ATLAS level-1 calorimeter trigger hardware: initial timing and energy calibration

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Abstract. The ATLAS Level-1 Calorimeter Trigger identifies high-pT objects in the Liquid Argon and Tile Calorimeters with a fixed latency of up to 2.5 μs using a hardware-based, pipelined system built with custom electronics. The Preprocessor Module conditions and digitizes about 7200 pre-summed analogue signals from the calorimeters at the LHC bunch-crossing frequency of 40 MHz, and performs bunch-crossing identification (BCID) and deposited energy measurement for each input signal. This information is passed to further processors for object classification and total energy calculation, and the results are used to make the Level-1 trigger decision for the ATLAS detector. The BCID and energy measurement in the trigger depend on precise timing adjustments to achieve correct sampling of the input signal peak. Test pulses from the calorimeters were analysed to derive the initial timing and energy calibration, and first data from the LHC restart in autumn 2009 and early 2010 were used for validation and further optimization. The results from these calibration measurements are presented.

ATL-DAQ-PROC-2010-025
01 August 2010

1. Introduction

The Large Hadron Collider (LHC) at CERN is designed to collide protons at a centre-of-mass energy of 14 TeV with an instantaneous luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The Level-1 Trigger (L1) is mainly composed of the Level-1 Calorimeter Trigger (L1Calo), the Level-1 Muon Trigger (L1Muon) and the Central Trigger Processor (CTP), but also includes the Minimum Bias, LUCID, Zero Degree Calorimeter, and Beam Pickup Triggers [1]. L1 is the first of three trigger levels that together reduce the 40 MHz input rate to approximately 200 Hz which is the typical limit on the rate for recording events. L1 itself reduces the 40 MHz input rate to a nominal rate of ∼75 kHz with a current latency of 2.0 μs. The rate is then further reduced by the Level-2 Trigger to 3 kHz. The Event Filter makes the final decision before the event (of approximately 1.3 MB in size) is recorded [1].

About 200,000 Liquid Argon and Tile Calorimeter cells are summed into 7168 analogue signals that L1Calo uses to form a trigger. These pre-summed signals, called Trigger Towers (TT), mostly have dimensions 0.1×0.1 in $\Delta\eta \times \Delta\phi$. They first arrive in the Receivers where an analogue gain can be applied to the signal. This is the primary method for calibrating the transverse energy (E_{T}) measurement in L1Calo. The PreProcessor Module (PPM) conditions and digitizes the signals and then uses the digitized signals to identify the associated bunch-crossing and measure the E_{T}. This information is sent in parallel to the Cluster Processor (CP) and Jet-Energy Processor (JEP) where high-p_{T} electrons/photons, hadrons/taus, and jets are identified. The multiplicities of these objects are counted for selected thresholds. The JEP also provides a total and missing E_{T} measurement. The multiplicities per threshold are then

transmitted to the CTP where they are used in conjunction with information from other L1 systems to form the Level-1 Accept (L1A) which begins the complete readout of the detector including the L1 trigger system. For more details about the L1Calo system see [2].

The 7168 analogue signals arriving in the PPMs must be digitized to within ± 5 ns of the analogue peak in order to achieve an energy measurement of better than 2% [3]. The calibration of the timing delays applied in the PPMs aim to fulfil this requirement in all L1Calo TTs. Once the timing is optimized, the gains in the Receivers can be calibrated to ensure correct energy calculation. The process of the timing calibration is described in Section 2 and the energy calibration in Section 3.

2. Analogue Input Signal Timing Calibration

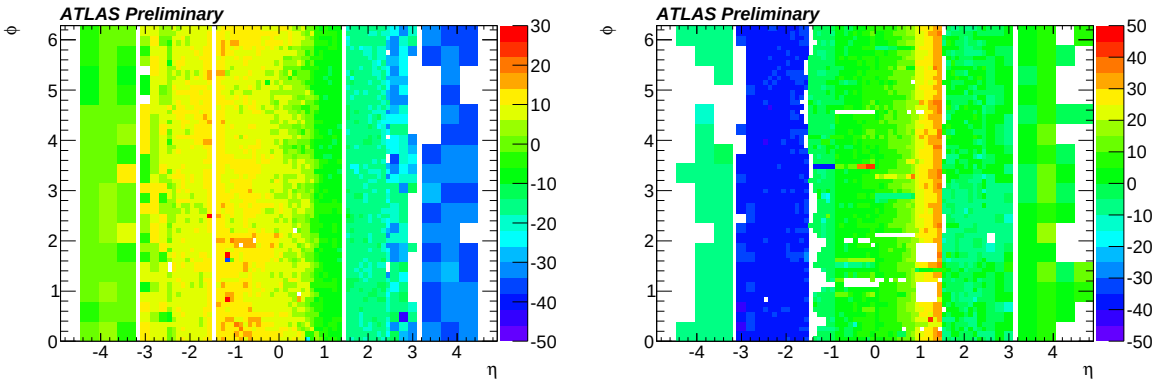
The analogue signals received by L1Calo are digitized in the PPMs at the LHC frequency of 40.08 MHz, which corresponds to one sample about every 25 ns. These digitized samples are used to assign the triggered event to the correct LHC bunch-crossing and to determine the energy deposited in the corresponding TT. It is important that the analogue signals are sampled at the peak in order to properly carry out these functions. Therefore, a nanosecond-step, or fine-timing, offset can be applied in order to adjust the sampling point [2]. As mentioned above, the analogue signals are composed of signals from multiple calorimeter cells which are summed to form a TT signal. If these calorimeter signals are not properly timed a TT signal may contain multiple peaks or other unwanted features. Extensive work has been done to ensure these timings are calibrated properly.

The fine-timing offset can be calibrated using test pulses from the charge injection and pulser systems of the Tile and Liquid Argon Calorimeters [1]. The timing of these test systems has been set to reproduce beam-like timing for the barrel regions ($|\eta| <\sim 1.5$) of both electromagnetic and hadronic calorimeters. However, variations in the timing across calorimeter partitions are difficult to determine a priori, so these and the initial per-partition TT timings need to be cross-checked and re-optimized using collision data. Only signals from real energy deposits provide the ideal input for the timing calibration.

LHC splash events from the November 2009 commissioning runs were used to cross-check and re-calibrate the initial timing of the L1Calo system derived from the calibration pulse systems. A splash event is produced by LHC beam packets interacting with the collimators located in the beam pipes at ± 145 m from the interaction point at the center of the ATLAS detector. These interactions create energetic secondary particle showers that traverse the ATLAS detector. Using the time-of-flight from the collimator to the detector and then from the detector to the collision vertex, estimates for the timing offsets can be cross-checked and corrections can be determined. Splash events were chosen for the initial timing calibrations due to the high occupancy of L1Calo channels. To reach this occupancy level with the expected collision luminosity that followed at the end of 2009 and early 2010 would have required much more time. Splash events from early 2010 were also analysed with improved calibration results, but were not available for presentation in these proceedings. However, the procedure remains the same.

2.1. Signal Fit Equation

The timing calibration begins by extracting the peak position of the analogue signal at the nanosecond level without any delay applied. To do this, a fit function is applied to the digitized signal in each TT. After investigating various fitting functions [4, 5], a Landau and Gaussian hybrid function was found to give the best fitting results for the analogue signal. The function is described by the expression,



(a) Electromagnetic layer

(b) Hadronic layer

Figure 1. Here an η-ϕ plot of the signal peak time with ns precision plotted on the z-axis for a single event is presented. The peak times (t_0) are measured by fitting each trigger tower signal with a Landau/Gaussian hybrid function. The timing on the z-axis is measured relative to the center ADC sample in the case of a zero fine-timing offset. The electromagnetic layer is shown in 1(a) with beam-1 approaching in the $-\eta$ direction. The hadronic layer is shown in 1(b) with beam-2 approaching in the $+\eta$ direction.

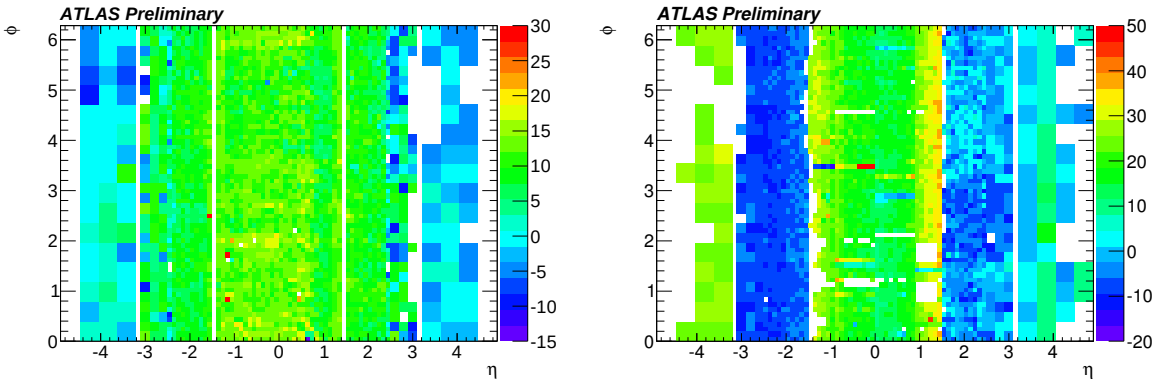
$$f(t \leq t_0) = A \cdot exp\left[-\frac{(t-t_0)^2}{2\sigma^2_{\text{gaussian}}} - \frac{1}{2}\right] + C$$
$$f(t > t_0) = \left(A + D \cdot exp\left(\frac{1}{2}\right)\right) \cdot exp\left[-\frac{1}{2}\left(\frac{t-t_0}{\sigma_{\text{landau}}} + exp\left(-\frac{t-t_0}{\sigma_{\text{landau}}}\right)\right)\right] + C - D, \qquad (1)$$

where A is the amplitude, t_0 is the peak position, C is the signal pedestal and D is the signal undershoot. With such a large parameter space and a small number of sample points, quality criteria are applied to ensure erroneous fits were excluded or corrected if possible.

Figure 1 shows the resulting peak position, t_0, after fitting all L1Calo TTs with Equation 1. Two different splash events are presented with Figure 1(a) showing the results of a splash event with beam-1 (moving in the $-\eta$ direction) in the electromagnetic layer and Figure 1(b) with beam-2 ($+\eta$ direction) in the hadronic layer. Allowing for some partition dependent offsets, the time of flight of the splash across the $\{\eta, \phi\}$ plane can easily be seen. These time-of-flight effects must be removed before calculating the fine-timing offset for collisions.

The empty bins in Figure 1 are caused by lack of suitable signals. The Tile Calorimeter in the hadronic layer ($|\eta| < 1.5$) is especially prone to pulse saturation in the splash events and this event was chosen for illustrative purposes due to the low number of saturated TT signals. Fit failures are seen in the electromagnetic and hadronic Forward Calorimeters (FCal) ($|\eta| > 3.2$) due to small signals failing the > 60 ADC units requirement. Near the outer edge of the Tile Calorimeter, signal saturation excludes extracting the peak location using the fit function.

Other empty TTs in Figure 1 are not yet fully commissioned and therefore excluded from the analysis. For example, the stripes in η in the hadronic barrel region are disabled sections of the Tile Calorimeter where L1Calo was not receiving signals. The stripes in ϕ at $|\eta| = 3.15$ are regions where the signal is suppressed by E_{T} corrections. The stripes at $|\eta| = 1.45$ in the electromagnetic layer are the overlap region between the Liquid Argon barrel ($|\eta| < 1.5$) and end caps ($1.5 < |\eta| < 3.2$) where TT signals will be summed from both layers. At the time, this region was not in a standard configuration and is therefore ignored in this analysis.



(a) Electromagnetic layer

(b) Hadronic layer

Figure 2. The corrected peak time location after correction for time-of-flight in nanoseconds is shown here for both calorimeter layers for a single event. The electromagnetic layer is shown in 2(a) with beam-1 ($-\eta$ trajectory). The hadronic layer is shown in 2(b) with beam-2 ($+\eta$ trajectory).

In the analysis presented here, the signal shapes produced by calibration pulses are assumed to be similar to those of beam collision and splash event signal shapes. However, this has not yet been verified and may be an unforeseen source of systematic errors. Also the pulse shapes vary as a function of detector partition such that Tile calibration pulses are not identical to those in the Liquid Argon hadronic end cap. Nevertheless, the Landau/Gaussian fit is adequate for pulses from both; fit parameters do, however, vary.

2.2. Time of Flight Correction

Beam splash event timing does not correspond to that of beam collision timing. Using the time-of-flight geometry of a splash event, the signal peak times from Figure 1 can be corrected to estimate the times for collisions. The positions used for the electromagnetic and hadronic layers are approximate because TTs are summed from calorimeter cells that vary in distance from the vertex. In order to minimize the effect of this approximation the halfway point between the outer and inner layers of the calorimeters was used. The correction is computed by subtracting the time-of-flight from the interaction point to the detector layer from the time-of-flight from the collimator to the same detector layer. The time-of-flight correction is then subtracted from the peak time extracted from the digitized signal using the fit function in the splash event. It is not necessary to compute this correction on a per TT basis due to the ϕ symmetry therefore it was calculated for each η-slice.

2.3. Collision Timing Offsets

The results of the time-of-flight correction described in Section 2.2 can be seen in Figure 2 for all L1Calo TTs. The electromagnetic layer, shown in Figure 2(a), is very uniform in η, ϕ with the FCal region exhibiting an overall lower offset. A perfectly timed system would have a flat response in η, ϕ. In the electromagnetic layer the timing is within ± 5 ns for the barrel and end cap regions which reflects the good timing of the calibration pulses.

The hadronic layer is less uniform than the electromagnetic layer, which can be understood as an effect of the different detector implementations involved. The border between the barrel ($|\eta| < 1.5$) and end caps ($|\eta| > 1.5$) can be recognized. These two regions were calibrated with independent signal pulser systems whose relative phase is not known. The end caps and FCal regions appear with different overall offsets for similar reasons.

A total of 55 splash events were used in this analysis, with 25 from beam-1 and 30 from beam-2. The final timing corrections applied to the L1Calo input signals were determined by averaging the results from all 55 splash events. Not all TTs include data from all 55 events due to the goodness of fit requirements. Only one splash event contributed to most TTs from the Tile Calorimeter because the signals were otherwise saturated.

The fit for some channels did not produce uniform timings for both beam-1 and beam-2 splashes, which is likely a result of the simplified geometry used in the time-of-flight correction described in Section 2.2. The variation is of the order $\sim \pm 3$ ns which is sufficient for the initial timing calibration and within the $\sim \pm 5$ ns timing goal. The effect appears mainly in the high η regions (FCal and some End Cap) where TTs are composed of larger calorimeter cells.

After considering all 55 events, the fine-timing offset could not be calculated for some TT. This included mainly Tile channels that saturated for all splash events and a few FCal channels that did not pass the minimum signal size requirement. These channels were corrected by hand using nearby channels as a guide. These calibration results will be verified using collision data, but the overall timing accuracy of L1Calo should be $\sim \pm 5$ ns using splash events.

3. Analogue Receiver Gain Energy Calibration

The energy calibration is implemented at the Receiver using an analogue gain applied to the signals arriving at L1 from the calorimeters. The energy measurement in the L1Calo PPM is based on the signal shape and height. This calibration is needed to correct for attenuation affects introduced in the long signal cables from the detector to the L1 hardware and ensures the measurement of E_{T} performed in the PPM correctly reproduces the energy seen in the corresponding calorimeter cells.

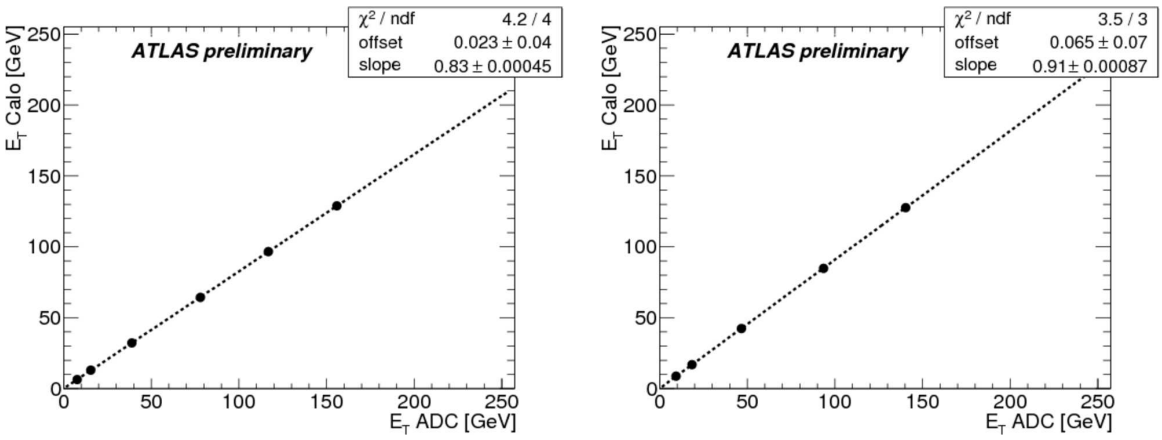
The first step is to produce input signals at various energies within the PPM readout energy range of 0 to 250 GeV with all Receiver gains set to one, which means no gain is applied. The calorimeters' calibration pulser systems are again used to provide these input signals. Using the calorimeter data one can reconstruct the transverse energy seen in a TT as measured by the calorimeter and make a linear comparison with the measured E_{T} in the PPM. The linear slope of this comparison directly corresponds to the analogue gain needed in the Receiver. This process is exhibited in Figure 3 for a single TT in the electromagnetic and hadronic layers. This calibration must be performed for all 7168 TT and the gains applied to each incoming signal in the Receivers.

About $100\,\mu\mathrm{b}^{-1}$ of 7 TeVcollision data were used to verify the results of this calibration and the result is shown in Figure 4 for the barrel region of both calorimeter layers. There is very good agreement between the calorimeter's measured transverse energy and that measured by L1Calo which indicates the calibration is effective. TTs with known problems have been excluded from these data.

4. Conclusion

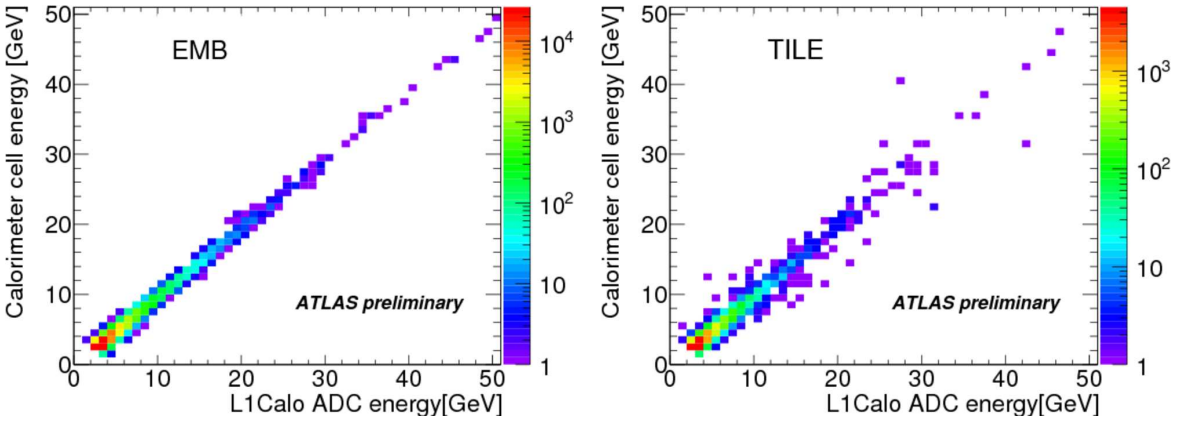
The initial fine-timing offsets in the L1Calo PPM were derived using LHC splash events in preparation for collisions in late 2009. It has been shown that correcting the input signal peak time for the geometric time-of-flight in these splash events is a useful method for producing the first estimates of the timing offsets. Since these initial offset were derived, the fine-timing offsets were updated using new splash events provided by the LHC in early 2010. Additional offsets are being derived at the time of writing using beam collision data, which should represent the last system-wide change of these settings for the foreseeable future. However, some channel-by-channel adjustments may still be required.

The analogue gains applied to the input signals at the Receivers can be optimized using the calorimeters' calibration pulser systems. This calibration adjusts the gain such that the PPM accurately reproduces the energy measured by the calorimeter. The results have been



(a) Electromagnetic TT (b) Hadronic TT

Figure 3. Here one barrel region TT per layer is shown with the reconstructed TT E_{T} measured by the calorimeter on the y-axis and the measured E_{T} from the PPM on the x-axis. The linear fit statistics are displayed on each plot.



(a) Electromagnetic barrel (b) Hadronic barrel

Figure 4. These plots show the energy correlation between the E_{T} measured by the PPM and the reconstructed value from the calorimeters in the barrel region of both calorimeter layers after the gain corrections have been applied. This uses about 100 $\mu\mathrm{b}^{-1}$ of LHC collision data at 7 TeV. TTs with known problems have been excluded from these data.

verified with collision data, which showed the method is effective. As new timing offsets become available, new gain calibrations will need to be produced.

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