Calibration and Performance of the ATLAS Level-1 Calorimeter Trigger with LHC Collision Data

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Abstract

The ATLAS Level-1 Calorimeter Trigger is one of the main elements of the first stage of event selection for the ATLAS experiment at the LHC. The input stage consists of a mixed analogue/digital component taking trigger sums from the ATLAS calorimeters. This stage determines the energies sent to the algorithmic trigger processors. The complete processing chain is performed in a digital, pipelined system, where programmable algorithms are performed in parallel with a fixed latency of 2 μs. The real-time output consists of counts of high-\(E_T\) physics objects (jets, electron/photon and tau candidates) and global energy sums. While the trigger system has been operational from the time of the very first LHC data taking, the final tuning of the timing and calibration had to wait for the higher luminosity proton-proton collision data delivered by LHC in 2010. Many configurable parameters had to be optimized in order to obtain the ultimate system performance in terms of bunch-crossing identification and energy resolution. The behavior of the system was also studied in detail to understand unusual signals, and improve their response. An overview of the current status of the calorimeter trigger hardware will be presented, along with the methods used to achieve these results via increasingly precise calibrations.

Keywords: ATLAS, LHC, Trigger, L1Calo

1. Introduction

The Large Hadron Collider (LHC) is designed to collide protons at a center-of-mass energy of 14 TeV with an instantaneous luminosity of \(10^{33} \text{cm}^{-2}\text{s}^{-1}\). Since the end of March 2010, the LHC has provided stable proton-proton collisions for physics analysis at reduced center-of-mass energy of 7 TeV. After a successful ramp-up of the instantaneous luminosity, as of today, more than 2.5 fb\(^{-1}\) have been delivered to each of the two large general purpose experiments ATLAS [1] and CMS [2]. As it is not possible to record all events, the challenge for any trigger at the LHC is to select new and interesting data out of the huge amount of already known physics. During one second at LHC design luminosity and energy, about \(10^9\) proton-proton interactions take place while interesting physics occurs at rates of approximately 10 Hz (e.g. for top-antitop production) or lower.

In order to fulfill these strong requirements on the online event selection, the trigger of the ATLAS detector is separated into a fast first-level hardware trigger (L1) and a subsequent high-level trigger (HLT) which runs software selection algorithms on farms with several thousand central processing units. The L1 trigger...
Fig. 1. The architecture of the Level-1 Calorimeter Trigger. The real-time data path proceeds from left to right and is indicated with black arrows while the readout data path in blue runs from bottom to top.

uses reduced granularity information from the calorimeters and dedicated fast muon chambers in order to achieve a rate reduction from the LHC bunch crossing rate of 40 MHz down to a maximum of 75 kHz within a fixed latency of 2.5 $\mu s$. The HLT itself is composed of two sub-levels. The Level-2 (L2) trigger operates only on so-called regions-of-interest (RoI) which are identified by L1 and include data at full granularity from selected sub-detectors. At L2 the outgoing L1 rate is reduced to about 3.5 kHz within about 40 ms. Finally, at the Event-Filter (EF) a refined event selection based on the full readout information allows to cut the rate down further to 200 Hz within about 4 s.

2. The ATLAS Level-1 Calorimeter Trigger

The Level-1 Calorimeter (L1Calo) trigger is one of the three main components of the first level trigger of the ATLAS detector which also includes the Central Trigger Processor (CTP) and the Level-1 Muon (L1Muon) trigger.

2.1. System Design and Architecture

L1Calo [3] is a fixed-latency, pipe-lined, hardware-based system using custom electronics. It consists of nearly 300 VME modules of about 10 different types, housed in 17 crates. The L1Calo electronics contributes a latency of less than a microsecond, resulting to a total latency of about 2.1 $\mu s$, well inside the required tolerance of 2.5 $\mu s$ for the ATLAS first level trigger. The L1Calo system is located entirely off the detector, in the large underground electronics cavern of the ATLAS experiment. A block diagram of its basic architecture is shown in figure 1.

The L1Calo trigger is a mixed signal system, receiving data from ATLAS’ two main electromagnetic and hadronic calorimeters, the Liquid-Argon (LAr) and Tile calorimeter. It consists of three main sub-systems: the PreProcessor, the Cluster Processor and the Jet/Energy-sum Processor. The 7168 analogue input signals are first conditioned, digitized and associated to a particular LHC bunch crossing in the L1Calo PreProcessor system. Digital transverse energies for every so-called trigger tower are then transmitted in parallel to the two separate processor systems which run the trigger algorithms [4] likewise in parallel. The Cluster Processor (CP) uses the full trigger tower granularity in the central region to search for small localized clusters typical of electron, photon and tau candidates. The Jet/Energy-sum Processor (JEP) operates on so-called jet elements with a granularity of $2 \times 2$ sums of electromagnetic and hadronic trigger towers to identify jet candidates and to form global transverse energy sums: missing, total and jet-sum transverse energy. For both the CP and the JEP systems, the results from entire crates are merged using common merger modules (CMM) providing system-wide counts of objects and sums which are compared to programmable thresholds. In total 104 result bits are sent to the CTP where the L1 trigger
2.2. Input Signals

The ATLAS electromagnetic calorimeter is based on liquid argon as active material for both the barrel and end-cap regions and uses accordion-shaped Kapton electrodes and lead absorber plates. In the barrel region it is surrounded by a scintillating-tile (Tile) hadronic calorimeter with steel absorbers while LAr-copper sampling technology is used for the hadronic endcap calorimeters. The two forward calorimeters, completing the ATLAS calorimetry on either side of the detector close to the beam pipe, are also based on LAr technology and use copper and tungsten absorber matrices in their electromagnetic and hadronic modules, respectively. Both the LAr and Tile calorimeter have pulser systems for charge injection into the electronic chain with high signal accuracy and timing stability which are used for calibrating the calorimeters’ hardware as well as the L1Calo trigger.

The L1Calo trigger decision is based on dedicated analogue trigger signals provided by the LAr and Tile calorimeters, independently from the signals read out and used at the HLT and offline. The analogue signals of the approximately 250,000 calorimeter cells are summed on the detector to 7168 trigger towers which span a region of $0.1 \times 0.1 \times \Delta \eta \times \Delta \phi$ for most of the system. At large values of $\eta$, the size of the trigger towers increases with $\eta$ and becomes less regular. The number of calorimeter cells summed to form trigger towers depends on the granularity of the respective calorimeter and ranges from three for some regions in the Tile calorimeter up to sixty for the barrel part of the LAr calorimeter.

2.3. The Analogue Signal Path

The analogue trigger tower signals from the calorimeters are routed through 30–70 m long cables to an analogue receiver system [5] situated next to the L1Calo trigger in the ATLAS electronics cavern. The receivers include linear variable gain amplifiers which are used to convert the raw signals of the hadronic towers to transverse energy and to set the proper $E_T$ calibration for all towers (cf. section 5). A system of patch panels before and after the receiver system provides correct signal distribution to the corresponding L1Calo PreProcessor modules.

The main tasks of the L1Calo PreProcessor system are the digitization of the analogue input signals, the identification of the bunch crossing in which the primary interaction took place and the preparation of precisely calibrated trigger tower energies for use in the algorithmic processors. These operations are symbolically illustrated in figure 2.

In the first step the analogue signals are received and digitized to a precision of 10 bit at the LHC bunch crossing frequency of 40.08 MHz, which corresponds to one sample about every 25 ns. The digitization phase is steered with nanosecond precision by a PHOS4 chip [6] such that the FADC strobe falls close to the peak position of each trigger tower signal (cf. section 3). The FADC output data are passed through a FIFO which provides coarse timing adjustment in 25 ns steps. The assignment of the energy deposits to the correct LHC bunch crossing is referred to as bunch crossing identification (BCID). L1Calo uses a digital filtering technique to associate the relatively wide analogue pulses with specific LHC bunch crossings. The Finite-Impulse-Response (FIR) filters sharpens the pulse and improves the signal to noise ratio in particular for small pulses (cf. section 4). The output of the BCID logic is a single 10-bit decision is formed. For all events that are selected by L1, a programmable selection of data from L1Calo is read out via Readout Driver modules to the ATLAS data acquisition system. On request, data are also sent to the Level-2 Trigger RoI Builder (RoIB) for further use by the HLT trigger algorithms.
value correctly synchronized to the main clock, which is then reduced to 8 bits by a look-up table (LUT). In this step pedestal subtraction and noise suppression take place as well as the final \( E_T \) calibration.

3. Timing Calibration and Performance

The analogue trigger tower signals need to be precisely aligned in time at the L1Calo input because sampling at the peak position is essential to ensure correct bunch crossing identification and the precise determination of the deposited energies. The timing calibration was first established with the calorimeter pulser systems and cosmic ray data and then refined using the first LHC beam delivered to the detector as splash events in November 2009 [7]. Improved timing delays were applied early after the first 7 TeV collisions were delivered by the LHC at the beginning of 2010, based on the analysis of the recorded collisions data. Since then the timing was incrementally improved, so that for the majority of recorded data the timing of most towers was better than \( \pm 2 \) ns, resulting in close to ideal trigger performance.

3.1. Fitting Method and Results

Figure 3 shows an example of a digitized LAr calibration pulse as read out by the L1Calo PreProcessor system using the extended readout mode with 15 digitized FADC pulses. Depending on the calorimeter partition, a hybrid function composed of either a Gauss or a Landau function applied on the rising edge combined with a Landau function on the falling edge was found to give the best fits. These Gauss/Landau or Landau/Landau fit functions are used to reconstruct the original pulses in order to extract the fine-timing information beyond the 25 ns sampling resolution. In order to avoid the large parameter space in these fitting functions, the values of some fit parameters are constrained. In particular the widths of the Gauss and Landau sub-functions are derived from special calibration runs and are fixed for the analysis of the proton-proton collision data. As it is known that the pulses provided by the calorimeter pulser systems are slightly broader than those created by particles from collisions, the impact on the fit method and on the timing results need to be understood in further analyses.

The status of the L1Calo trigger timing as achieved at the start of the 2011 data taking period is depicted in figure 4. Shown are the distributions of the offsets from the ideal timing, defined as the mean difference between the fitted maximum position \( t_0 \) and the middle of the central bin, in units of nanoseconds (cf. figure 3). The \( \eta - \phi \) maps compare the distributions at the beginning of the 2011 running period with those after having applied resulting correction factors to the hardware timing delays. While the timing for the majority of the trigger towers is within \( \pm 2 \) ns already in the initial measurement, isolated larger offsets resulting mainly from the repair of calorimeter electronics during the 2010/11 winter shutdown were compensated for by the applied corrections.

3.2. Timing Monitoring

Using the fitting method described in section 3.1, the absolute L1Calo trigger tower timing can be determined to well within \( \pm 2 \) ns. The precision currently is mainly limited by the degree of understanding of the differences in shape between calibration pulses and physics signals. For fast online monitoring however this technique is too complex and a simplified method is used in order to track potential relative timing drifts. A simple formula as depicted in figure 5 was found to give meaningful results. The success of this method is demonstrated in figure 6 which shows the time evolution of this quantity, averaged over all trigger towers for different regions of the EM calorimeter. Due to transmission of the LHC clock signal through a several
Fig. 4. L1Calo trigger tower timing offsets in ns as function of $\eta$ and $\phi$ for the electromagnetic (EM) calorimeter layer. The plot on the left side shows the results using collision data from the initial 2011 running period while the corresponding plot on the right side shows the results after applying corrections to the timing delays. White bins have no measurement due to lack of statistics.

Fig. 5. A simplified method to determine the trigger tower fine timing. The quantity $f = (c - a)/(2(2b - c - a))$, where $a$, $b$, and $c$ label samples as shown in the figure, was found to be a sensitive indicator of relative timing changes.

Fig. 6. Mean L1Calo timing as function of date for the electromagnetic (EM) calorimeter partitions. The vertical lines indicate adjustments of the global CTP clock phase.

kilometer long optical fiber, its distribution to the ATLAS detector is sensitive to environmental effects such that regular manual readjustments of the clock phase in the CTP are needed. The L1Calo timing monitoring is accurate enough to measure these changes of the LHC clock phase, as demonstrated in figure 6. It should be noted that for the start of the 2011 data taking period the CTP hardware had been improved in order to semi-automatically stabilize the ATLAS clock phase to better than 0.5 ns.

4. Digital Filter Calibration and Performance

Identifying the correct LHC bunch crossing down to lowest energies is of utmost importance for the efficient operation of the L1Calo trigger. Since the analogue trigger tower signals span several bunch crossings in time, a robust method of assigning the pulse to a particular bunch crossing has to be used. It must operate correctly for signals down to lowest possible energies and up to very large saturated pulses. For saturated pulses, a method based on the shape of the leading edge is used and has been shown to ensure correct BCID up to trigger tower energy deposits of about 3.5 TeV; the main method for unsaturated signals below approximately 250 GeV utilizes a FIR filter which sharpens the pulse before putting it through a peak finder. As illustrated in figure 2, on each bunch crossing five successive samples are multiplied by programmable coefficients. The sum of these five products is compared to the corresponding sums from the two neighbor-
Fig. 7. The pedestal subtracted and normalized FADC pulse shape for an example trigger tower as derived from the analysis of 2010 collision data.

The initial FIR filter coefficients used for the beginning of the data taking period in 2010 were derived from the analysis of calibration pulser runs [8]. After sufficient collision data were recorded, an improved set of coefficients was determined in the analysis of normalized pulse shapes as measured from proton-proton collisions. Figure 7 shows the pedestal subtracted and normalized FADC pulse shape for an example trigger tower. The sum of the two peak surrounding samples ($S_1 + S_3$), where $S_i$ is the normalized peak height of the $i$-th FADC sample as illustrated in figure 7. The plots show the results from the analysis of 2010 collision data.

Fig. 8. Efficiency for an EM trigger tower energy to be associated with the correct bunch crossing as a function of the sum of the raw cell $E_T$ within that tower.

Fig. 9. The sum $S_1 + S_2$ as a function of $\eta$ and $\phi$ for the electromagnetic (EM) and hadronic (Had.) calorimeter layer. The value $S_i$ is the normalized pulse height of the $i$-th FADC sample as illustrated in figure 7. The plots show the results from the analysis of 2010 collision data.

ing bunch crossings in order to test for the existence of a peak. Low-order bits are then discarded to produce a 10-bit output value used as input to the LUT.

A good indication of the success of the bunch crossing identification as well as the timing calibration is the efficiency of associating small energy deposits to the correct bunch crossing. Figure 8 shows the efficiency for an EM trigger tower energy to be associated with the correct bunch crossing, as a function of the raw cell $E_T$ within that tower for different partitions of the EM calorimeter. In order to remove the majority of fake triggers due to small energy deposits, a noise cut is applied to the trigger tower energy in the LUT. The effect of this cut at around 1.2 GeV is reflected in the turn-on curve which is in line with the optimal performance as expected from simulations.
5. Energy Calibration and Performance

A critical aspect of the operation of the L1Calo trigger is the energy calibration of the input signal which translates FADC counts in the PreProcessor system to tower transverse energies delivered to the CP and JEP systems for further processing. Currently all calibration coefficients are implemented in the analogue receiver gains (cf. section 2.3) while it is planned to use the LUT for future corrections of dead material, crack losses and non-linearities. The present calibration is derived from the analysis of dedicated calibration pulser runs which are regularly taken between LHC luminosity fills. In these runs signals of controlled amplitude are stepwise injected using the calorimeter charge-injection systems which produce pulses at a variety of energies. Based on these energy ramps, the analogue gain factors are derived for every trigger tower by comparing the energy measured in L1Calo to the more precise calorimeter measurement. The proper status of the energy calibration is regularly verified in the analysis of collision data. Figure 10 shows the energy correlation plots between trigger and offline calorimeter transverse energy and reflects the good agreement between the L1Calo and calorimeter measured energies.

By the end of the 2010 running period, sufficient data had been collected in order to perform detailed studies of the energy calibration on tower-by-tower basis and as a function of relevant observables. Figure 11
Fig. 12. Unprescaled L1 rates from the initial 2011 data taking period as a function of the instantaneous luminosity for an electromagnetic trigger with a threshold of 14 GeV, a tau trigger with a threshold of 15 GeV and a jet trigger with a threshold of 30 GeV. The instantaneous luminosity used is the online measurement.

Fig. 13. Efficiencies for e20_medium at each trigger level (L1, L2 and EF) measured with Z → ee events using the tag-and-probe method. Efficiencies are measured as a function of the offline electron $E_T$ for candidates satisfying tight identification requirements. Opposite sign electron pairs with $80 < M_{ee} < 100$ GeV are used for the $Z \rightarrow ee$ selection.

shows the derived fractional difference between L1Calo and offline transverse energy as a function of the offline transverse energy. The L1Calo energy is calculated using two different methods: the energy based on the FADC peak sample and the energy based on the result of the LUT. Disregarding a minor overall offset, the 2010 calibration reveals small LUT deviation at low energies. This effect was found to be due to a rounding bias in the the LUT derivation which was successfully corrected for the 2011 data taking period.

6. Conclusions

The Level-1 Calorimeter Trigger is one of the three main components of the first level trigger of the ATLAS detector. It provides triggers for localized objects, such as electrons, photons, taus and jets, as well as global transverse energy triggers. After commissioning with cosmic ray and first collision data, L1Calo ran stably and essentially error free. During the 2010 data taking period, incremental improvements of the timing, the BCID performance and the energy calibration established the L1Calo system with close to ideal performance such that in 2011 only minor adjustments were necessary from time to time. With even larger data samples recorded in near future, further optimization of the calibration will be possible such as a tower-by-tower energy calibration based on identified physics objects with precisely known energies, for example electrons from $Z$ boson decays. The trigger rates themselves are stable and mostly scale well with luminosity over a wide range of luminosity and time as depicted in figure 12. As expected, pile-up effects mainly affect the missing and total transverse energy triggers as well as the jet trigger items based on forward calorimetry. Finally the good performance of the L1Calo system manifests itself in steeply turning-on trigger efficiency curves saturating at high values as depicted in figure 13 for an inclusive electron trigger.

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