADC measurement of the area of narrow laser pulses.

4 Relative calibration

The end use of the data is a relative calibration measurement for each tube. For each shot, the pedestal and pedestal-subtracted pulse area is found for each tube. The area is then normalized by the mean area for all tubes for that shot, removing any variations in the laser, fibers, and optical components. This normalized pulse area is called the relative gain.

Typically, 100 shots are fired for each tube each night, giving 100 relative gain measurements. The mean of those measurements is then stored in a database for use in correctly understanding tube response during EAS reconstruction. The mean relative gain of a typical tube over several months is shown in figure 5. The relative gain measurement from a night on which absolute calibration is performed can be correlated to the absolute gain measurement, anchoring the plot.

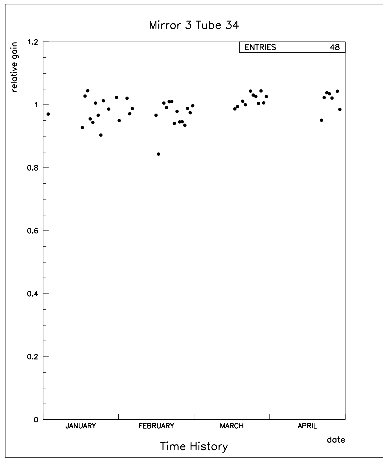

Fig. 5. Time History of relative gain of tube 34 in mirror 3. The RMS deviation is less than 4%.

5 Conclusion

The fiber-optic calibration system was installed at HiRes-II. 355nm light from a single YAG laser is distributed to more than ten thousand PMTs distributed in 21 buildings. The entire system can be operated remotely.

Differences in the amount of light delivered between detectors are within $\pm 10\%$. The relative shot-to-shot variation in the amount of light delivered is monitored to better than 1% by two different measurements. The ratio of light delivered between fibers was found to be stable at the 1% level over 150,000 laser shots which would correspond to six months of operation at the observatory.

Nightly monitoring of the stability of the calibration system continues, and the relative gain of each tube is tracked on a nightly basis.

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