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Design and performance of analog fiber optic links used on the Whipple 10 metre air Čerenkov telescope

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Abstract. The use of fiber optics instead of coaxial cable for signal transmission in atmospheric Čerenkov telescopes can reduce pulse dispersion and attenuation and so allow a shorter ADC gate to be used. Results indicate that the night sky background component could thus be significantly reduced. A prototype system of links is in use on the Whipple 10 m telescope and the performance has been assessed over more than a year of operation. The bandwidth is $150\ \mathrm{MHz}$ and the dynamic range of the output is from $2\ \mathrm{mV}$ to $1.0\ \mathrm{V}$. The average gain of the 120 channels is 4.1 and is stable to within a few percent over a typical 3 week observation period. The baseline noise level is $0.5\ \mathrm{mV\ rms}$ but this can increase to $6\ \mathrm{mV\ amplitude}$ at certain resonance points in the value of the laser bias current. The deviation from true linearity is typically less than $7\ \%$.

1 Introduction

The Whipple 10 m telescope camera consists of 379 close packed 13 mm photomultiplier tubes (PMTs) surrounded by three outer rings of 111 28 mm tubes (Finley et al. (2001)). The PMT signals are typically pulses lasting $7\ \mathrm{ns}$ FWHM with rise times of 1-2 ns. The signals are ordinarily transmitted over 50 m of coaxial cable to the electronics room where they are amplified and stored in 50 m of delay cable while awaiting the trigger decision. RG58 coaxial cable is used for most of this distance. A system of 120 fiber optic links was installed in 1999 and is used for the PMTs in the outer rings. The performance of this system was tested at installation and is continually monitored.

Fiber optic cable has a higher bandwidth and can reduce pulse dispersion and attenuation. Here, keeping the pulse width narrow offers the opportunity to reduce the ADC gate from 25 ns to 15 ns with the corresponding reduction in night sky background. In particular techniques to discriminate the gamma-rays from muons and hadrons at low energies are sensitive to noise and would benefit greatly from reduced background. Fiber optics also offer practical advantages in terms of weight, volume and lightning protection.

For a Čerenkov telescope array e.g. with telescopes spaced ∼80 m apart, a high bandwidth, low attenuation link would allow the signals to be brought together to a central data acquisition site. This facilitates the introduction of sophisticated triggering strategies to reduce the number of false array triggers due to cosmic rays and night-sky background (NSB) and hence give a lower energy threshold.

2 Design

The design of the transmitter electronics was based on the Honeywell vertical cavity surface emitting laser (VCSEL), HFE4085-321. This device offers the high coupled power output (1.25 mW typical coupled power) and fast response time (≈100 ps) necessary to meet the fall time and dynamic range performance specifications. The advantages of VCSELs over edge-emitting lasers are their low cost, good temperature stability and their circular symmetry which makes coupling into the fiber easier. The laser is contained within a TO-can which is mounted in an ST connector barrel. The laser is biased above threshold between 4 mA and 6 mA. The selection of bias current was based on the noise characteristics of each individual VCSEL. A schematic of the circuit design is shown in Figure 1. After the first stage voltage limited amplifier, the signal enters the OPA660 operational transconductance amplifier. This is capable of supplying a maximum current of 15 mA. Adding this to the bias current gives a maximum current through the laser of 20 mA. Honeywell have since reported that it is possible to drive the VCSEL at far greater currents for short pulses at low repetition rates. This would allow a greater dynamic range whilst increasing the signal-to-noise ratio. The overall weight of the package is 650 g for a 12 channel module of dimensions 220×65×46 mm. The power dissipated predominantly in the amplifiers is

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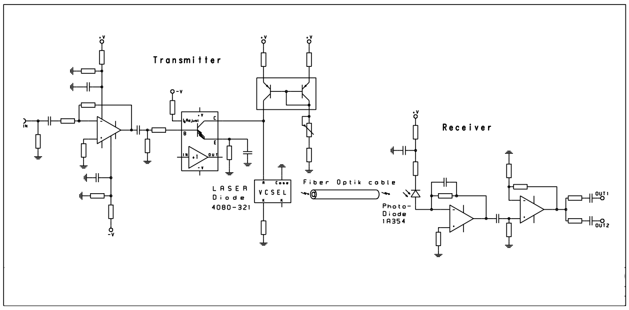

Fig. 1. Schematic of the circuit for the analog fiber optic link.

about 0.5 W per channel. This requires a substantial heatsink which contributes most of the weight.

The receivers use the Mitel 1A354 photodiode mounted in an ST housing. The 1A354 has a responsivity of 0.45 A/W. The maximum expected optical power coupled into the fiber is ≈1.5 mW. A transimpedance amplifier converts this to a voltage of about 0.1V. The OPA620 was chosen due to its low current noise (2.3 nV/sqrt(Hz) over a bandwidth of 200 MHz). A second amplifier is used to give an output of 1V for the maximum signal size. This matches the input range of the ADC (LeCroy Model 2249A) in the data acquisition electronics. The modules were constructed with 12-channel boards and are mounted in a 19” Euro sub rack.

The system uses 62.5/125 micron multimode graded index glass fiber. This has a bandwidth of 200 MHz/km which corresponds to 1.3 GHz over our cable. The cable had to be rugged, water resistent, UV resistent and rodent resistent. It also had to be able to tolerate the continual torsion and flexure due to the telescope movement. The 30 core cable was 12 mm in diameter and weighed 145.4 g/m. High quality ST connectors were attached at one end of the cable with a 50 cm length of tight buffered fibers broken out of the jacket. At the receiver end, the fibers were spliced to conventional 3 mm jacketed pigtails using a mechanical splice.

3 Performance

A 12 channel prototype was built at the Max-Plank-Institut fuer Physik in 1998. This showed good linearity, rise times, dynamic range and noise values. However the amplitude of the signal varied substantially as the fiber optic connector was touched. This occurred in more than 50% of the samples and these were rejected. The results from this assessment are given in Rose (2000).

3.1 Optical coupling

The use of a higher quality ST connector reduced the incidence of extreme instability but still approximately one-third of devices showed significant changes when touched. Furthermore, there was a large variation in the amount of light coupled into the fiber from each VCSEL. The wide spread in coupling efficiency means that the power launched into the fiber for a given input pulse height varies over a factor of three for our links. The resulting spread in the link gain can be compensated for by changing the amplification of the PMTs but this leads to early saturation of the drive electronics for low gain channels and an increase in noise for high gain channels. A link voltage gain of 5 corresponds to a power of 1 mW coupled into a 62.5/125 micron graded index multi-mode fiber. The average gain of the 120 channels is 4.1 and the standard deviation of the variation between channels is $\pm$ 2.3. This large variation in gain from channel to channel is also partly due to an attenuation of 1-3 dB in the fiber splices. These inexpensive, mechanical splices contributed significantly to the attenuation in the fiber and varied greatly from one to another. The mean fiber transmission, as measured by a calibrated source and power meter, is $\sim$78$\%$ with a standard deviation of 10.

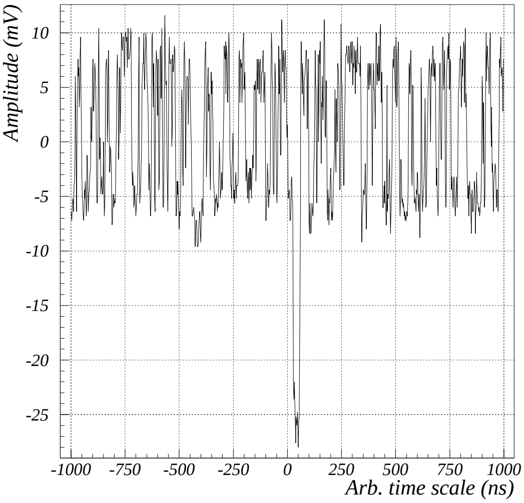

Fig. 2. A 30 mV signal against background noise recorded while the laser was in a resonant state.

3.2 Noise and bistability

The noise due to the laser varied erratically with bias current and showed strong resonances which sometimes took the form of square waves. Figure 2 shows an oscilloscope trace of the signal at a resonance point. The main peak is a signal pulse. During initial testing in the lab, 35% of the VCSELs showed fluctuating noise at around the chosen bias current (5 mA) and most of these were rejected. A related feature was that some devices showed a fluctuation in pulse amplitude particularly for large pulses. The pulse height varied between two amplitudes. The difference in amplitudes was 10%-50% of the correct pulse height.

It is suspected that these problems are a result of the transverse mode behaviour of the VCSELs which are 15 μm across and therefore can contain multiple optical modes. The initial mode is a central peak which should couple well into

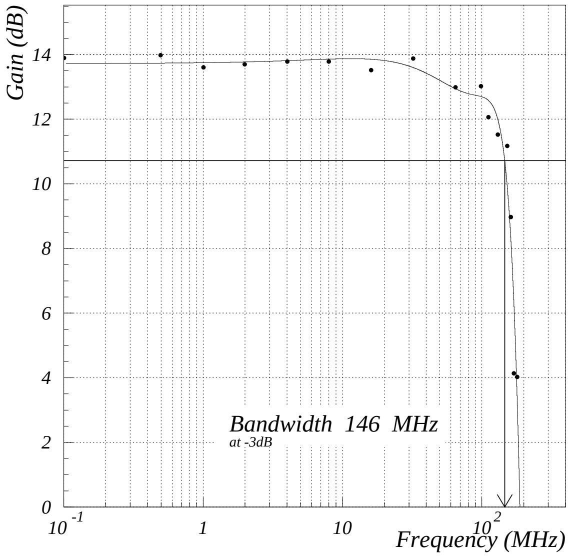

Fig. 3. Gain as a function of frequency.

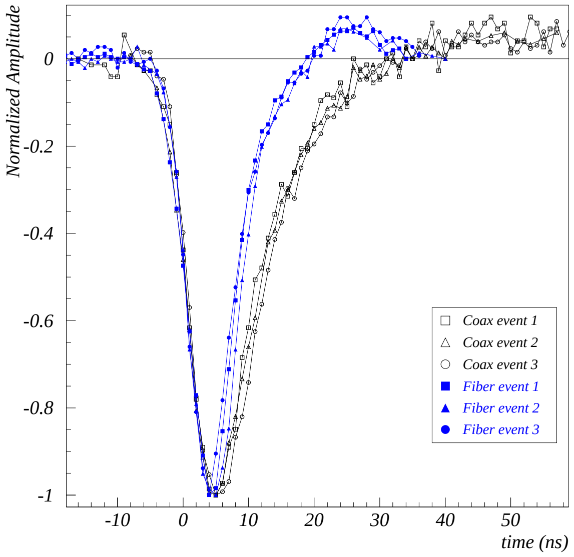

Fig. 4. Čerenkov pulse shapes from three pairs of PMTs taken from three air shower events. Each pair has one PMT connected via coaxial cable and one via fiber. The amplitudes have been normalised for comparison.

the fiber. As the amplitude of the pulse is increased, higher modes are excited. This changes the distribution of light emission across the surface. If the light from the different areas is coupled with different efficiency then problems such as those observed arise.

The noise contributed by the fiber optic links was measured in two ways. Firstly, a series of data runs were taken with the high voltage to the PMTs turned off. The ADCs therefore measured the link noise integrated over 25 ns. A series of 5000 readings was taken for each link. The mean noise contributed by the fiber links is 1.0 ADC counts, as compared to the 0.8 ADC counts contributed by the amplifiers in the coaxial cable links.

With the current pixel sizes and high voltage settings at the Whipple telescope the night-sky background for the fiber channels is about 2.3 ADC counts and that of the coax channels is 4.8 ADC counts.

Additionally the noise for each link was measured over 500 ns using an oscilloscope with a 1 GHz sample rate. An average noise level of $0.5\ \mathrm{mV\ rms}$ with a standard deviation of 0.4 was obtained for 115 links after 3 months of operation. The rms noise is correlated to the gain of the channel. The system was designed to give a gain of 5. Those channels with a gain of ~5 show a rms noise of about 1 mV.

3.3 Rise time and bandwidth

The bandwidth of the transmitter and receiver system was tested in the laboratory with a 3 m fiber cable. Figure 3 shows the amplitude versus the frequency for an input sine wave of amplitude 5 mV. For the telescope system the fiber is 94 m long but will contribute only about 0.3 ns to the rise time with the transmitter and receiver electronics contributing about 1.9 ns. Oscilloscope traces were taken of Čerenkov events observed in two adjacent PMTs, one of which was transmitted through fiber and one through coaxial cable. This was done three times with different pairs of channels as shown in Figure 4. The pulse heights have been normalised to show the relative dispersion in the two channels. The FWHM for the fiber channels is 8 ns as opposed to 12 ns for the coaxial cable channels. In total the pulses that have been transmitted through the coaxial cable are longer by 10 ns. This illustrates the potential advantage of fiber optic links in this application. With the current system, reducing the ADC gate from 25 ns to 15 ns would increase the signal to noise ratio by $\sim 25\%$.

3.4 Linearity

The linearity of a fiber channel which showed no excess noise or bistability was measured using an electrical pulse generator. The graphs shown in Figure 5 give the output pulse amplitude as a function of the input pulse amplitude and the deviation from true linear behaviour. The channel has a gain of 7.6 with less than 7% deviation from perfect linear behaviour. The linearity of all of the channels was assessed by illuminating the camera with the nitrogen flasher at different levels of attenuation to give pulses over the whole dynamic range. Although there was often some nonlinearity, with the gain relative to that of the non-fiber channels varying by of the order of ± 20 % over the full dynamic range of the ADCs, it is quite a stable phenomenon and could be corrected for in software calibration. This non-linearity is probably due to mode switching and might be reduced if the optical coupling

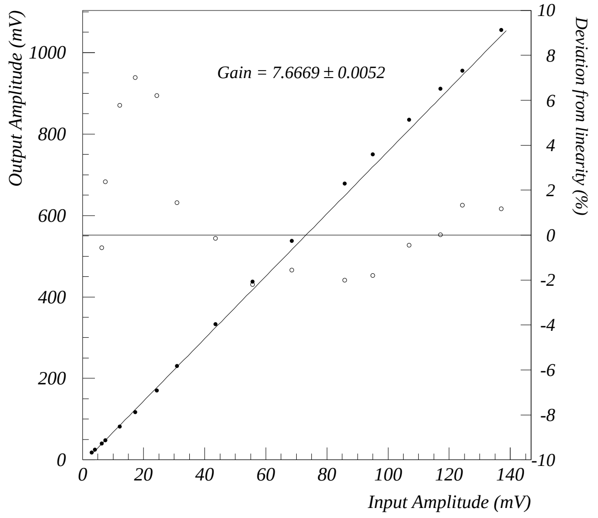

Fig. 5. The output amplitude is plotted against the input amplitude in filled circles (left hand scale). The deviation from true linearity is shown in open circles (right hand scale).

were improved.

3.5 Reliability

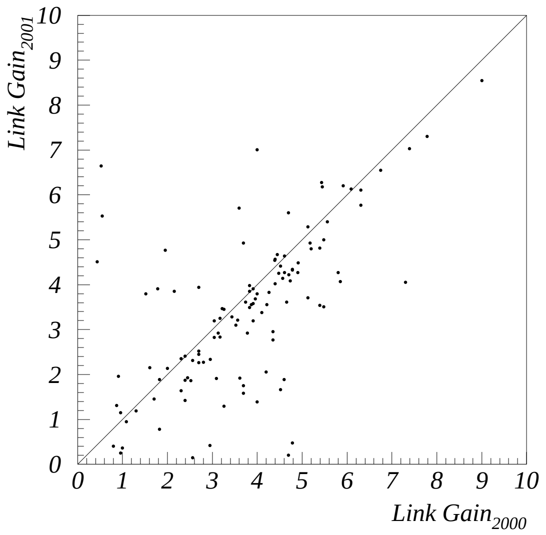

Fig. 6. Gain of the fiber links at installation versus gain after one year of operation on the Whipple 10 m telescope.

The performance of all of the channels is continuously monitored by examining the gains calculated during the routine calibration of the camera at the beginning of each observing night. The stability of the gains of individual channels over a 20 day period was found to be better than 3% as a percentage of the mean gain. In addition, the gain of the fiber links themselves was measured using a test pulse input directly to each transmitter at the beginning and end of the first year of operation. As shown in Figure 6, a reasonable correlation exists between the two link gain measurements.

Excluding infant mortality the failure rate of the fiber links is less than 2 per year. When a channel fails it is a time consuming task to get access to the fibers to test them and to replace bad channels. This will be simplified in future designs.

4 Conclusion

Where there was good coupling between the VCSEL and the fiber, the links gave high performance. They showed acceptable linearity with low noise and were able to transmit the Čerenkov pulses with minimal distortion. A new design incorporating improvements to both the electronics and the fiber optics is envisaged.

In practical terms, the fibers were found to need a high degree of protection and delicate handling and attention has to be given to laser safety issues. There are still some issues to be addressed in terms of coupling the light into the fiber more reliably. The performance of the good channels was well within our specification. Fiber links offer the potential of a useful alternative to coaxial cable for high bandwidth analog signal transmission.

5 Acknowledgements

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