Performance Study of a Digital Camera Trigger for CTA

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Abstract: We present a design study for a trigger system for the imaging cameras of the "Cherenkov Telescope Array" (CTA). The proposed FPGA-based camera trigger operates on 400MHz time-sliced 1-bit-camera images. It allows to search for topological majority patterns, and is capable to search for complex space- or space-time patterns; it also allows for an image-driven readout control. A MC comparison of this and alternative trigger concepts is done.

Keywords: Gamma Ray, Imaging Atmospheric Cherenkov Telescope, CTA.

1 Triggering of CTA-Cameras

The next generation VHE gamma-ray observatory "Cherenkov Telescope Array" (CTA) is currently in its preparatory phase[1]. It will consist of 50-80 Imaging Air-Cherenkov Telescopes. The low and mid energy range of 0.010 - 10 TeV will be covered by Large Size (LST) and Medium Size Telescopes (MST) with 23m and 12m dishes. In the baseline design, the LST and MST cameras have 2841/1765 pixels (PMTs), arranged in hexagonal clusters of 7 pixels, as shown in fig.1. LST and MST are made of 400 and 250 cluster, respectively.

A typical gamma-ray shower generates a light flash of few nsec duration in spatially neighbored pixels (for $\gg$1 TeV with duration up to several tens of ns). The background is dominated by random night-sky-background (NSB) photons, causing at least 120 MHz pixel countrates (at single photoelectron (pe) threshold), and by large amplitude PMT afterpulses (APs) faking large pixel signals.

Trigger strategies used in current generation telescopes are based on either the topological distribution of pixel hits (ie. PMTs with signals above a discriminator threshold), or on the analog sum of the PMT signals : (1) Majority trigger : At least N_{maj} pixels are above threshold (a few pe) for a coincidence gate of few ns
(2) SumTrigger: The analog sum of all pixel amplitudes must be $>A_{Sum}$ (20pe typical). To suppress afterpulse triggers, each pixel signal is clipped (at $\sim$ 6pe).

A camera trigger in this approach occurs, if the trigger condition is fulfilled for at least one out of a number of predefined static search regions (typically made up of tens of pixels each; and covering the full camera or part of it).

For this study, we use 7 pixels as base unit to build various search regions (see fig.1): Cluster-Doublets (pairs of neighbouring camera clusters), Cluster-Triplets (compact triplets of neighbouring clusters), and Cluster-Singlets ("scanning" singlets, build around every pixel). By construction, these search regions have a high degree of overlap, to avoid trigger inefficiencies due to edge effects.

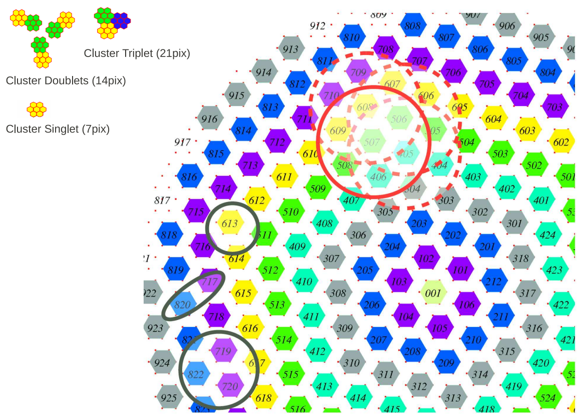

Figure 1: The cluster structure of a MST-Camera (part): each hexagon represents a 7-pixel-cluster. The grey upper circles indicate 3 neighboured supercluster (each made of 7 next neighbour clusters, corresponding to 49 pixels, ie. the region available for each Cluster-FPGA algorithm). Indicated also baseline search geometries: Cluster-Singlets, Doublets and Triplets (grey lines); also given in the insert.

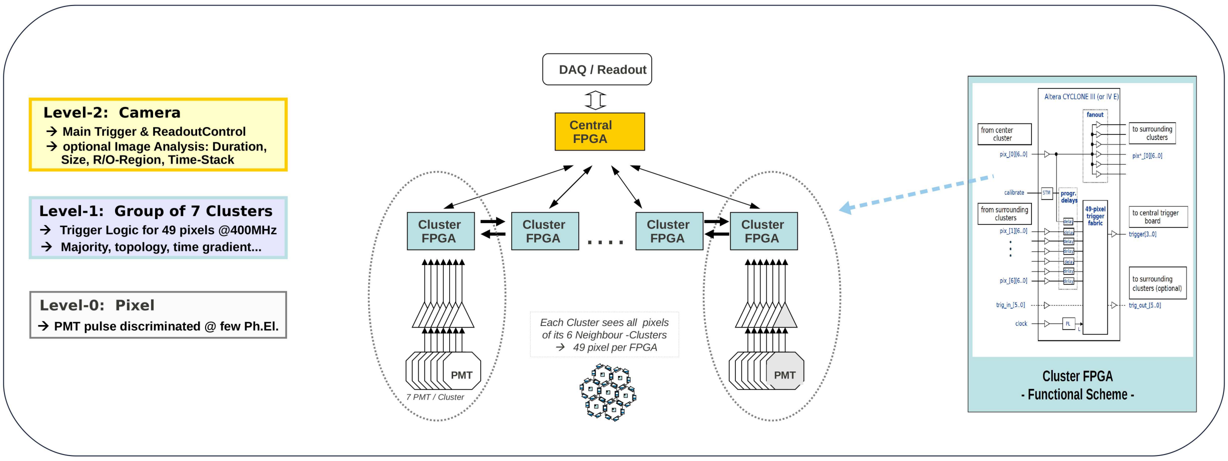

Figure 2: Block scheme of the FPGA-based Camera Trigger. Each *Cluster-FPGA* operates on 49 pixels/PMTs (7 direct and 6x7 neighbouring cluster pixels). *Central FPGA* at camera level: allows for optional Level-2 trigger / image classification. *Right insert:* Functional scheme for each Cluster-FPGA: input (7+42 pixel), digital delay lines, trigger factory, 7-pixel fanout to neighbouring cluster and trigger output (3 bits).

2 The FPGA Camera Trigger: Concept

The proposed digital FPGA camera trigger analyzes the discriminated PMT signals of all camera pixels, as illustrated in fig.2.

At *Cluster-level* (level-1 in fig.2), each cluster (7 pixels) is connected to its cluster-FPGA board (a single, cheap 400MHz FPGA), together with all 42 pixels of the surrounding six clusters. This 49-pixel super-cluster region is analyzed by the baseline trigger algorithms running on the 400MHz FPGA. Thus, the main trigger is essentially based on 400MHz time-sliced 1 bit-camera images. Additional advantages of the FPGA design is a simple implementation of internal programmable digital delays (auto-calibration), and of asynchronous pixel coincidences (i.e. without synchronizing the input signals to the FPGA clock) to avoid image splitting between time slices. Beyond the basic majority algorithms, also complicated topological algorithms are possible, including simple (1-bit) image-cleaning. In addition, if needed, the full pixel time history is available at super-cluster level; which can be used to find e.g. large-impact showers, but also allows to extract information after an array-level trigger for non-triggered telescopes.

At *Camera-level* (level-2 in fig.2), a simple centralized solution using a single FPGA is possible, collecting results of the various parallel trigger algorithms running on the Cluster-FPGAs. This provides a classification of images wrt. their duration, essential to adapt the camera readout time window to prevent signal loss.

The Cluster FPGA functional scheme is given in fig.2(right). First boards, with algorithms implemented, are being successfully tested (see fig.3).

3 Detailed Camera-Trigger MC Simulations

The generation of photoelectrons in the camera plane by γ-showers is done with the default CTA-MC package *SimTel-Array*[2]. Photoelectrons are then processed by a dedicated trigger package *TrigSim* (scanning a large trigger parameter space).

The subset of investigated trigger scenarios shown here is (all for asynchronous FPGA-coincidences):
MajorityTrigger: ScanningCluster-Singlets/Majority_3 (*ScSinglMaj3*, i.e. N_{maj}=3), Cluster-Doublets/Majority_4 (*DoublMaj4*), Cluster-Triplets/Majority_5/7/9 (*TriplMaj5/7/9*), CompactThreeNextNeighbours (*3NN*);
SumTrigger: ScanningCluster-Singlets (*SumSingl*), Cluster-Doublets (*SumDoubl*), with clipping at 6pe (broad minimum - not optimized).

The parameters varied are : NSB-rate (MHz/pixel) = 125/250; PMT afterpulse rate (>4 pe) = 0.013% (*E4*) / 0.0434% (*E3*); analog bandwidth - the 1pe pulse-fwhm is the relevant input variable = 2.6 / 5 / 10ns; coincidence window (majority) = 1.7 / 5 / 8.3 ns.

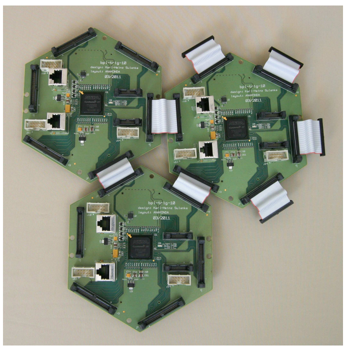

Figure 3: Prototype Cluster FPGA trigger boards, interconnected for inter-cluster data transfer.

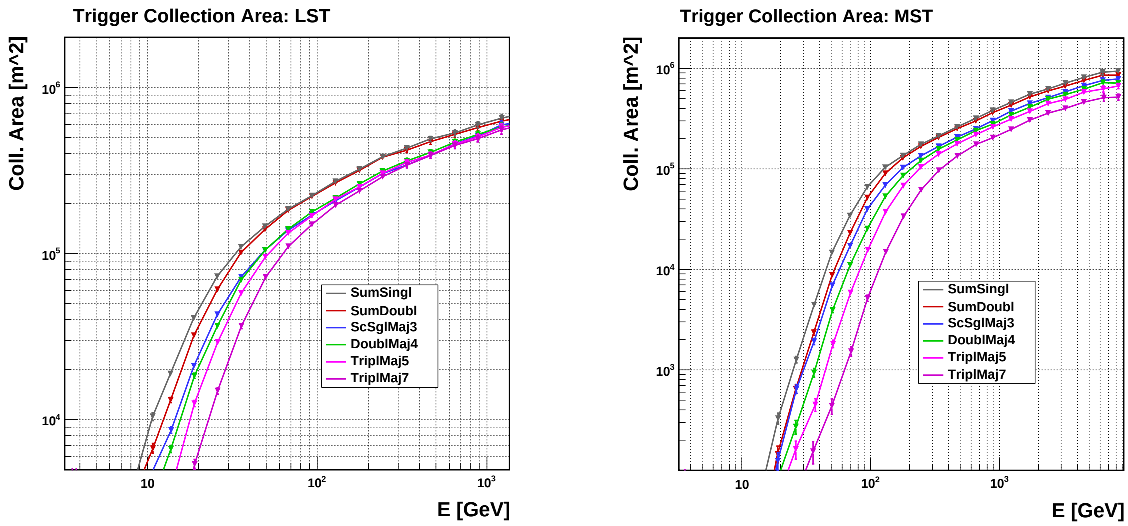

Figure 5: Trigger collection area for LST and MST for SumTrigger (SumScSingl, SumDoubl) and Majority trigger scenarios (ScSglMaj3, DoublMaj4, TriplMaj5/7).

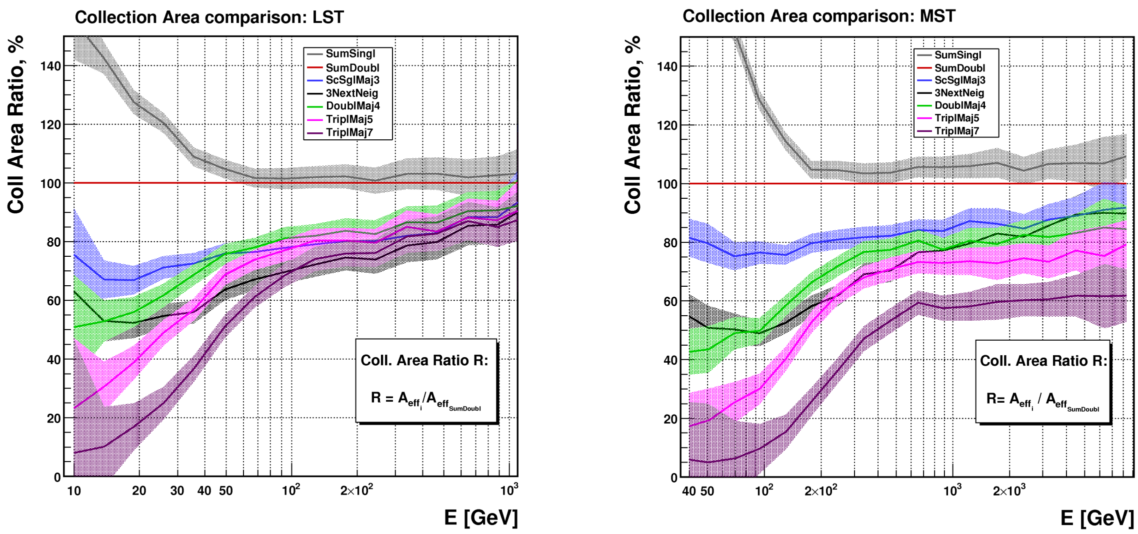

Figure 6: Trigger collection area for LST and MST from fig.5, normalized to Sumtrigger 'SumDoubl'.

The MC procedure for each chosen parameter set and trigger scenario is: First, obtain the working points, ie. find those pixel- / analogsum-thresholds that keep the camera trigger rate for NSB-only events at <100 Hz, see fig.4. For these, the trigger collection area for γ's is determined. An optional image cleaning roughly verifies the triggered image quality.

4 Results: Comparing trigger Scenarios

The trigger collection areas for various algorithms for LST and MST are shown in fig.5. The parameter space for trigger optimization is large, results here are limited to optimal conditions (125MHz NSB, low AP-rate *E4*, high bandwith (fwhm 2.6ns) and coincidence window 1.7ns. The two SumTrigger scenarios are performing best over the entire energy range. Fig.6 gives the trigger collection areas normalized to that of the DoubletSumtrigger (a realistic analog sumtrigger). The so far tested (simple) majority schemes perform for MST 20% (lowest) to 10% worse (highest energy) than sumtrigger; lower majority multiplicities N_{maj} (ScSglMaj3, DoublMaj4) seem to work better than larger (TriplMaj5/7, with lower pixel amplitude threshold). At high energy, though, better performance is found for larger coincidence windows (5.0/8.3ns), see fig.7; large multiplicities (TriplMaj5/7) and low thresholds alone already reach >90% of the SumTrigger collection area. Note, that low thresholds imply less severe PMT AP-requirements.

The dependence of collection area on the bandwidth (pulse fwhm of 2.6/5.0/10.0ns) is given in fig.8 for the default majority scheme (ScSglMaj3) and coincidence window of 1.7ns. For LST, due to higher pixel thresholds, larger pulse-

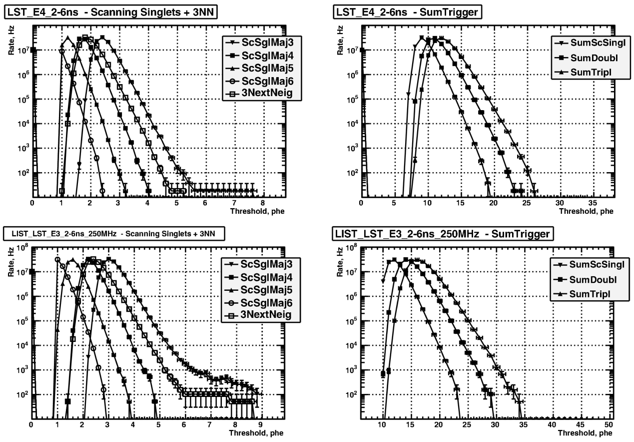

Figure 4: Pure NSB simulation. Camera trigger rate versus pixel-/analogsum-threshold. Upper plots: NSB 125, AP *E4*; lower plots: NSB 250, AP *E3*. Left: Majority trigger for ScSinglMaj3-6, 3NN; right: SumTrigger for SumScSingl, SumDoubl and SumTripl. (Rate drop at >10MHz/low thresholds is a MC-artefact due to counter saturation (10ns update window)).

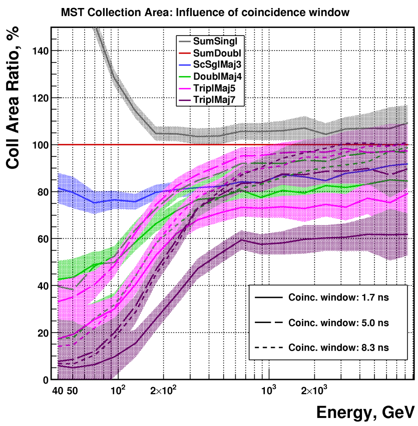

Figure 7: Relative MST collection area as function of coincidence window: 1.7, 5.0, 8.3ns (NSB/AP as in fig.5). At high energy, larger windows are favored.

fwhm (ie. lower bandwidth) results in worse sensitivities already for 5ns fwhm.

5 Conclusions

We presented the basic design ideas and a detailed MC-simulation for a FPGA based digital camera trigger, that could be used for CTA telescopes. The concept offers

- a simple and realistic hardware implementation for a camera trigger; detailed hardware tests underway;
- majority algorithms yield good collection area; FPGA resources allow for more complex and for several, parallel running algorithms;
- a natural implemenation of a 2nd-level trigger, and a baseline image analysis at trigger level ;

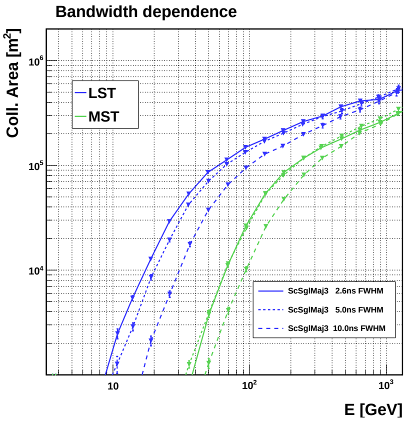

Figure 8: Bandwidth dependence of collection area for LST and MST for 250MHz NSB, AP *E4*.

- an easy image-type classification at trigger level, thus for high energy large shower impacts an extended camera readout window prevents signal loss.

From a quantitative comparison of alternative trigger algorithms for the Large/MediumSize CTA telescopes, we find:

- AnalogSum and Digital-Majority scenarios show a similar performance. The AnalogSum yields lower threshold for LST, and o(15%) area improvement for MST/LST at medium energy scales;
- Best AnalogSum-trigger performance is for a scanning-single-cluster algorithm (difficult to realize in hardware, except for a digital FADC readout);
- Digital trigger scenarios require PMTs with low afterpulse-rate PMTs (unless also using AP-clipping, or working with low threshold/high majority);
- Image cleaning has a good efficiency for all scenarios, this indicates good physics performance of the trigger algorithms.

Next steps of this analysis aim at an improved sensitivity at high energies ($\gg$1 TeV) by including larger time intervals and by improved image search topologies. For better low-energy performance, we plan to go beyond simple digital majority-schemes. With a second discriminator threshold, improved majority performance is expected. To realistically quantify the relative performance gain of sum- and majority-trigger concepts, we extend the analysis to the CTA-array trigger.

Acknowledgements We gratefully acknowledge financial support from the agencies and organisations listed in this page: http://www.cta-observatory.org/?q=node/22 .

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