A low cost system for implementing FADCs in imaging atmospheric Ĉerenkov astronomy

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Abstract. The success of early imaging cameras in ground based Ĉerenkov astronomy has led to demand for increased imaging resolution. New camera designs, both proposed and already built, contain many hundreds of photomultiplier tubes. In this paper we present a low cost system based on commercially available analogue switches which reduces the number of charge analogue to digital converters (ADCs) needed to instrument a Ĉerenkov imaging camera. A further benefit of this system is that it reduces the amount of data recorded for each image - which is useful if flash ADCs are used. Detailed Monte Carlo simulations of an atmospheric Ĉerenkov detector are used to demonstrate the feasibility of the proposed system. We present results of tests on switching circuits which could be used to build such a system and we discuss the implications of the triggering requirements on the quality of the imaging that can be achieved.

1. Introduction

While the field of ground based Ĉerenkov astronomy has been active for more than 30 years, it is only since the advent of the imaging technique that consistent and believable results have been achieved. The imaging technique uses a "camera" consisting of an array of photomultiplier tubes (PMTs) viewing a mirror which is typically several tens of square meters in area. The angular resolution of the camera provides a measurement of the arrival direction of the primary and the longitudinal and lateral development of the extensive air shower allowing for the selection of gamma-ray candidates from the overwhelming hadronic background.

Currently operating Imaging Atmospheric Ĉerenkov Telescopes (IACT) have cameras with hundreds of PMTs (CANGAROO, Whipple, CAT, Durham and HEGRA telescopes) and proposed multi-telescope arrays such as VERITAS and HESS will use thousands of pixels. While increased camera resolution provides lower energy thresholds and more efficient gamma/hadron separation, it also leads to much greater cost in instrumenting the PMTs of the camera. The need for good quality charge information necessitates the use of expensive ADCs that can be gated quickly enough (<20ns) to reduce contamination of the Ĉerenkov signal by electronic and sky background noise. A further refinement would be to have each PMT signal read by a high bandwidth flash

ADC (FADC), which would allow an a-posteriori selection of the part of the PMT pulse corresponding to the Ĉerenkov flash. Despite the advantages of FADCs, instrumenting each PMT in a large camera with them is difficult because of the high cost involved and the large amount of data that would be generated.

2. A reduced ADC/FADC system

The system that we propose takes advantage of the compact nature of the Ĉerenkov images to reduce the number of ADC channels needed. Each image consists of a number of photons that illuminate a small number of typically co-located pixels. In the vast majority of Ĉerenkov images only a small fraction of the total number of pixels are exposed to any Ĉerenkov light at all. In its most basic form a reduced ADC system can be implemented by selecting groups of PMTs that are well separated in the camera and feeding them into a common ADC. An analogue switch isolates each PMT from the ADC unless its discriminator has fired (see figure 1).

If all PMTs in a common ADC are sufficiently well separated then only a maximum of one PMT per common ADC should be part of the Ĉerenkov image. By recording which discriminators have fired it is then possible to uniquely assign the charge recorded by an ADC to the correct image tube. In this way the number of ADCs required is reduced without degrading the signal to noise ratio of the charge measurement of any image tube. As well as reduced cost, this system has the further benefit of reducing the readout time of the electronics. This is particularly important if the ADCs are replaced by FADCs.

High bandwidth analogue switches, such as those used in fast video switching applications, are cheap and readily available. These are tri-state devices allowing PMT channels that are not activated to be isolated from the bus that feeds the ADC input.

The circuit shown in figure 1, while simple to implement, has a serious limitation - only the signals for those PMTs whose discriminators fire can be recorded. The discriminator levels must be set sufficiently high that both the trigger generation and ADC system are not affected by a high rate of “accidental” triggers. We will consider a more sophisticated system where a PMT whose discriminator triggers not only enables its own ADC, but also enables ADCs for those PMTs that are direct neighbors (a total of 9 PMTs). While this triggering condition complicates the circuit wiring, it should be possible to route the switch enabling signals easily because the demands on the bandwidth of the the gating signal are quite small. We envisage that the switch enabling

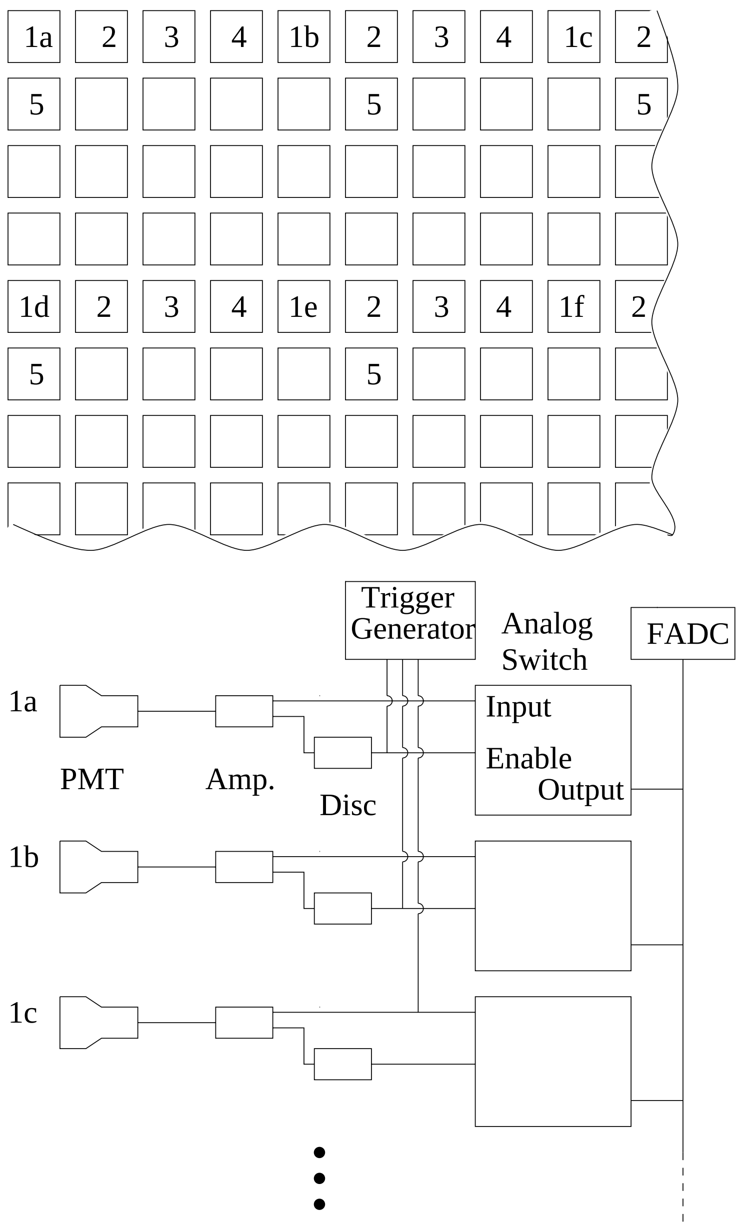

Figure 1. A simple schematic example of the reduced ADC system. PMTs in the camera, that are physically well separated, are connected to a common ADC via analogue switches (all PMTs with the same number label will have a common ADC). If there is a total of 576 PMTs in the camera, this example has a "multiplicity" of 36 (groups of 36 PMTs will share a common ADC). The signal from a PMT is only sent to the ADC if its discriminator fires and enables the switch.

signal will be $\sim$40ns in duration allowing 10ns each for switching the signal on and off, with a "signal region" of 20ns. Any switching jitter or transient at the beginning or end of the signal region is not important because it will be outside of the ADC gate.

3. Monte Carlo Simulations

We have tested the proposed ADC system with detailed simulations based on the CORSIKA EAS simulation package. We have considered a generic high resolution imaging telescope with a 7m diameter reflector at sea level and a camera consisting of a square array grid of 576 (24 X 24) photomultipliers subtending a total FOV of 3.6° (side-side).We describe the noise characteristics of the telescope by extrapolating the measured noise performance of existing telescopes to the system described above ((Barrau, 1998)). Background noise has been added to each PMT signal from a distribution based on a mean arrival rate of sky background photoelectrons of 0.03/ns/pixel. Also included is the effect of AC coupling (based on an RC time constant of 5μs) and gaussian distributed electronic noise with a SD of 1/2 photoelectron for a 15ns ADC gate.

We have chosen a trigger condition that requires at least 4 PMTs to exceed 8.0 photoelectrons producing an estimated singlefold rate of $\sim$3kHz. The singlefold PMT rates have an important effect on the ADC system that we are considering here. As the singlefold rates increase there is a larger probability that a tube discriminator not associated with the Ĉerenkov image will fire and enable its ADC during the arrival of the Ĉerenkov signal. While it may be possible to minimized the effect of many of these "accidental" events with software processing it is desirable to keep the image contamination rate low at the hardware level. At a singlefold rate of 3kHz only a few percent of images should suffer from a noise-based tube trigger within 60ns of the image signal.

Using CORSIKA, we have generated a library of gamma-ray and cosmic ray images. The gamma-ray energy threshold for triggered events is 300GeV. We have simulated gamma-rays from a point source at the center of the camera. The minimum gamma-ray energy is 100GeV and the integral source spectral index is 1.4. Background protons, with a minimum energy of 200GeV, have also been simulated.

We have implemented the reduced ADC system by selecting groups of PMTs from evenly spaced square grids to be connected to a common ADC. We have considered the cases of 1X1 (one ADC per PMT) 2X2 .... 6X6 multiplicities where 1, 4 .... 36 PMTs respectively are sent to the same ADC. From here on we will use the term "multiplicity" to refer to the number of PMTs that share a common ADC channel. With each ADC being connected to a number of PMTs it is inevitable that some images will cause more than one PMT signal to be switched into the same ADC. Cosmic ray images will be most susceptible to this problem because they are generally larger than the gamma-ray images and produce small amounts of light well away from the main image. Multiple signals in one ADC will cause a number of problems : more than one Ĉerenkov signal, background noise from more than one PMT and a change in the impedance of the ADC bus as more than one switch is activated. Although it is possible that an algorithm could be developed to recover some information in the case of multiple triggering, we will not include any such PMT signals in our analysis of an image.

The gamma-ray selection domain is optimized for the standard width, length and alpha parameters. When deciding which PMTs will be included in the image we have made the standard image/border selection - optimized to give the best signal enhancement. We compare the imaging quality for each ADC multiplicity by measuring the quality factor of the discrimination between the gamma-rays and the hadrons, where the quality factor (q) is defined as

$$q = \frac{\frac{N_\gamma acc}{N_\gamma tot}}{\sqrt{\frac{N_p acc}{N_p tot}}} \tag{1}$$

where $N_\gamma acc$ and $N_p acc$ are the number of gamma-rays and protons respectively accepted by the imaging cuts from the total number of gamma-rays ($N_\gamma tot$) and protons ($N_p tot$). In all cases the total number of gammas and protons are defined as the raw number that satisfy the trigger conditions of the camera. The quality factor for each ADC multiplicity is shown in figure 2.

4. Hardware tests

We have made some basic tests on switching fast signals by constructing a circuit with four analogue switches connected to an ADC bus. For the analogue switch we have chosen the Analog Devices' AD8182. This device is cheap (∼US10 per channel), has a fast switching time (∼10ns) and high bandwidth (750MHz - 3dB). The high impedance state of the output provides 50dB of attenuation at 200MHz allowing non-signal channels to be effectively isolated from the ADC bus. We have used a fast pulse generator and a digital oscilloscope to verify the performance of the switches. We find that signals passing through the

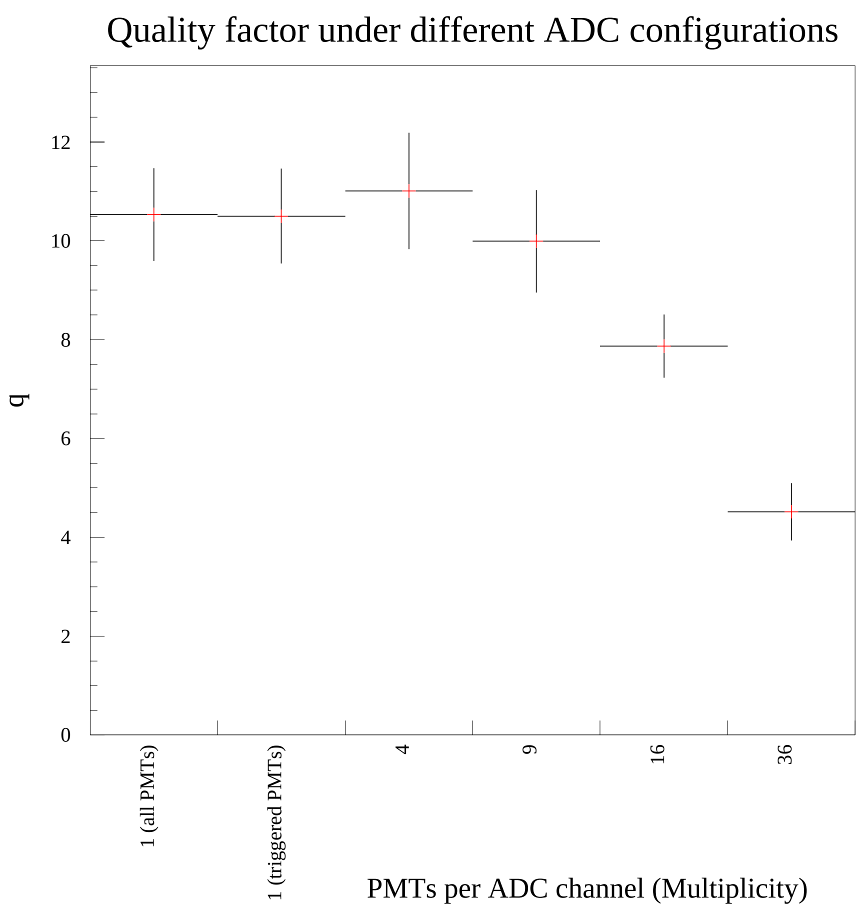

Figure 2. Quality factor for imaging vs "multiplicity", where multiplicity is the number of PMTs that share a common ADC. The left most point shows a "standard" system where each PMT has an ADC and all ADCs are recorded for each image. Up to a multiplicity of 9 (3X3 array of PMTs separated by 1.2°), there is no degradation of the imaging quality.

switches are faithfully reproduced on the ADC bus up to the bandwidth limit (200MHz) of the oscilloscope.

Based on the noise characteristics and dynamic range of the switch we estimate that it has a dynamic range for charge measurement of 9-10 bits (for a 6ns wide symmetric pulse).

5. Discussion

A large effort is currently being made to reduce the energy threshold of IACTs to below 100GeV. For array type experiments, which will consist of a number of telescopes of similar size to those already existing, the small Ĉerenkov images from low energy gamma-rays will be strongly affected by the night sky background. A considerable improvement can be made to charge measurement if the fixed gate ADCs are replaced by fast sampling FADCs, which allow an a-posteriori selection of the part of the PMT pulse corresponding to the Ĉerenkov flash. FADCs are also optimal in a system where multiple separated mirrors are used to generate an event trigger. In this case cable delays between telescopes lead to a delay in trigger generation of several hundreds of nano-seconds. Using a FADC with a deep memory the Ĉerenkov signal can be recovered with no loss of S/N and without needing to sample-and-hold at high rate at each telescope while coincidences are decided. Despite the advantages of FADCs instrumenting each PMT in a large camera with them is difficult because of the high cost involved and the large amount of data that would be generated.

Figure 2 shows that it is possible, using cheap and simple circuitry, to reduce the number of FADCs needed to instrument a camera by almost a factor of 10 without degrading the gamma-ray discrimination capability.

The exact reduction in the number of required ADCs will depend strongly on the telescope under consideration (angular extent of the camera, how fine the pixelation is, the trigger arrangement etc). Detailed simulations would need to be made of any camera system to determine the exact benefits of implementing the reduced ADC system. The savings in the number of ADC channels achieved and the reduction in the amount of data recorded could then be judged against the cost of implementing the reduced ADC system.

6. Conclusion

We have presented the results of Monte Carlo simulations of a reduced ADC/FADC system for imaging atmospheric Ĉerenkov astronomy. The system takes advantage of the compact nature of gamma-ray images to make a hardware selection on which PMT signals will be recorded. Our simulations show that the number of ADC/FADC channels needed can be reduced by an order of magnitude for a 576 pixel camera subtending 3.6°.

References

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