The VERITAS Trigger System

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Abstract: The VERITAS gamma-ray observatory, situated in southern Arizona, is an array of four 12-m 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-level 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 12-m 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.

The VERITAS trigger system is a three-tier system designed to reduce these backgrounds. An initial trigger (L1) acts at the single pixel level, a pattern trigger (L2) acts on the relative timing and distribution of pixel-level triggers within a single telescope camera, and a multi-telescope array trigger (L3) requires simultaneous observation of an air-shower event in multiple telescopes. The array trigger system is centrally located; it receives input in the form of L2 triggers, and provides output instructions to the telescope data acquisition systems. All communication is done via ECL signals that are converted and transmitted via optical fiber, using custom-built pairs of Digital Asynchronous Transceiver modules (DATs).

VERITAS has operated in a three-telescope configuration with the full trigger system since December 2006, and introduced a fourth telescope to the array in March 2007.

Level One (Pixel) Trigger

The first tier (level one, or L1) of the VERITAS trigger system consists of custom-built Constant Fraction Discriminators (CFDs), one for each photomultiplier tube (PMT) pixel in a telescope camera [3]. The output of the PMT is routed directly to the input of the CFD, which triggers (produces an output pulse) if the voltage of the output from the PMT 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 preferentially selects the more compact Cherenkov light images and reduces 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 [1], but with an improved channel-to-channel timing jitter of $<1 \text{ ns}$ [2]. 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 trigger 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 6 ns.

Level Three (Array) Trigger

The array trigger’s primary purpose is to determine when L2 triggers from individual telescopes are consistent (in terms of relative timing) with an air shower. It also monitors rates and dead-times, tags the shower event with identifying information, and sends instructions to the telescope data acquisition systems.

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 is a programmable digital delay module with 32 independently programmable delay lines, each with a 2 ns step size and a 100 ns-16 µs range. The SubArray Trigger (SAT) board performs the majority of the critical array trigger functions. The board is designed to handle up to eight telescopes in any possible combination (subarrays); it is also designed to be capable of triggering multiple independent subarrays.

Event Identification

The process of identifying Cherenkov events is divided into two stages: a timing correction and programmable coincidence logic.

Identification of Cherenkov shower events depends on the relative timing of the telescope pattern 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 programmable delay lines of the Pulse Delay Module (PDM) and updated on a thirty-second basis.

After the delays are applied, there is a residual spread in 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), making it possible for the SAT board to identify events by requiring pattern triggers from several telescopes within a fixed coincidence window (1-125 ns).

The SAT converts the arrival times of the delay-corrected L2 signals into digital time-stamps via 1.25 ns resolution time-to-digital converters (TDCs) and buffers them for use in the coincidence logic. The coincidence logic algorithm, which is configured by a programmable pattern lookup table, searches through the time-stamp buffers until one of the programmed patterns is found within the coincidence window. While the array trigger currently uses a multiplicity requirement for the coincidence logic, the lookup table can be used to suppress or privilege particular telescope combinations.

Interface to Telescope Data Acquisition

Custom-built 500 MHz flash-ADC (FADC) modules (one FADC channel per pixel) digitize the PMT signals with a memory buffer depth of 64 µs.
The telescope data acquisition systems read out a portion of this buffer (24 samples) for every channel, but only do so when directed to by the array trigger system.

The array trigger system initiates telescope readout via a logical signal (the “L3 trigger”) which is sent back to each telescope. Via a combination of outgoing PDM delays and internal compensation on the SAT board, the array trigger ensures that the L3 trigger is received at the telescope a fixed time after the L2 trigger is produced. The data acquisition can then “look back” a fixed number of FADC samples and initiate readout from that point. This look-back time is on the order of 3µs 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. Supplementary information, including the event number and array configuration—is sent to the data acquisition system via a 48-bit serial transmission.

Each telescope inhibits the coincidence logic of the SAT board by raising an ECL BUSY level while being read out. In addition, there is a 10 µs veto after each SAT event decision to allow for L3 signal propagation to the telescopes.

**Local recording of event information**

The event information described in the previous sections, along with additional event information such as a GPS timestamp, is recorded in a FIFO. The information in the FIFO is polled asynchronously in software and 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 up to a rate of 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 [2] that a multi-telescope coincidence requirement eliminates triggers due to local muons at the 90% level or better and as will be shown, the array trigger is also extremely effective at suppressing background due to NSB.

There are a large number of adjustable operating parameters for all three levels of the trigger, and full optimization studies over this entire parameter space have not yet been performed. However, preliminary studies have been 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 variation in array trigger rate observed for different coincidence window widths. We find 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 provides precise hardware monitoring of the system dead-time via a 10MHz reference clock and a set of 32-bit scalers on the SAT board. The array dead-time is expected, to first order, to be a function of the array trigger rate (125-250Hz, depending on array configuration and weather conditions) and the average telescope readout time (400 µs for 24 samples without zero-suppression). We find the measured array dead-time to be about 6-7% for an array rate of 150-170Hz, and 10-11% for an array rate of 250Hz, which is consistent with expectations. Since the VERITAS array dead-time
Figure 1: Dependence of the array trigger (L3) and pattern trigger rates (L2) on CFD threshold, for a three-telescope array configuration with a 50 ns coincidence window. The pattern trigger rate (upright triangles) shown is averaged over the three telescopes. The L3 rate is shown for two different multiplicity requirements: 2/3 (filled circles) and 3/3 (open circles). The expected accidental trigger rate for the 2/3 requirement, as predicted from the measured L2 rates, is indicated by the solid line. The standard L1 threshold used in array operation is indicated by the dashed line.

does not scale in any way with the local pattern trigger rates, it is possible to operate the array successfully in situations in which the pattern trigger rates vary by several orders of magnitude, including partial moonlight conditions.

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 1 illustrates the dependence of the L2 and array trigger rates on CFD trigger threshold and array trigger multiplicity requirement, for a three-telescope VERITAS array configuration with a 50 ns coincidence window. 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 fluctuations. The array trigger coincidence requirement continues to suppress the night-sky background component of the array trigger rate, down to 40 mV (3-4 photoelectrons) for a 2/3 coincidence requirement, and about 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) [2]; for array operation, a loose multiplicity requirement of two telescopes and a CFD threshold set 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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References