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The VERITAS Trigger System

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Abstract: The VERITAS gamma-ray observatory, situated in southern Arizona, is an array of four 12m diameter imaging Cherenkov telescopes, each with a 499-pixel photomultiplier-tube camera. The instrument is designed to detect astrophysical gamma rays at energies above 100 GeV. At the low end of the VERITAS energy range, fluctuations in the night sky background light and single muons from cosmic-ray showers constitute significant backgrounds. VERITAS employs a three-tier trigger system to reduce the rate of these background events: an initial trigger which acts at the single pixel level, a pattern trigger which acts on the relative timing and distribution of pixel-level triggers within a single telescope camera, and an array-level trigger which requires simultaneous observation of an air-shower event in multiple telescopes. This final coincidence requirement significantly reduces the rate of background events, particularly those due to single muons. In this paper, the implementation of all levels of the VERITAS trigger system is discussed and their joint performance is characterized.

The VERITAS gamma-ray observatory, situated in southern Arizona, is an array of four 12m diameter imaging Cherenkov telescopes, each with a 499-pixel photomultiplier-tube camera. The instrument is designed to detect astrophysical gamma rays with energies above 100 GeV. At the low end of the VERITAS energy range, fluctuations in the night sky background light (NSB) and single muons from cosmic-ray showers constitute significant backgrounds, which the three-tiered VERITAS trigger system is designed to reduce.

VERITAS has operated in a three-telescope configuration with the full trigger system since December 2006. A fourth telescope was added to the array in March 2007.

Level One (Pixel) Trigger

The first tier (level one, or L1) of the VERITAS trigger system acts at the single pixel level. It consists of custom-built Constant Fraction Discriminators (CFDs), one for each photomultplier tube (PMT) pixel in a telescope camera [1]. The output of the PMT is routed directly to the input of the CFD, which produces an output pulse if the sum of the voltages from the PMT pulse and a time-delayed copy crosses a threshold. The VERITAS CFDs are equipped with a rate feed-back (RFB) loop, which automatically increases the effective threshold when the noise level (and thus CFD trigger rate) rises.

Typical CFD operating parameters for the array involve a 50mV CFD threshold (corresponding to approximately 4-5 photoelectrons), a 10ns output pulse, and an RFB setting of 60mv/MHz.

Level Two (Pattern) Trigger

At each telescope, a pattern trigger system uses the relative timing and distribution of L1 triggers within the camera to preferentially select the more compact Cherenkov light images and reduce the rate of triggers due to random fluctuations of night-sky background light. The pattern trigger, hereafter referred to as L2, is similar to that used on the Whipple 10m telescope [2], but with an improved channel-to-channel timing jitter of $<1\mathrm{ns}$[3]. It consists of two elements, an ECL signal splitter which copies and redirects signals from the CFDs, and 19 pattern selection trigger (PST) modules. The PST modules are arranged to cover overlapping patches of the VERITAS camera and contain memory chips which can be pre-programmed to recognize patterns of triggered pixels within the camera. The standard pixel coincidence requirement is three adjacent pixels within a patch; the required overlap time between adjacent CFD signals is $\sim$ 6ns.

Level Three (Array) Trigger

As shown in Figure 1, the multi-telescope array trigger (L3) receives information from the L2 trigger system at each telescope, uses it to identify events that are consistent with simultaneous observation of an air-shower in multiple telescopes, and provides instructions to the telescope data acquisition systems. The array trigger communicates with the other systems via ECL signals; as it is centrally located, these signals are converted and transmitted via optical fiber, using custom-built pairs of Digital Asynchronous Transceiver modules (DATs).

A pair of custom-built VME modules, the Pulse Delay Module (PDM) and SubArray Trigger board (SAT), together with a commercial VME GPS clock, comprise the core of the array trigger hardware. The PDM has 32 independently programmable digital delay lines, each with a 2ns step size and a 100ns-16μs range. The SubArray Trigger (SAT) board performs the majority of the critical array trigger functions. It is designed to handle up to eight telescopes in any possible combination (subarrays).

Identification of Cherenkov shower events depends on the relative timing of the L2 triggers. Two main factors influence the relative arrival times of L2 triggers at the central control building: fixed differences in signal transmission time (due to varying optical fiber and cable lengths) and the arrival time of the Cherenkov light front at the different telescopes. The first component is corrected for exactly; the second varies as the source is tracked across the sky, but can be approximately calculated based on the current pointing of the telescope system. These corrections are applied in hardware via the delay lines of the Pulse Delay Module (PDM) and updated on a five-second basis.

There is a residual spread in the delay-corrected L2 trigger arrival times due to the width and curvature of the Cherenkov wavefront, variation in the L2 trigger response with respect to image size, and timing jitter in the various electronics components. This spread is small (on the order of tens of nanoseconds), allowing the SAT board to identify events by requiring L2 triggers from multiple telescopes within a fixed coincidence window (1-125ns). The SAT converts the arrival times of the delay-corrected L2 signals into digital timestamps via 1.25ns resolution time-to-digital converters (TDCs) and buffers them; the coincidence logic algorithm, which is configured by a programmable pattern lookup table, searches the timestamp buffers until a programmed pattern is found within the coincidence window. While the lookup table can be used to suppress or privilege particular telescope combinations, all observations to date use a simple multiplicity requirement.

Custom-built 500MS/s flash-ADC (FADC) modules (one FADC channel per pixel) digitize the PMT signals with a memory buffer depth of 64 μs. When the array trigger identifies an air shower event, it sends a logical signal (the "L3 trigger") to each telescope, directing the telescope data acquisition system to read out a portion of this buffer (24 samples) for every channel. During readout, each data acquisition system inhibits the array trigger coincidence logic by raising a BUSY level. The SAT also self-vetos for 10 μs after an event decision, in order to allow for L3 signal propagation to the telescopes.

Via a combination of outgoing PDM delays and internal compensation on the SAT board, the array trigger ensures that an L3 trigger is received at the telescope a fixed time after the corresponding L2 trigger was produced. The data acquisition then "looks back" a fixed number of FADC samples and initiates readout from that point. This look-back time is on the order of $3\mu s$ for all telescopes. Telescopes that do not participate in an event decision may still receive an L3 trigger ("forced readout" mode), whose timing is determined from the timing of the participating telescope triggers.

The array trigger also tags the event with supplementary information, including an event number,

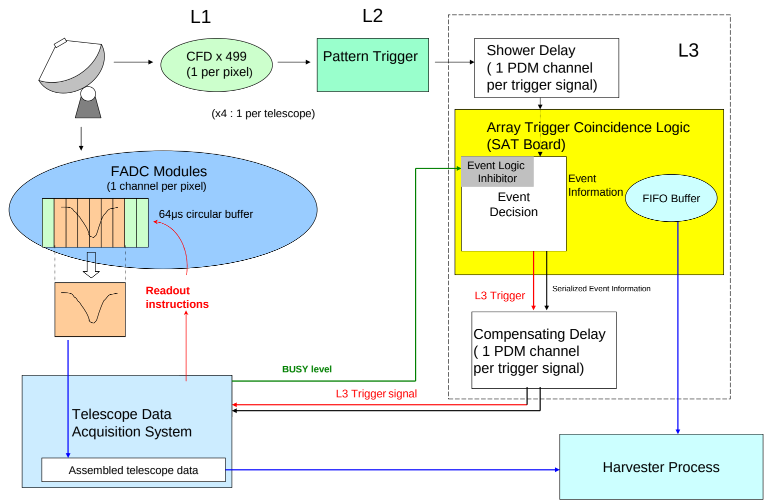

Figure 1: Illustration of the trigger system's operation and interface with data acquisition.

and sends it to the data acquisition system via a 48-bit serial transmission. This information, along with additional event information such as a GPS timestamp, is also recorded in a FIFO. The FIFO is polled asynchronously in software and the results are sent to another software process, the Harvester, which binds together the array trigger and telescope-level information into complete events. Current polling speeds allow the array trigger to operate at rates as high as 2kHz without data loss.

Preliminary Array Trigger Characterization

Early array trigger performance is excellent. The array trigger rates are extremely stable with respect to large fluctuations in the L2 rates. Studies of image shape parameters have already shown [3] that a multi-telescope coincidence requirement eliminates triggers due to local muons at the 90% level or better. As will be shown, the array trigger is also extremely effective at suppressing background due to NSB.

There is a large space of adjustable operating parameters for all three levels of the trigger; full optimization studies over this entire space have not yet been performed. However, preliminary studies were performed *in situ* to validate and characterize array performance.

Telescope delays and coincidence window

The time-stamps recorded by the SAT board allow us to study the pairwise L2 arrival time difference between telescopes for actual cosmic-ray showers. This approach lets us validate the telescope delays and assess the residual spread in L2 trigger arrival times. We find that these distributions are centered on zero, showing that the telescope delays have been correctly adjusted, and are more than 99% contained for pattern trigger separations of ± 25 ns, with negligible contributions from accidental coincidences. Since the minimum coincidence window width is dictated by the spread in L2 arrival times, this behavior is consistent with the fact that the array trigger rate is stable and independent of coincidence window width for window sizes above 20-25ns.

Dead-time determination and monitoring

Accurate knowledge of the array dead-time is required in order to determine the fluxes and spectra of astrophysical sources. The array trigger uses a 10MHz reference clock and a set of 32-bit scalers on the SAT board to precisely monitor this dead-time, which is dominated by the time it takes to read out telescope information (the average telescope readout time is $\sim 400\ \mu$s). As expected, the array dead-time scales linearly with the array trigger rate, reaching ~6-8% at 150-170Hz, and 10-11% at 225Hz.

As this dead-time does not scale with the L2 trigger rates, it is possible to operate the array under conditions (such as partial moonlight) where the pattern trigger rates vary by several orders of magnitude.

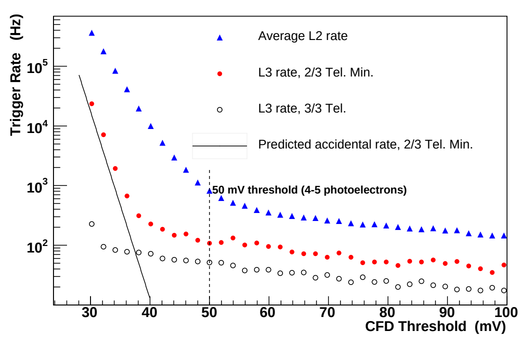

Figure 2: Dependence of the L2 and L3 trigger rates on CFD threshold, for a three-telescope array with a 50 ns coincidence window. The L2 rate (upright triangles) is averaged over all telescopes. Also shown: the L3 rates for a 2/3 (filled circles) and 3/3 (open circles) telescope coincidence requirement, the expected accidental trigger rate for the 2/3 requirement, as predicted from the measured L2 rates (solid line), and the standard L1 threshold used in array operation (dashed line). Error bars are commensurate with marker size.

Threshold and trigger rates

The CFD trigger threshold, along with the other trigger operating parameters, directly affects the energy threshold of the array. Operating parameters must be chosen to give the lowest possible energy threshold, while maintaining a stable array trigger rate with an acceptable level of dead-time for a variety of conditions.

Figure 2 illustrates the dependence of the L2 and L3 trigger rates on CFD trigger threshold and array trigger multiplicity requirement. Scans of the CFD threshold were performed with normal telescope readout disabled, so the rates shown are not affected by the usual dead-time. All scans were done while pointing at a dark patch of sky near zenith, under moderate weather conditions.

In all cases, the rates have a simple power law dependence at high thresholds, where air-shower triggers dominate. The L2 rates increase rapidly in the regime dominated by accidental pixel coincidences due to night-sky background (NSB) fluctuations. The L3 coincidence requirement continues to suppress the NSB component of the L3 rate, down to ~ 40 mV (3-4 photoelectrons) for a 2/3 multiplicity requirement and ~ 30 mV (2-3 photoelectrons) for 3/3. Below these thresholds, the array trigger rate increases rapidly until it is saturated by accidental coincidences.

In order to achieve stable operation with a single telescope, the CFD threshold was set at around 70mV (6-7 photoelectrons) [3]; for array operation, a loose multiplicity requirement of two telescopes and a CFD threshold of 50mV (4-5 photoelectrons) is used. It is clear that a more stringent coincidence requirement of three telescopes would allow operation at significantly lower thresholds, but at some cost in cosmic-ray rate.

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