A Fast Topological Trigger for Real Time Analysis of Nanosecond Time Scale Phenomena

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1. Scientific/Technological Opportunity

Gamma Ray astronomy with ground-based telescopes has made dramatic advances over the last decade with the detection of more than 30 astrophysical gamma-ray sources at TeV energies. The primary technique in this field uses imaging atmospheric Cherenkov telescopes (IACTs), which measure the Cherenkov light produced from interactions of gamma-rays in the upper atmosphere. The current generation of these IACTs are able to observe both galactic and extra-galactic sources of TeV gamma rays with large photon statistics and to perform high quality spectrometric, temporal and morphological studies. These instruments are used to address many of the current "hot" topics in the fields of High-Energy Astrophysics, Astroparticle Physics, Particles physics and Cosmology today. Some of these topics inculde: Understanding the accretion processes onto a supermassive black hole and what is the nature of a cosmic accelerator (HE Astrophysics/Astroparticle Physics), what is dark matter (Astroparticle Physics, Particle physics and Cosmology), and what is the cosmic history of star formation (Ong 2005).

The cross-fertilization between these fields for scientific study has also created a synergy in the development of the technology. The detectors and instrumentation in the current generation of IACTs are already very similar to those used in high-energy physics (HEP) experiments, where the measurements require high-speed digitization, high precision timing and sophisicated triggering. However, current IACTs have not yet implemented ultra-fast pattern triggers in the early triggering stages, relying instead on higher-level processing later in the data acquisition system. Having this capability earlier in the data processing chain would make it possible to trigger on low energy events with the high precision angular resolution obtainable by IACTs. This would be a significant advance in the field, since triggering on lower energies is synonymous with observing sources at greater distance, or farther back in time. Currently, none of the modern IACTs have this capability.

We propose to design a prototype of a fast topological pattern trigger using field reprogrammable gate arrays (FPGAs). While this technique has been used in HEP experiments for some time, the significant challenge in this application is that the data processing speed must be on order of 400 MHz. This is faster by an order of magnitude than state-of-the-art HEP triggers. The immediate beneficiaries of this development would be imaging detectors which rely on off-line analysis to extract signal from measurements that are dominated by background. This triggering technique would greatly benefit the next generation of ground-based imaging telescopes by lowering of energy thresholds from the current values of 50-100 GeV to possibly 10-30 GeV.

This energy regime opens up new regions of phase space with the large collection area typical of a ground based instrument. Another possible beneficiary would be PET imaging systems. We are exploring this application. The most intriguing aspect of this proposal is to provide the capability to extract patterns from a measurement field dominated by noise or background events, at a very high speed.

2. Applications:

2.1. Particle Astrophysics and Gamma Ray Astronomy

Fast Cherenkov flashes from air showers are used to detect gamma rays at Very High Energies (0.05 - 10 TeV). This technique has been greatly advanced with imaging telescopes over the last 15 years. A fast topological trigger with the capability of carrying out a basic image analysis in real time would be extremely useful for two purposes: first for reduction of cosmic ray background events, and secondly for the reduction of night sky background which limits the technique at the lowest energies.

The geometries of typical hadron initiated and gamma-ray initiated air showers at VHE energies differ substantially with regard to their lateral and longitudinal charged particle distributions. The resulting Cherenkov light image properties are the basis for an intelligent array trigger design that reaches a decision based on the parallactic displacement of the Cherenkov light flashes seen from different viewpoints at the ground. This trigger could be used to suppress a large fraction of cosmic-ray background showers and reduce the chance coincidences from night sky background fluctuations by 3 orders of magnitude.

Figure 1 illustrates the basic idea of using the parallactic displacement of Cherenkov light images to discriminate between gamma-ray and hadron induced air showers utilizing the different viewpoints in an IACT array. Whereas Cherenkov light images from gamma ray showers point with their major image axis in the direction of the physical shower axis in 3-dimensional space, the Cherenkov light images from hadronic showers exhibit large fluctuations in the light distribution perpendicular to the major image axis. This is largely due to fluctuations in the hadronic cascade and the large transverse momenta of the neutral pions feeding the electromagnetic component. These fluctuations translate into a large spread in the shower core reconstruction in the telescope plane. The consequences of these fluctuations and their effect on the parallactic displacement of images with application to stereo array analysis were pointed out by Krennrich & Lamb (1995a). They introduced the parameter "Parallaxwidth". Parallaxwidth is a measure of the spread in the reconstructed shower core location[1].

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[1](Parallaxwidth = $\sqrt{\sum_{\mathrm{i}} \frac{(\mathrm{r_i}-\bar{\mathrm{r}})^2}{\mathrm{n}}}$, with $\mathrm{r_i} - \bar{\mathrm{r}}$ = distance between individual intersection point i from averaged intersection point, n = number of intersection points.)

Figure 2 shows the Parallaxwidth distribution for simulated 80 GeV gamma-ray events and proton showers sampled from a cosmic-ray spectrum. The average number of telescopes participating in the reconstruction is between 4 and 5, showing that arrays of 4 telescopes are sufficient to make use of this technique (for further details see Krennrich & Lamb 1995b). The separation power can be expressed in the figure of merit, the Q-factor[2]: the application of Parallaxwidth for 80 GeV gamma ray showers gives a Q-factor between 2 and 3 depending on the number of telescopes used. This directly translates into sensitivity improvement. It is apparent that the reconstruction of the shower core requires at least two telescopes, however, with three telescopes the core reconstruction is overconstrained, providing the spread in its estimation. A three telescope coincidence using the parallactic displacement also allows the rejection of accidentals from night sky fluctuations randomly occuring in the field of view.

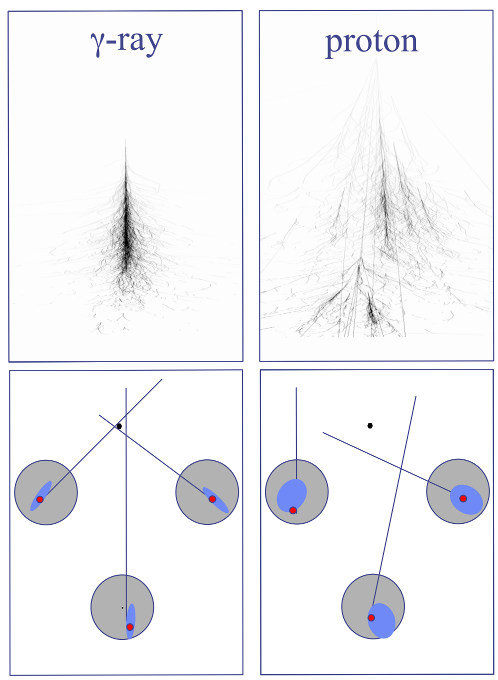

Fig. 1.— Illustration of using the parallactic displacement for hadronic background suppression. The shapes of the electromagnetic component of a gamma ray and a proton induced shower are shown, and the effect on the shape and orientation of Cherenkov light images in the cameras is depicted in a schematic view. The shower core on the ground (black dot in lower figure) for a gamma-ray primary can be reconstructed by extrapolation of the line between image centroid and

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[2] $Q = \frac{\epsilon_\gamma}{\sqrt{\kappa_{\rm hadron}}}$, with ϵ_γ = gamma detection efficiency, $\kappa_{\rm hadron}$ = hadron detection efficiency.

the arrival direction (known point source at center of field of view). Proton showers suffer on average a large transverse spread and therefore show a large spread in the core reconstruction.

Utilizing parallactic displacement could significantly advance the IACT technique. There are two key aspects to this technique: reducing the energy threshold of an IACTs array and suppressing hadronic background at the trigger level. Both could lead to a substantial sensitivity/versatility improvement of IACT arrays. For example the low energy mode could be used for the study of gamma ray pulsars, whereas the "low background" mode could be extremely useful for a search for transient phenomena in a sky survey, making maps of excess events in real time! A combination of the low energy mode with the low background mode could substantially improve the low energy sensitivity of an array.

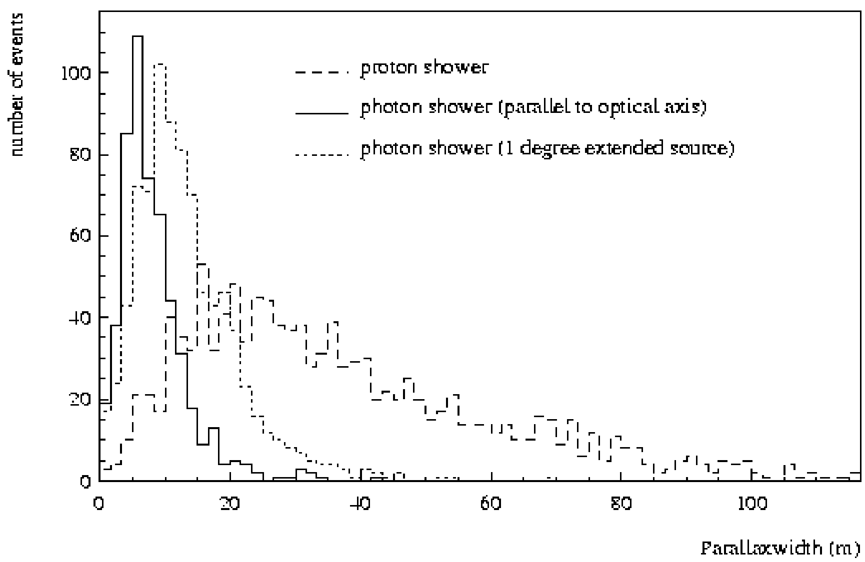

Fig. 2.— The Parallaxwidth distribution is shown for gamma-ray (solid line) and proton (dashed line) induced showers. Also gamma-ray showers for an extended gamma-ray source is shown (dotted line). These results are based on array configuration with an average of 4-5 telescopes participating in the reconstruction. It should be noted that the trigger condition required depends on the pixel size and mirror area of the telescope, here we used 0.26° and 75 m^2, respectively. The trigger threshold was set to 30 photoelectrons. For a VERITAS or HESS telescope (mirror area would be 100 m^2 and the pixel size of 0.15°) the trigger threshold would correspond to 6 photoelectrons per pixel.

In the following we outline a more detailed strategy/algorithm for reducing the chance coincidences from night sky fluctuations, with the goal of reaching at the lowest possible energy threshold for shower detection. Furthermore, we describe an algorithm that reduces hadronic showers at the trigger level.

2.1.1. Low Threshold Trigger Mode:

Reducing the energy threshold of an array can be achieved by eliminating a large part the combinatorial background from night sky fluctuations while increasing the gamma ray detection efficiency. This can be done by tailoring the trigger criteria such that they best fit the shower properties of low-energy gamma-ray events. The most obvious criterion is to require a coincidence between two neighbor pixels to detect the arrival of a Cherenkov light flash, which is done in most IACTs. One, perhaps less apparent strategy is to restrict a low threshold setting to the camera pixels of a "donut" shaped area in the focal plane, mapping the atmospheric height of maximum Cherenkov light production into angular space and in the corresponding region of the camera. For example, 20 - 50 GeV showers have their largest fractional Cherenkov light production around 13 km altitude, making the annulus between 0.1-0.4 degree (Cherenkov angle) around the point source position the most effective trigger area. Figure 3 shows a typical 20 GeV gamma-ray Cherenkov flash image in the focal plane of an IACT. The centroid position of the image (close to the brightest pixel) is at a distance of about 0.2 degree offset from the direction of the point source in this case at the center of the field of view.

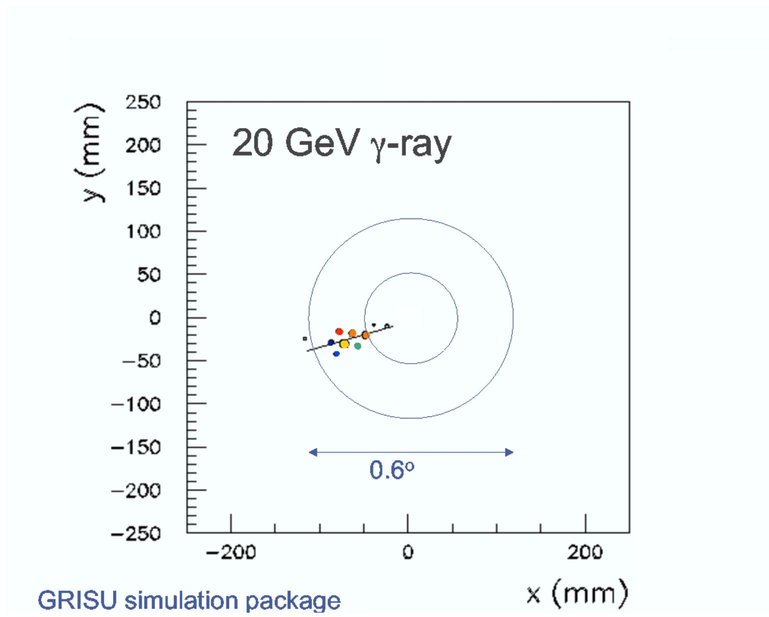

Fig. 3.— A typical simulated 20 GeV gamma ray event in an IACT. The largest trigger probability is between 0.1 - 0.4 degree off-axis, here the point source is located at the center of the field of view.

Restricting a lowest threshold setting to the "donut" shaped trigger area as opposed to the entire camera reduces the rate from night sky background accidentals by already a factor of 20 - 30 (40-60), when scaling the area of the donut versus the entire camera for which we assume a camera with 3.5 (5.0) degree diameter field of view. This already allows a slightly reduced threshold setting for this restricted area.

The second step in lowering the chance for accidentals is to require the correct parallactic displacement as would be expected from the faint light flash caused by an air shower. The Cherenkov light image's centroid position in the focal plane is determined by the absolute shower core distance and the location of the shower core on the ground with respect to the telescope. Using the air shower geometry leads to positional constraints in the telescope focal planes (Hillas).

The real-time calculation of the impact point for faint Cherenkov flashes in IACT arrays reduces the number of chance coincidences by another factor of 10 to 20, depending mostly on the instrument's point spread function and shower fluctuations. The total reduction of night sky background rate amounts to 200 - 1200, depending on the camera used. Assuming a power law with an index of 10.8 for the night sky rate (indicated by measurements & simulations) the reduction in trigger threshold of 40% is possible, e.g., from 5.5 p.e. to 4 p.e. This reduction in trigger threshold cannot be simply translated in a reduction of energy threshold in a linear fashion. However, by taking into account the Cherenkov light output as a function of energy in the regime below 200 GeV (LeBohec, Krennrich & Sleege 2005), a reduction from 5.5 p.e. to 4.0 p.e. would correspond for a VERITAS-like telescope array a reduction from 110 GeV to 50 GeV. The absolute accuracy of these numbers are to be taken with caution and require more detailed simulations, however, the relative reduction in energy threshold is correct.

2.1.2. Reduced Background Trigger Mode:

The differences between gamma ray and hadronic showers detected in faint Cherenkov light images become blurred as they are photon starved and contain only few pixels - not enough to calculate meaningful Hillas parameters (Hillas 1985). However, when using an array and combining the faint images from the various viewpoints, the information about the nature of the primary particle can be restored, since the information about the fluctuations is contained in the parallactic displacements of the multiple Cherenkov images. Hence, a unique feature of arrays of IACTs is that the low energy regime with faint images can still be used to separate gamma ray showers from hadronic showers. In fact the array imaging technique could be applied before triggering and recording the images using fast digital electronics.

When reconstructing the shower core for even small/faint images, the spread in the reconstructed shower core postion can be used to distinguish gamma ray from hadronic showers. This technique requires a minimum of 3 telescopes and, according to simulations the background from cosmic ray showers, can be reduced by 90% while maintaining 60% of the gamma ray showers. Parallaxwidth works for point sources as well as extended sources, hence a trigger using the parallaxwidth criterion would be very useful for sky surveys to provide a fast real-time feedback due to the greatly reduced amount of data. It is important to point out that the Parallaxwidth technique requires simply the first moments such as the image centroid position allowing it to be used at the low energy regime for which the images of faint Cherenkov flashes do not permit accurate calculation of Hillas parameters (Hillas 1985). Therefore, using Parallaxwidth for a real time analysis of faint Cherenkov flashes is a promising approach to reduce the background from cosmic ray showers at the lowest energies: this trigger mode could be used to reduce the energy threshold of IACT arrays and could improve the sensitivity for the detection of pulsars and GRBs for which a low energy threshold is critical.

The low background mode could also be applied at higher energies to reduce the data rate which is dominated above 100 GeV by cosmic rays. A factor of 10 reduction in data rate could be used in special observing modes such as fast sky survey for transient phenomena, it could speed up the real time quicklook analysis of IACT arrays.

It is also important to realize that a fast FPGA trigger would enable one to run various trigger modes in parallel increasing the sensitivity and versatility of an IACT array. For example a low energy photon trigger ("donut" trigger) combined with a Parallaxwidth algorithm could run in parallel with a standard all camera trigger improving the low energy collection area while maintaining the performance at higher energies. Using reprogrammable gate arrays such as the XILINX VIRTEX-4 family would enable one to tune the algorithm required for special observation modes.

2.2. Positron Emission Tomography (PET)

High resolution PET has seen a rapid development over the last decade with regard to spatial resolution and applicability to cancer research. Small animal PET scanners are used to study the impact of chemotherapy on cancer growth in small mammals. Those MicroPET scanners are important for drug discovery and form an important bridge to the medical use and diagnostics of large PET scanners.

The desire for better resolution instruments has led to miniaturized scintillator blocks (BGO, LSO) and photomultiplier readout to using Avalanche Photodiode Detectors (APDs) with spatial resolutions of of 2-3 mm. In fact submillimeter resolution is currently being explored. The high resolution detectors with $10^4 - 10^5$ detector elements require cost effective and potentially fast readout or real time trigger systems. The projected benefit from a fast real-time reconstruction system could be the rejection of Compton scattered events and the rejection of chance coincidences. Both types of background limit the achievable signal-to-background ratio for PET. A fast FPGA trigger would enable the rapid analysis of imaging and timing properties of many interactions in parallel and thus allow the rejection at the trigger level.

3. Technical Requirements for a fast Topological Trigger

Air shower physics and the number of pixels of modern/future IACT arrays ($10^4/10^5 - 10^6$) impose a set of basic requirements for the implementation of a fast array trigger to perform real-time imaging analysis. Recent advances in the technology of FPGAs are now within the realm of performance needed to implement this intelligent array trigger in hardware at a reasonable cost. Present Cherenkov telescope arrays consist of a basic cell of 4 telescopes that lie within the Cherenkov lightpool of an air shower, which is typically 250 m in diameter. Hence we consider Parallax-Trigger design that uses 4 telescopes in coincidence as the baseline design for a proof of principle study. It is howerever straightforward to expand the concept to a larger number of telescopes and to other types of fast detectors with a large number of channels. This design could easily be implemented in the next generation of large IACT array such as the instruments just now being considered (see http://gamma3.astro.ucla.edu/future_cherenkov). The Parallax-Trigger concept we discuss here consists of 4 identical camera trigger units, one at each telescope, and a centrally located array parallax trigger unit receiving information from each telescope camera trigger.

The following specifications are a guideline for the requirements of the array trigger:

• Data Processing Bandwidth: $\geq$ 400 MHz. A Cherenkov light flash from an air shower has a typical pulse width of 4-8 ns and depends on primary energy and shower core location. Modern IACT arrays achieve better than 2 ns absolute timing resolution, which should be matched by the Parallax-trigger.

• Maximum background rate input per channel: 10 MHz. This is motivated due to the fact that a photomultiplier in a typical modern large Cherenkov telescope (100 m^2 mirror and pixel size 0.15°) has a singles rate from the night sky fluctuations of 1 MHz (4 MHz) at a threshold of 5 (4) photoelectrons. The number of 4-5 photoelectrons is the typical trigger threshold that could be achieved with a sophisticated array trigger electronics proposed here. This is based on a night sky as is found in a dark location, e.g., at major observatories for optical astronomy (N.S.B = 2×10^{12} photons m^{-2} sr^{-1} s^{-1} (Mirzoyan et al. 1994).

• Trigger Decision time 1 μs. This is a non-critical specification and must be tuned for a specific application. Modern IACT arrays have trigger latencies on the order of several microseconds. The basic data processing of the trigger will be pipelined, and require some minimum time, depending on the nature and sophistication of the algorithm. This specification sets an upper limit on the processing time.

• Timing precision of the individual camera trigger decision:. 1 clock period or less. This is important so that the coincidences can be properly superimposed in subsequent image analysis.

• Coincidence gate width for array trigger decision: adjustable between 4-60 ns. Since the shower front of the Cherenkov light is conical and the arrival direction not known a priory, the coincidences from several telescopes require flexible time windows. For example, if the arrival time of Cherenkov light as a function of shower core distance is shifted by 10 - 15 ns (Karle 1994).

The overall structure of a Parallax-Trigger is shown in Figure 4. The system consists of 2 main components, the camera trigger providing information about the image pattern in the focal plane of each individual telescope and the central array unit that combines the camera patterns and analyzes the parallax of the pattern in real time. In the following we first discuss the design considerations of a camera trigger and then we explain the array trigger.

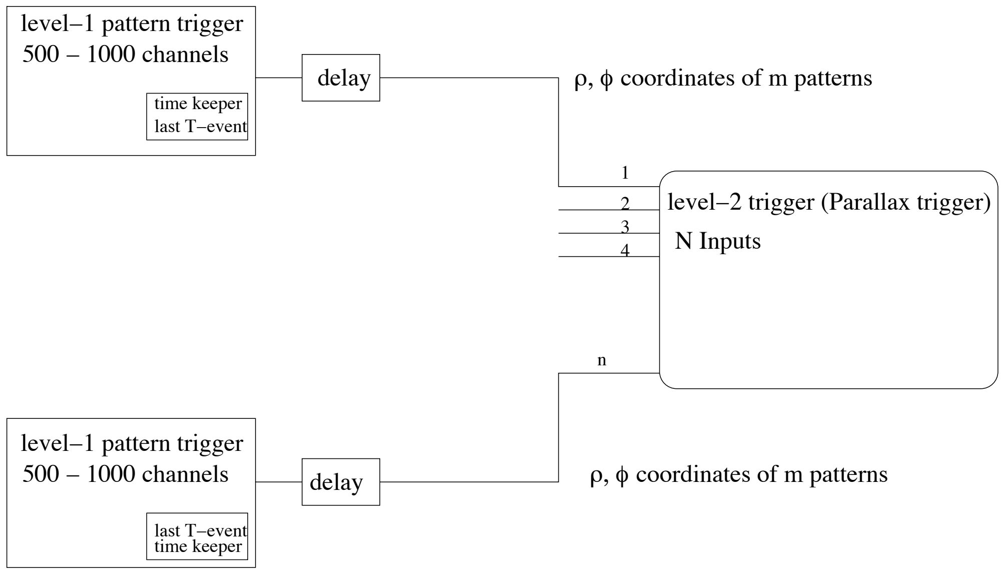

Fig. 4.— The basic structure of a Parallax Trigger/Camera trigger for an IACT array is shown. The level-1 and the level-2 stages of the trigger could be used in any other application using multiple imaging systems and the combined information for stereoscopic pattern recognition.

3.1. Design Considerations for a Level-1/Camera Trigger:

In this approach, it is assumed that the front-end electronics of the IACT array would provide a fast discriminated output, where the threshold is set to the 4-5 photoelectron level per channel. Because of the fast timing requirements, it is desirable for this to be implemented using Constant Fraction Discriminators (CFDs.) It is desirable to have the capability to set the CFD thresholds separately for individual channels so that selected parts of the camera could be run at a lower discriminator threshold as a means to study the performance of the low energy threshold trigger.

Having a single threshold per channel means that the resolution in determining the x-y-position of an image pattern would not make use of pulse-height information, and hence will limit the gamma/hadron separation capability somewhat for larger images consisting of many pixels. Simulations are required to estimate the loss in resolution and gamma/hadron separation when using only a single trigger threshold, and this is part of the scope of this proposal. However, preliminary simulations indicate that the loss in resolution will be small, given the goal of achieving a low energy threshold using images with only few pixels.

The individual camera of 500-1000 pixels would be read into a single FPGA. The algorithm in the FPGA would use a look-up table (LUT) to search for pattern matches in the input bit stream, evaluating all possible n-fold multiplicity patterns within a selected time window. The size of the LUT is estimated to require 150,000 logic cells, which is achievable with modern high-performance FPGAs. The output would be the multiplicity and position of all patterns found. For the case where there are multiple patterns in a given time window in different parts of the camera, perhaps due to night sky noise fluctuations or a large hadronic shower, additional processing would be needed. Multiple patterns produced by a single telescope trigger could be compared with the stereo view from the other telescopes, and an array trigger issued only when the geometry is correct. The best way to handle multiple patterns would be studied in simulations as part of the scope of this proposal.

3.2. Design Considerations of the Level-2/Parallax Trigger:

A parallax array trigger requires the knowledge of the image pattern positions in the cameras of the individual telescopes in the array, expressed in polar coordinates, phi and r. This would allow to use phi only when using the trigger solely for the purpose of gamma/hadron separation, and use the combination of both if a lower energy threshold and fewer chance coincidences due to the night sky are desired. Again, an LUT could be used for estimating the position. The n-fold coincidence will provide n values for phi and r. The LUT could also be used on different patterns to apply a position dependent correction if needed.

The transfer of phi and r values to other telescopes or central location must be achieved so that the data is aligned in time. Since the IACT arrays might be distal, it is desirable to have each camera trigger append a ”timestamp” onto the data. This would be used by the Parallax Trigger to align data fragements as they arrive, without needing to have crisp timing over great distances. The problem of data alignment then reduces to synchronizing the timestamp circuits on each camera trigger. Modern techniques for achieving timing synchronization use Global Positioning Systems (GPS), which are commercially available, low cost, and have the needed timing accuracy.

The data from the different telescopes would be sent to the Parallax Trigger serially. The fast serial transfer between telescopes with approximately 64 bits of data per telescope and can be done via commercially available optical fiber receivers and transceivers (1 bit for valid trigger, 4 bit for n-fold coincidence, 13 bits for geometry information, 32 bits of timestamp.) At this stage it would be sensible to introduce the necessary timing correction (zenith angle dependent) to account for the different arrival times of the Cherenkov front at the different telescopes. By using digital delay units to delay the bitstreams between the telescope trigger and the Parallax Trigger array trigger, it would be possible to correct for the timing of the individual telescope triggers before reaching the Parallax Trigger unit.

4. Research and Development Plan

The preceeding sections describe implementations for specific applications of this Parallax-Trigger concept. For this R and D program, we propose to build a prototype that demonstrates the feasibility of this approach, and to obtain benchmarks that could be used as a basis for studying specific implementations and applications. We feel that a collaboration between the people involved in this project would be particularly effective: Gary Sleege of Iowa State University has extensive experience in FPGA board design and programming due to his work on the Level-1 trigger for the PHENIX experiment at RHIC and his involvement in the VERITAS and SGARFACE electronics design. Gary Drake is the engineering group leader at the high energy physics division at ANL and has extensive experience in fast analog electronics, critical to the successful interfacing between digital and analog. The PI has been leading the design and development of the VERITAS cameras including the front-end electronics system and the SGARFACE experiment. Both systems are working and taking data sucessfully.

The prototype would consist a VME card that hosts the FPGA for doing the Level 1 Triggering. This card would be capable of having 500 inputs, and could operate at design speed. The testing of the device would be performed at two levels: The Level 1 card would have the capability to have test vectors written into the FPGA through the VME interface. The board would be put into a test mode where these test vectors would be written to the inputs at design speed, internally to the Level 1 card. The second stage of testing would be to develop a companion VME test card that hosts large memories, which could be loaded with test vectors from a host computer. The output of the test card would then be used as the input to the Level 1 card. The test card would also have the capability to receive outputs from the Level 1 card, and store them in a memory. The test card would have a state machine that initiates data transfers to the Level 1 card in response from a start command from a host computer. The data processing could be operated either as a single sequence, or in a looping mode. The results stored in the memory on the test card would be read at the end of each sequence, and evaluated for accuracy. The test vectors used in either test would be arranged to be background mixed with real signal, and constructed to reasonably approximate signals from IACTs. The choice of an implementation in VME could open the possibility of further tests beyond the scope of this R and D proposal in specific applications.

The steps in the Research and Development plan are as follows (not necessarily sequential):

- 1. Construct initial test vectors for simulations.
- 2. Simulate different algorithms in software.
- 3. Selection of appropriate devices for data processing and test data processing.
- 4. Design of FPGA algorithms for a specific device.
- 5. Design and fabrication of PC boards for the Level 1 card and the test card.

- 6. Development of software for downloading test vectors, and evaluating results.
- 7. Execution and evaluation of test program. Refinement and enhancement of test vectors.
- 8. Publication of results.
- 9. Exploration of implementation in specific applications.

5. Timeline and Budget:

5.1. Timeline:

Table 1: Project Timelines

FY	Goal
Spring 2006	Monte Carlo Simulations of imaging array pattern-trigger algorithm
Fall 2006	Start board design for a 500 channel FPGA based pattern trigger
Spring 2007	Start board design of auxiliary FIFO board to test the pattern trigger
Spring 2007	Test Parallaxwidth performance in off-line analysis using VERITAS-4 data
Summer 2007	Fabricate pattern trigger and auxiliary board
Fall 2007	Test performance of the pattern trigger: parallax/imaging algorithm/analysis
Spring 2008	Final performance evaluation

5.2. Budget:

The budget is divided into 2 subgroups, effort (table 2) and materials and supplies (table 3).

A summary including a 2 year budget schedule is shown in table 4.

Table 2: Cost for Board Layout

Parts	Institution	months	Cost per item	Total Cost
Engineering Labor	Argonne National Lab	12		$ 80,000
Contingency	Argonne National Lab		1	$8,500
Engineering Labor	Iowa State University	2		$ 12,000
Contingency	Iowa State University	-	1	$ 6,000
Subtotal				$106,500

At ISU Gary Sleege would be providing engineering support for FPGA programming and testing the trigger algorithm. Argonne's Gary Drake would carry out the board design, implementation and electronics testing.

The following table shows the costs for building a proof-of-principle system of a fast pattern trigger. This would consist of a pattern trigger board with 500 input channels and an auxiliary board consisting of programmable shift registers that could be used to simulate signals coming from an imaging camera. Simulated image patterns could resemble what is expected from fast light signals from air showers. The cost for the pattern trigger also includes two dedicated 9U VME systems to be able to work in parallel at ISU and Argonne, utilizing ISU and Argonne personnel most effectively.

Table 3: Cost of prototype pattern trigger and auxiliary test module.

Parts	Manufacturer	QTY	Cost per item	Total Cost
pattern trigger board		3	$5,000	$15,000
auxiliary test module		2	$5,000	$10,000
2 x 9U VME Crates		2	$5,000	$10,000
2 x 9U VME Crate Controler		2	$3,000	$6,000
Subtotal for prototypes				$41,000

The following gives the cost estimate for support for graduate student Asif Imran to work part time on implementing and testing the pattern recognition algorithms. This will involve a few trips from Ames to Argonne National Laboratory. Also travel support for the PI is requested.

Table 4: Travel support of Iowa State University PI and student

Personnel	Trips to Argonne	Cost per trip	Total Cost
Grad. student	5	$600	$ 3,000
Principal Investigator	5	$600	$ 3,000
Subtotal			$6,000

Table 5: Support of Iowa State University student Asif Imran

Personnel	months	cost per month	Total Cost
Grad. student	6	$1,800	$ 9,000
Subtotal			$9,000

Furthermore, to upgrade the board testing facility to GHz time scale ISU is requesting to purchase a 1GHz oscilloscope and a GHz pulse generator: total cost: $40,000. Iowa State University will provide this equipment as matching funds.

Table 6: 2 year budget

Equipment	year 1	year 2	total
9U VME Crate	$ 5,000	$ 5,000	$ 10,000
Crate Controler	$ 3,000	$ 3,000	$ 6,000
pattern trigger board	$ 5,000	$ 10,000	$ 15,000
auxiliary test module		$ 10,000	$ 10,000
Oscilloscope*	$ 20,000*		$ 20,000*
Fast Pulse generator*	$ 20,000*		$ 20,000*
subtotal	$53,000	$28,000	$ 81,000
Operational			
Argonne Engineering	$ 60,000	$ 20,000	$ 80,000
ISU Engineering	$ 5,000	$ 7,000	$ 12,000
Contingency Engineering		$ 14,500	$ 14,500
Travel	$3,000	$ 3,000	$ 6,000
Grad. student support	$4,650	$ 4,650	$ 9,300
student tuition		$ 1,777	$ 1,777
subtotal	$72,650	$ 50,927	$ 123,577
total	$125,650	$ 78,927	$ 204,577
ISU matching funds*	$ 40,000*		$ 40,000*
DoE (no overhead)	$ 85,650	$ 78,927	$ 164,577
DoE incl. indirect costs**	$ 102,671	$ 82,420	$ 185,091

* funds committed by Iowa State University to match DoE funding

** DoE funding requested including overhead (for details see attached budget pages)

REFERENCES

See for instance Rene Ong's Rapporteur Talk at the 29th International Cosmic Ray Conference (Pune) (2005)

Krennrich, F. and Lamb, R.C.Experimental Astronomy, 6, 285-292 (1995a)

Krennrich, F. and Lamb, R.C.Proceed. of Towards a Major Atmospheric Cherenkov Dtetector III, Padua (1995b)

see http://veritas.sao.arizona.edu/

see http://www.mpi-hp.mpg.de/hfm/HESS/HESS.html

private communication with A.M. Hillas.

LeBohec, S., Krennrich, F. & Sleege, arXiv:astro-ph/0501199 v1, (2005).

Hillas, A.M., in Proc 19th I.C.R.C. (La Jolla), Vol 3, p. 445 (1985).

see http://gamma3.astro.ucla.edu/future_cherenkov

Mirzoyan, R. et al., Nucl. Instr. Meth. A351, 513 (1994).

Karle, A., PhD Thesis, Ludwig Maximilians University (Munich) (1994)

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Positions

Research Assistant, Cern, Geneva (Switzerland), 1990-91

Research Associate, Max-Planck-Institute of Physics and Werner-Heisenberg-Institute (Munich), 1991-94

Research Associate, Iowa State University, 1994-96

Research Associate, Whipple Observatory for Iowa State University, 1996-97

Assistant Professor of Physics, Iowa State University, 1997-2001

Associate Professor of Physics, Iowa State University, 2001-present

Research Areas: Gamma Ray Astrophysics, ground based detection techniques of cosmic ray phenomena, detector design

Awards

Outstanding Junior Investigator Award by the High Energy Physics Division at the Department of Energy 2000

Early Excellence in Research Award by the College of Liberal Arts and Science at Iowa State University 2000

Selected publications in refereed journals

1. ”Simultaneous Constraints On The Spectrum Of The Extragalactic Background Light And The Intrinsic TeV TeV Spectra of Mrk 421, Mrk 501 and H1426+428”, E. Dwek and F. Krennrich, Astrophysical Journal, 618, 657, (2005)

2. ”SGARFACE: A Novel Detectors For Gamma Ray Bursts”, S. LeBohec, F. Krennrich & G. Sleege, Astroparticle Physics, 23, 238-248, (2005)

3. ”Discovery of Spectral Variability of Markarian 421 at TeV Energies”, Krennrich, F., I.H. Bond, S.M. Bradbury, J.H. Buckley, D.A. Carter-Lewis, M. Catanese, W. Cui, S. Dunlea, D. Das, I. de la Calle Perez, D.J. Fegan, S.J. Fegan , J.P. Finley, J.A. Gaidos, K. Gibbs, G.H. Gillanders, T.A. Hall, A.M. Hillas, J. Holder, D. Horan, M. Jordan, M. Kertzman, D. Kieda, J. Kildea, J. Knapp, K. Kosack, M.J. Lang, S. LeBohec, B. McKernan, P. Moriarty, D. Müller, R.A. Ong, R. Pallassini, D. Petry, J. Quinn, N.W. Reay, P.T. Reynolds, H.J. Rose, G.H. Sembroski, R. Sidwell, N. Stanton, S.P. Swordy, V.V. Vassiliev, S.P. Wakely, T.C. Weekes, Astrophysical Journal Letters, 575, L45 (2002)

4. ”Detection Techniques of Micro-second Gamma-Ray Bursts using Ground-based Telescopes”,F. Krennrich, S. LeBohec, T.C. Weekes ApJ, 529, 506 (2000)

5. ”Very Rapid and Energetic Bursts of TeV Photons from the Active Galaxy Markarian 421”,Gaidos, J. A., Akerlof, C. W., Biller, S. D., Boyle, P. J., Breslin, A. C., Buckley, J. H., Carter-Lewis, D. A., Catanese, M., Cawley, M. F., Fegan, D. J., Finley, J. P., Hillas, A. M., Krennrich, F., Lamb, R. C., Lessard, R., McEnery, J., Mohanty, G., Moriarty, P., Quinn, J., Rodgers, A., Rose, H. J., Samuelson, F., Schubnell, M. S., Sembroski, G., Srinivasan, R., Weekes, T. C., Wilson, C. L. and Zweerink, J. 1996, Nature 383, 319.

COLLABORATORS:
Whipple Collaboration, VERITAS Collaboration and SGARFACE Group

Number of refereed publication: 61

Number of invited talks: 29

a. Professional Preparation

Year	*Degree*	*Institution and Location*	*Field of Study*
1982	B.S.E.E	University of Wis. - Madison	Electrical Engineering
1983	M.S.E.E	University of Wis. - Madison	Electrical Engineering

b. Professional Appointments

- Apr. 1997 – Present: Electronics Group Leader, High Energy Physics Div., Argonne Nat. Lab, Argonne, IL
- Oct. 1995 – Apr. 1997: Asst. Elec. Group Leader, Fermi National Accelerator Laboratory, Batavia, IL
- Oct. 1983 – Apr. 1997: Electronics Engineer, Fermi National Accelerator Laboratory, Batavia, IL

c. List of Publications

1. T. Cundiff, J. W. Dawson, L. Dalmonte, G. Drake, T. Fitzpatrick, W. Haberichter, D. Huffman, W. Luebke, C. Nelson, D. Reyna, J. L. Schlereth, P. Shanahan, J. L. Thron, M. Watson, "The MINOS Near Detector Front End Electronics," Presented at IEEE Nucl. Sci. Symp., Rome, Italy, Oct. 18-22, 2005.
2. A. Byon-Wagner, K. Byrum, J. Dawson, G. Drake, C. Drennan, G. Foster, W. Haberichter, J. Hoff, S. Kuhlmann, M. Lindgren, L. Nodulman, J. Proudfoot, J. Schlereth, J. Wu, "The Shower Maximum Front End Electronics for the CDF Upgrade," *IEEE Trans. Nucl. Sci.*, TNS-49, pp. 2567-2573, 2002.
3. S. Magill, S. Chekanov, G. Drake, S. Kuhlmann, B. Musgrave, J. Proudfoot, J. Repond, B. Stanek, R. Yoshida, A. Bamberger, "E-Flow Optimization of the Hadron Calorimeter for Future Detectors," 10th International onference on Calorimetry in High Energy Physics (CALOR 2002), Pasadena, California, Mar. 25-30, 2002, Published in *Pasedena 2002, Calorimetry in Particle Physics*, pp. 806-813.
4. J. Hoff, A. Byon-Wagner, G. Drake, G. Foster, M. Lindgren, "SMQIE: A Charge Integrator and Encoder Chip for the CDF Run II Shower Max Detector," *IEEE Trans. Nucl. Sci.*, TNS-47, pp. 834-838, 2000.
5. G. Drake, D. Frei, S.R. Hahn, C.A. Nelson, S.A. Segler, W. Steurmer, "The Upgraded CDF Front End Electronics for Calorimetry," *IEEE Trans. Nucl. Sci.*, TNS-39, pp. 1281-1285, 1992.
6. The CDF Collaboration, "The CDF Detector: An Overview." *Nucl. Instrum. Meth.,* A271, pp. 387-403, 1988.
7. G. Drake, T.F. Droege, S. Kuhlmann, C.A. Nelson, Jr., S.L. Segler, W. Stuermer, K.J. Turner, "CDF Front nd Electronics: The RABIT System," *Nucl. Instrum. Meth.,* A269, pp. 68-81, 1988.

d. Synergistic Activities

Relevant Research Experience

1. 1998 – present: Level 3 Mgr., Electronics for Near Detector of MINOS Exp. At Fermilab
2. 1988-1999: Project Eng., Shower Max Electronics, CDF Exp. At Fermilab.