Whipple Telescope observations of the Crab Nebula with a Pattern Selection Trigger

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Abstract

For imaging Cherenkov telescopes the single pixel trigger rate is heavily influenced by fluctuating night sky brightness. The random trigger rate of an N pixel coincidence quickly escalates with decreasing energy threshold. To keep the data rate to a manageable level, by further requiring that N signals are adjacent, we developed CAMAC Pattern Selection Trigger modules, in which the pixel fire pattern is compared with the contents of a delay memory pre-programmed with allowed patterns of 2, 3 or 4 pixels.

This system has been used as a next neighbour trigger for the 331 pixel camera of the Whipple 10m telescope, to acquire data at a 20% lower discriminator threshold than that sustainable with a simple multiplicity trigger. We discuss the performance of the trigger modules and present the results of our analysis of data recorded on the Crab Nebula at this reduced threshold.

1 Introduction:

In increasing the field of view of an imaging Cherenkov telescope's camera with additional pixels, one naturally raises the probability of triggering the telescope on random noise under the condition that *any N* pixels simultaneously contain a signal. The individual pixel trigger rate is heavily influenced by ion feedback in the photo-multipliers (afterpulsing) and fluctuations in night sky brightness. The telescope accidental trigger rate can be limited so that it does not exceed the maximum recordable data rate by allowing only Cherenkov-like events containing *N adjacent* pixels.

1.1 Topological Trigger: A *topological hardware trigger* has been designed by Leeds University and Hytec Electronics Ltd, with the 331 pixel camera of the Whipple 10 m telescope in mind, based on CAMAC Pattern Selection Trigger (PST) modules (Bradbury et al. 1997).

The PST can recognise and trigger on patterns of $\geq N$ adjacent pixel signals, where $N = 1, 2, 3$ or 4. To select patterns of 4 adjacent pixels in a typical hexagonally symmetric camera, one must test for a signal in not only the six neighbouring channels of a triggered pixel but also in their neighbours i.e. within a hexagonal patch of 19 pixels. This is achieved by comparing the latched pixel fire-pattern (discriminated photo-multiplier signals) with the contents of a pre-programmed delay memory (programmable gate arrays could not cover all 2^{19} possible trigger decisions). The memory look-up only occurs if a voltage comparator signals that $\geq N$ pixels fired. Each PST module accepts 59 ECL inputs which are arranged into 5 overlapping groups of 19 channels to be fed into 5 memory chips, each corresponding to a patch of 19 neighbouring pixels. The module provides three levels of information:

1) a valid pattern generates a TTL *trigger flag* to be OR-ed with those of other modules
2) each patch can generate an ECL *patch flag* to indicate which group(s) of 19 pixels fired
3) the *pixel fire-pattern* within each patch of 19 pixels can be read via CAMAC

Thirteen PST modules make up the topological trigger for the Whipple 331 pixel camera. The ECL outputs of 21 16-channel discriminators are copied and redirected to the appropriate PST module(s) by a custom "ECL signal splitter" crate. A wired-OR of the 13 PST trigger flags can trigger the readout process. The PST modules are versatile in that their memories can be re-written to alter the telescope trigger condition in 2 to 3 minutes (programmed for 2-fold, 3-fold or 4-fold adjacency in 10 s per PST module). One can also disable a patch, i.e. remove a group of 19 pixels from the trigger, without any hardware changes. The PST data words containing the pixel fire pattern are read into each event record before the trigger is re-enabled. This information is a valuable diagnostic tool e.g. in identifying triggers due to discriminator cross-talk.

2 Trigger Performance:

We compare the performance of the topological trigger with that of the conventional "any 2/331 pixels fired" 2-fold coincidence trigger (summed discriminator outputs triggering a multiplicity discriminator). The coincidence resolving time of both triggers is ~ 8 ns. The PST returns a positive trigger decision after 65 ns and can then be reset (via a NIM fast-clear input) in 22 ns.

2.1 Background Suppression: We expect the telescope raw trigger rate to be a combination of night sky background (NSB) triggers, some PMT afterpulsing extending the noise trigger component to higher thresholds (Mirzoyan & Lorenz, 1995) and cosmic ray events. As shown in Figure 1, at high discriminator thresholds the 2-fold PST and coincidence trigger rates are similar, both being largely due to genuine air-shower events. In the steepest part of the 2-fold curves, approximating to a power law of rate $\propto$ threshold^{-8}, sky noise dominates. At ~ 50 mV discriminator threshold the 2-fold PST provides $\sim \times 10$ background rejection over the coincidence trigger to give us our target data rate of 100 Hz (indicated by the arrow in Figure 1). The cross-over of the NSB noise and cosmic-ray components is most sharply defined for the 3-fold PST; according to the simulations of Weekes et al. (1999) the *3 adjacent* trigger condition effectively eliminates the effects of afterpulsing.

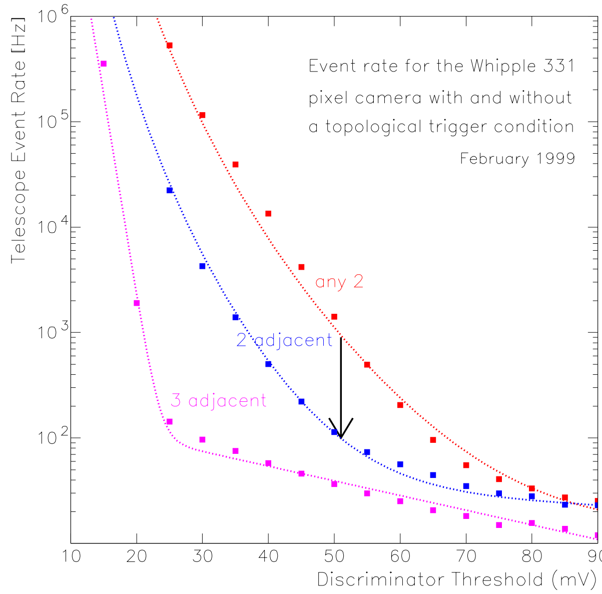

Figure 1: Whipple 10m telescope trigger rate as a function of discriminator threshold (February 1999).

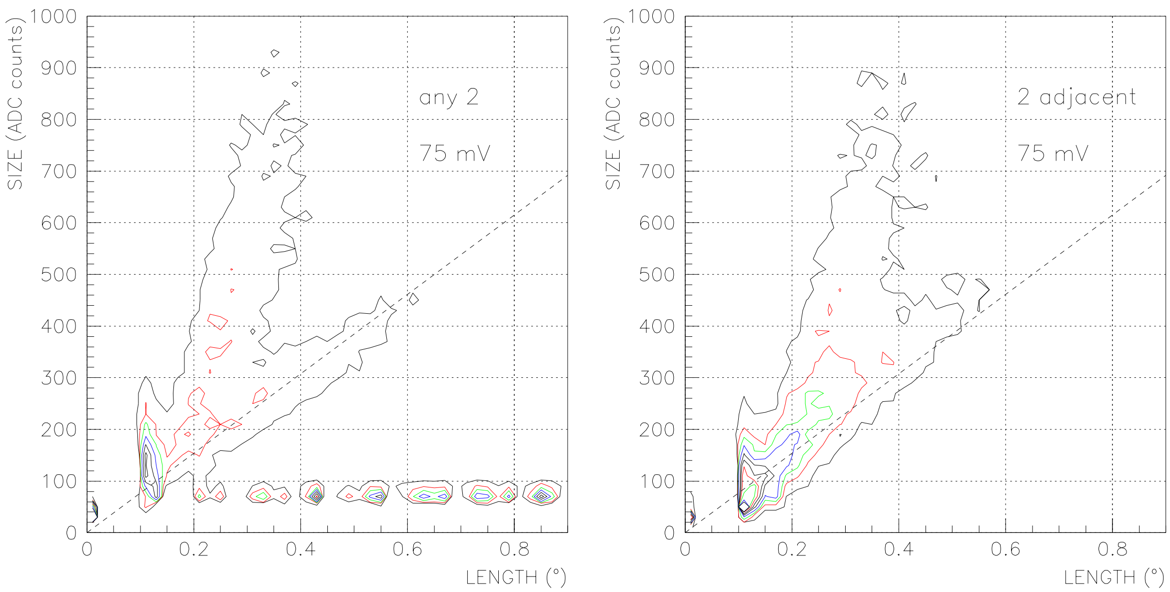

Figure 2: Comparison of calibrated image SIZE as a function of the Hillas parameter LENGTH for data recorded at a discriminator threshold of 75 mV with the 2-fold coincidence trigger (left) and the 2-fold PST (right). Contours indicate 30 to 300 events in 30 event steps.

In winter 1998/99 the Whipple 10 m Telescope was normally operating with the 2-fold coincidence trigger at a discriminator threshold of 75 mV. To assess the relative efficiency of the PST we recorded data on the Crab Nebula at 75 mV under four different telescope trigger conditions: **1**: *2*-fold PST .OR. *2*-fold coincidence **2**: *3*-fold PST .OR. *2*-fold coincidence **3**: *2*-fold coincidence **4**: *2*-fold PST.

The data were analysed following the standard Hillas parameter based "supercut analysis". For condition **1** (cf. condition **2**), 72% (44%) of the raw events recorded passed both the PST and coincidence triggers, increasing to 93% (53%) after cuts on the image shape and 97% (70%) of the γ-candidate events pointing towards the source position (ALPHA $< 10°$). From this we conclude that the PST, whether requiring 2 or 3 adjacent pixel signals, was, in real-time, preferentially recording events which meet our γ-ray selection criteria.
In Figure 2, we compare the data taken under trigger conditions **3** and **4** by plotting image SIZE (the number of calibrated ADC counts in the image) as a function of the Hillas parameter LENGTH (the signal-weighted r.m.s. spread of pixel signals parallel to the major axis of an ellipse fitted to the image). A software trigger cut has been applied to retain only pixel signals above 4.25σ and their neighbours above 2.25σ of the NSB level. In the left hand plot (trigger condition **3**) three distinct image populations are apparent. The horizontal branch below 100 ADC counts distributed across the LENGTH scale represents images containing two random pixels, at separations dictated by the granularity of the camera. The near vertical branch of LENGTH 0.2°-0.4° extending to large SIZE consists of cosmic ray air-shower images. The third branch, at LENGTH/SIZE ≈ 0.0013 (indicated by the dashed line), we attribute to ring or partial ring Cherenkov images due to single muons (e.g. Vacanti et al. 1994). Beyond LENGTH $= 0.45$ these images contain at least 9 pixel signals above noise. This is consistent with muon events occurring near the trigger threshold. The right hand plot (trigger condition **4**) shows that the PST 2-fold adjacency condition eradicates the horizontal branch at the hardware level. We may also expect slightly fewer muon images with condition **4** than condition **3**, since the probability that a ring image of a given SIZE, where all signals are near the discriminator threshold, will cause a telescope trigger is slightly lower under the condition that the two triggering pixels be adjacent.

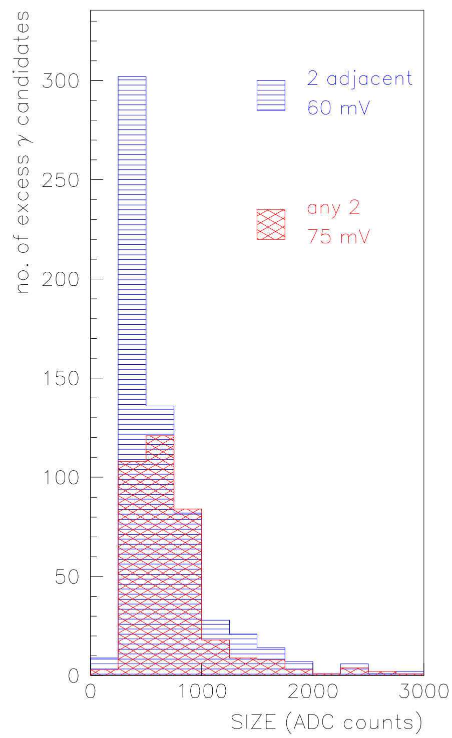

Figure 3: SIZE distribution of γ-ray candidate events after background subtraction (see section 2.2) for the 2-fold PST and the 2-fold coincidence (hatched area) triggers recorded at 60 mV and 75 mV discriminator thresholds respectively.

2.2 Crab Nebula Observations: In February 1999, using the 2-fold PST to trigger the telescope at a discriminator threshold of 60 mV, we recorded 5.2 hours of data on the Crab Nebula interleaved with an equivalent amount of off-source data required for background subtraction. These data were compared with a dataset of the same length recorded under similar conditions but using the simple 2-fold coincidence trigger at a threshold of 75 mV. Candidate γ-ray events were selected from the 75 mV data on the basis of the Hillas parameter "supercuts" applied to 1998 Whipple Telescope data by Quinn et al. (1999). We re-optimised these cuts slightly for the 60 mV data to obtain the maximum statistical significance for the Crab Nebula signal. In particular, for the 60mV (cf. 75mV) data we required > 66 (75) ADC counts in the brightest pixel, a LENGTH of $0.13° - 0.405°$ ($0.16° - 0.44°$) and DISTANCE $< 1.20°$ (1.25°). In Figure 3 we compare the distribution in SIZE of excess γ-candidate events (on - off-source data) for the two datasets. By using the PST and reduced discriminator threshold we do gain principally low energy γ-ray events. As expected, the excess is similar for PST and coincidence trigger data at SIZE $>$ 500 ADC counts. We might benefit from a tiered system of energy dependent cuts, treating our low-energy events as a separate dataset.

The integral Crab Nebula spectrum measured by Whipple in the TeV range is $E^{-1.49}$ (Hillas et al. 1998). Under the simplistic assumption that the telescope's energy threshold is proportional to discriminator threshold, we would expect a factor of $\approx$ 1.4 increase in the measured γ-ray rate on reducing the discriminator threshold from 75 mV to 60 mV. If we apply the standard 75 mV cuts to the 60 mV data we obtain a ratio of rates for the PST data relative to the coincidence trigger data of 1.48$\pm$0.17. With the cuts optimised for significance on this PST dataset this ratio becomes 1.68$\pm$0.19. Simulations and further Crab observations are needed to properly estimate the new trigger efficiency.

3 Outlook:

A topological trigger condition has been implemented for the Whipple Telescope's 331 pixel camera using Pattern Selection Trigger modules designed by the University of Leeds and Hytec Electronics Ltd. We have good quality data on the Crab Nebula recorded using the 2-fold PST at a conservative telescope trigger rate of $\approx$ 55 Hz from which, after preliminary cut optimisation, we obtain a γ-ray rate of $\sim$ 1.7 times that from the simple coincidence trigger at the higher threshold. For future Crab observations we expect to further reduce our threshold and operate at 100 Hz. It may be worthwhile to introduce energy dependent cuts to take advantage of the increased dynamic range (e.g. Petry & Kranich 1997, Moriarty et al. 1997) and search for the signature of the Crab Pulsar in low threshold events.

An exchange of the Whipple 10 m telescope's 331 0.25° pixel camera for one with a core of 331 0.125° triggering pixels is planned. It is probable that we will then wish to operate the PST with the *3 adjacent* pixels trigger condition. The angular scale of γ-ray images will be well-matched by 3 adjacent pixels and the more stringent trigger condition will further eliminate accidental noise triggers. A 3-fold adjacency trigger employing this technology has been proposed for the Very Energetic Radiation Imaging Telescope Array System (Weekes et al. 1999, Bradbury et al. 1999).

Acknowledgements

We would like to thank our colleagues of The Whipple Collaboration and acknowledge in particular the assistance of Mike Catanese, Kevin Harris and John Quinn. Our research is supported by the U.K. Particle Physics and Astronomy Research Council.

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