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Analysis of Flash ADC Data With VERITAS

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Abstract: VERITAS employs a 12m segmented mirror and pixellated photomultiplier tube camera to detect the brief pulse of Cherenkov radiation produced by the extensive air shower initiated by a cosmic high-energy gamma ray. The VERITAS data acquisition system consists of a 500 Mega-Sample-Per-Second custom-built flash ADC system, which samples the Cherenkov light pulse every 2 nanoseconds. The integrated charge in each flash ADC channel is proportional to the amount of Cherenkov light incident on the corresponding photomultiplier tube. Accurate reconstruction of the integrated charge is required for accurate energy estimation and spectral reconstruction. A reliable calculation of the integrated charge at low intensities can lead to a reduction in the energy threshold of the system, and an increase in sensitivity. This paper investigates and compares several approaches for evaluating the integrated charge. The Cherenkov pulse timing information in the flash ADC readout has the potential to assist in background rejection techniques. Various methods for extracting the timing information are investigated and excellent timing resolution is achieved.

Introduction

There are many methods [1] which can be used to evaluate the digitised Cherenkov signal produced by the VERITAS FADC [2] system. In this paper, five such methods (referred to as *trace evaluators*) are described and the charge integration characteristics of each method compared using a Monte-Carlo simulated photon data set. This study could aid accurate reconstruction of low-intensity events, which is one of the most challenging aspects of the analysis of Cherenkov telescope data. Laser [3] calibration data are used to compare the timing resolution inherent to each trace evaluator, and a digital processing scheme which can further enhance the timing resolution is introduced. These methods have been developed and implemented with VEGAS [4].

Methods

In this section each trace evaluator will be described and the manner in which the integrated charge and pulse arrival time is calculated is discussed. The integrated charge is defined as the sum of the trace in digital counts over some integration window. The pulse arrival time (hereafter T_0) is defined as the time at which the pulse reaches 50% of its absolute maximum.

The first method is the *simple-window* trace evaluator which assumes a-priori knowledge of the location of the Cherenkov pulse in the readout window. The second method is the *dynamic-window* trace evaluator which improves on charge integration by sliding an integration window along the readout window to seek the Cherenkov pulse. The first two evaluators only calculate T_0 to the nearest sample. The third method is the *linear-interpolation* trace evaluator. This is not significantly different in terms of charge integration, but substantially improves on the calculation of T_0. The fourth method is the *trace-fit* trace evaluator which fits the following function to each trace:

$$q(t) = \begin{cases} q_0 \exp \frac{-(t-t_0)^2}{2\sigma^2} & \text{for} \quad t \le t_0 \\ q_0 \exp \frac{-(t-t_0)^2}{2\sigma^2+\alpha(t-t_0)} & \text{for} \quad t > t_0 \end{cases} \quad (1)$$

In this equation, $q(t)$ is the FADC charge at time t, t_0 is the time of trace maximum, q_0 is the trace amplitude at $t = t_0$, and σ and α are parameters describing the shape of the trace. This fit function essentially has an asymmetric-Gaussian shape and improves the calculation of T_0 over the *simple-window* method. The fifth method is the *matched-filter* trace evaluator which uses a digital filter based on the assumed shape of the FADC pulse to integrate the charge. The *matched-filter* trace evaluator is a somewhat more sophisticated than the other methods, thus it is described here in more detail.

A *matched filter* is so called because its shape is defined by the expected form of the received data. The *matched filter*'s pulse shape is a time-reversed version of the expected pulse shape. Thus for an expected pulse shape $h(t)$, the ideal *matched-filter* $h_m(t)$ is

$$h_m(t) = h(T - t) \qquad (2)$$

for $0 \leq t \leq T$ where T corresponds to the end of the trace. The output from a filtering application is calculated by a convolution of the input with the filter

$$y(t) = \int_0^T r(t) h_m(T - t)\, dt \qquad (3)$$

which reduces to the cross correlation of $r(t)$ and $h(t)$ with zero lag.

$$y(t) = \int_0^T r(t) h(t)\, dt \qquad (4)$$

In order to construct the matched filter a standard laser calibration run is used which is normally used to flat field the camera. For each event, and for each channel, a section of the laser pulse is extracted, and aligned relative to some predetermined point. This extracted pulse is summed for all events for each channel. The summed trace is normalised (Figure 1), and Fourier transformed. The filter is applied to the FADC data by multiplying the Fourier transform of the FADC trace (denoted $S(\omega)$) with the conjugate of the filter transform, $\overline{H}(\omega)$, and then applying an inverse Fourier transform

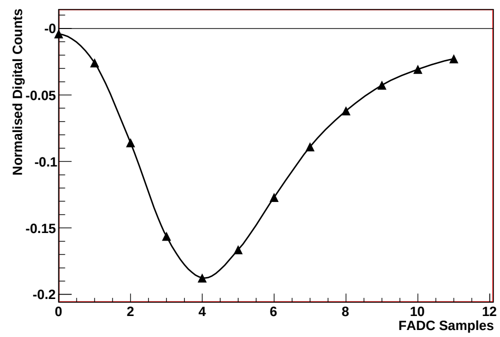

Figure 1: Normalised subset of FADC trace used to construct a *matched filter*.

$$y(t) = \mathcal{F}^{-1}\left[S(\omega) \times \overline{H}(\omega)\right] \qquad (5)$$

which yields the cross correlation function $y(t)$. The maximum of the cross correlation is proportional to the integrated charge of the FADC trace. In order to establish the constant, a series of special laser calibration runs is taken with continuously increasing laser intensity. The integrated charge as measured using the *dynamic-window* trace evaluator is compared to the output of the *matched-filter* trace evaluator and used to establish the constant [5].

When analysing data, the charge from a trace is derived by applying the *matched-filter* trace evaluator, and multiplying the output by the appropriate constant for that channel. The pulse arrival time is determined by the location of the maximum of the cross correlation, thus the arrival time can only be determined to the nearest FADC sample (much like the *simple-window* trace evaluator).

Integral Charge Evaluation

In order to examine the charge evaluation quality of each trace evaluator, a data set of photon impacts on the camera is simulated. The arrival time of the photons is assumed to be Gaussian with an RMS of 2 ns. The simulation is performed using GrISUDet [6]. A comparison of an FADC trace simulated in this way with a real trace from a laser calibration run is shown in Figure 2.

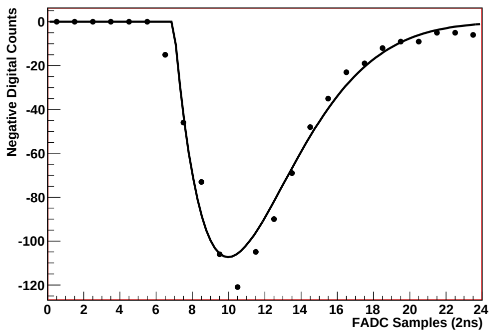

Figure 2: Comparison of real and simulated FADC trace. The real trace is indicated by the points.

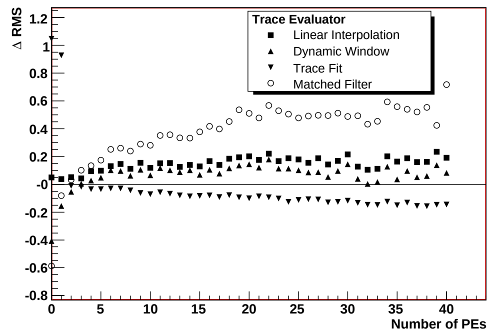

Figure 3: Comparison of charge resolution relative to the *simple-window* trace evaluator.

The simulated data set is divided into subsets such that each subset only has events with a certain number of photoelectrons. Data sets with from one to thirty photoelectrons are generated in this way. This allows the charge reconstruction as a function of the known number of photoelectrons to be evaluated. For each trace evaluator, a distribution of integrated charges (in digital counts) is generated for each photoelectron multiplicity. In terms of charge evaluation, the quality of the trace evaluator is determined by the RMS of the distribution of integrated charges for a constant input. The difference in the RMS of the *simple-window* trace evaluator, and each other trace evaluator as a function of the number of photoelectrons is shown in Figure 3. Thus, the RMS of the *simple-window* trace evaluator is used as a baseline against which the other trace evaluators can be compared. For small pulses (<5 photoelectrons), the *matched-filter* trace evaluator provides the smallest RMS, however the RMS quickly increases with the number of photoelectrons. This is to be expected as although small pulses are dominated by noise, the matched filter is is able to pick out the signal from the trace. Conversely, the *trace-fit* trace evaluator gives a very large RMS for small pulses. This is attributed to ill-fitting of small, poorly-defined pulses. At approximately four photoelectrons, all the trace evaluators yield similar results. Beyond that, the *trace-fit* trace evaluator is superior, and only the *matched-filter* trace evaluator is significantly worse.

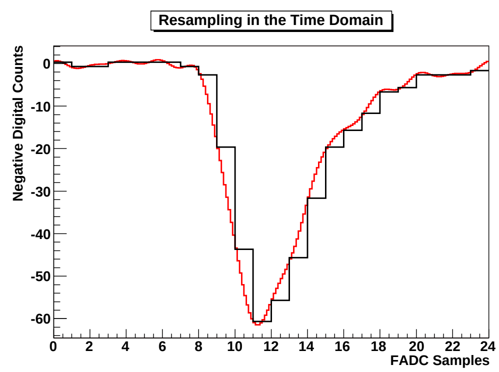

Figure 4: Comparison of original and resampled FADC trace.

Trace Resampling

One tool commonly used in digital signal processing is *resampling* in the time domain. The resampling is achieved by applying a Fourier transform to the FADC trace, *zero-padding* in the frequency domain, and applying an inverse Fourier transform. Zero padding in the frequency domain is achieved by simply *adding* zeros to the end of the Fourier-transformed trace. This has the effect of setting higher frequencies to have zero amplitude. The inverse Fourier transform results in a trace which has been resampled in the time domain. Figure 4 shows a comparison between a raw and resampled trace.

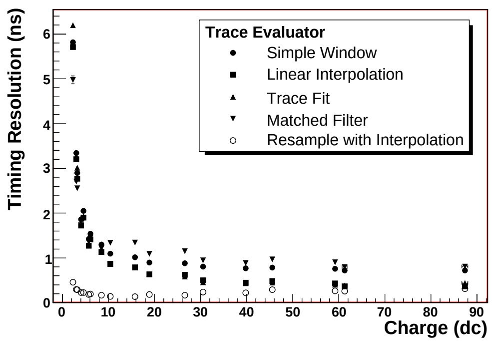

Figure 5: Timing resolution as a function of FADC trace size.

Timing Resolution

The timing resolution is determined by how well the arrival time of an asynchronous laser flash incident on the camera plane can be measured.

The timing resolution is defined as the width of a Gaussian function fit to the distribution of measured differences between event arrival and channel arrival time for a series of laser pulses for each channel. The event arrival time is defined as the *average* arrival time of all the channels in the camera. The timing resolution as a function of integrated charge is shown for all methods in Figure 5. As expected, the timing resolution improves as a function of pulse size, as for larger pulses the time structure is better defined. Above an integrated charge of $30\ \mathrm{dc}$, the timing resolution is roughly linear as a function of charge. The timing resolution for pulses greater than $30\,\mathrm{dc}$ is shown in Table 1.

Evaluator	Resolution (ns)	Error (ps)
Simple Window	0.77	3.2
Linear Interpolation	0.45	2.9
Trace Fit	0.46	2.9
Matched Filter	0.91	2.7
Resampling	0.22	10.9

Table 1: Timing resolution for pulses greater than $30\ \mathrm{dc}$.

As expected, the *linear-interpolation* trace evaluator has excellent timing resolution for all trace sizes. The *matched-filter* trace evaluator is excellent for small traces, however as pulse arrival times can only be calculated to the nearest FADC sample, it is not as good for large pulses. The *trace-fit* trace evaluator has poor timing resolution for very small pulses - mirroring the effect seen with the study of charge resolution, indicating that the fit function is not suited to small pulses. For large pulses the *trace-fit* evaluator has a superior resolution. However, the best timing resolution is achieved using a combination of the resampling technique and the *linear-interpolation* trace evaluator. Together, these fast robust techniques provide a timing resolution of just $0.22\ \mathrm{ns}$ with these data.

Conclusions

Five trace evaluation techniques and a digital filtering technique have been described and compared using real and simulated data. The *matched-filter* technique holds promise for the evaluation of small sub-threshold events. Optimal timing resolution has been achieved using an FADC resampling technique in concert with the *linear-interpolation* trace evaluator.

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