ATLAS High Level Calorimeter Trigger Software Performance for Cosmic Ray Events

Denis Oliveira Damazio on behalf of the ATLAS Collaboration
Brookhaven National Laboratory, Physics Department, Bldg 510A - Upton, N.Y., USA
E-mail: Denis.Oliveira.Damazio@cern.ch

Abstract. The ATLAS detector is undergoing intense commissioning effort with cosmic rays preparing for the first LHC collisions late 2009. Combined runs with all of the ATLAS subsystems are being taken in order to evaluate the detector performance. This is an unique opportunity also for the trigger system to be studied with different detector operation modes, such as different event rates and detector configuration. The ATLAS trigger starts with a hardware based system which tries to identify detector regions where interesting physics objects may be found (e.g. large transverse energy depositions in the calorimeter system). An accepted event will be further processed by more complex software algorithms at the second level where detailed features are extracted (full detector granularity data for small portions of the detector is available). Events accepted at this level will be further processed at the so-called event filter level. Full detector data at full granularity is available for offline-like processing with complete calibration to achieve the final decision. This year we could extend our experience by including more algorithms at the second level and event filter calorimeter trigger. Clustering algorithms for electrons, photons, taus, jets and missing transverse energy are being commissioned during this combined run period. We report the latest results for such algorithms. Issues such as hot calorimeter regions identification, processing time for the algorithms, data access (specially at the second level) are being evaluated. Intense usage of online and quasi-online (during offline reconstruction of runs) monitoring helps to trace and fix problems.

1. The ATLAS Detector at the Large Hadron Collider

The ATLAS experiment[1] is one of the 6 detectors on the Large Hadron Collider (LHC[2]) beam line. The LHC will collide bunches of protons with 14 TeV energy in the center of mass at a luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$ when operating in nominal conditions. The design bunch crossing rate is 40 MHz. Up to $10^9$ events per second are expected, the most interesting higher transverse momentum ones are rare and immersed in a huge background events produced through QCD processes. Due to the amount of data (around 2MB) produced by the detector per event, only up to 200 events can be saved per second. An efficient trigger system must perform the online selection of the precious physics events, recording them for the more detailed offline studies.

Presently, all of the ATLAS subdetectors (tracking detectors, calorimeters and muon spectrometers) are taking commissioning and integration runs with cosmic rays, awaiting for the first LHC collisions later in 2009. See Figure 1 for a schematic view of the detector depicting its various subsystems. The cosmic ray runs provide important opportunities to exercise the full data acquisition chain and the trigger systems, processing data in a more realistic scenario than with simulated data. The trigger system could be used, for instance, to select muon tracks which can help in the alignment process of the muon spectrometer and the inner detector[3].
The present work describes the exercise of the calorimeter software trigger during such integration runs with cosmic rays. Details such as the global performance and the treatment of noisy detector readout elements will be discussed. The next section describes the ATLAS calorimeters. The third section summarizes the relevant details about the ATLAS trigger and data acquisition systems with special emphasis on the software for calorimeter trigger data preparation. The fourth section describes the results obtained with cosmic ray runs detailing the treatment of noisy detector elements. The fifth section brings other results like the output of the calorimeter $e/\gamma$ algorithms and the time performance of some of the L2 algorithms. The last section brings the final conclusions.

2. The ATLAS Calorimeters
ATLAS has 4 different calorimeter technologies. The electromagnetic (EM) calorimeter covers the area up to pseudo rapidity $\eta = 3.2$. It is made of lead absorbers immersed in liquid argon. The particle showers caused by electrons or photons in the absorbers ionize the liquid argon. High voltage thin copper plates collect the electrons produced providing an analogue pulse proportional to the energy of the incoming particle. The Hadronic (HAD) section covers from $\eta = 1.2$ up to $\eta = 3.2$ uses copper absorbers and also has liquid argon as the sampling medium[4]. For lower pseudorapidity ($|\eta| < 1.6$) a hadronic calorimeter based on iron absorbers and scintillating plastic plates is used. Incoming hadronic particles, such as protons, neutrons and pions interact strongly with the iron absorbers and the showers produced illuminates the plastic scintillators proportionally to the original particle initial energy. The light signal is guided by optical fibers to photomultipliers which provide analogue pulses proportional to the energy deposition[5]. The calorimeter system is complemented by two forward calorimeters covering up to $\eta = 4.9$. The full ATLAS calorimeter comprises about 200 thousand readout elements.

The analogue pulses are sampled by the front-end electronics and only sent for further processing in case the hardware part of the ATLAS trigger accepts the event (see the next section). When an accept signal is issued for a given event, the related samples are sent to a set of more than 700 Digital Signal Processors (DSPs) which form the Read-Out Driver (ROD) system. Signal processing techniques[6, 7] are used to calculate cell energy information to each readout channel.

The ATLAS calorimeters have been studied in standalone calibration runs and combined cosmic runs with a special set up for the L1 trigger during the last two years[8, 9]. During this
period, for instance, noisy calorimeter readout elements have been identified. Such problematic readout elements are declared in the detector condition database to be masked in the offline physics analysis and, more recently, at the hardware and software trigger levels. Since this masking procedure affects on the trigger efficiency, this information is registered for later analysis.

3. The ATLAS Trigger and Data Acquisition System

The ATLAS calorimeter and muon systems are able to provide an analogue coarse granularity version of the detector readout. For example, the electronic shaped ionization pulses from up to 60 cells in the EM calorimeter are analogue summed, forming a single signal representing a $0.1 \times 0.1$ projective region in the $\eta \times \phi$ space, a so called trigger tower. There are EM and HAD trigger towers to help in particle identification. These signals are fast enough to be used by the Level 1 hardware based trigger system to perform particle identification and start the data acquisition process[11]. For the events accepted by the L1, the coordinates of the L1 fired regions are used to seed the Level 2 software algorithms. This is the so-called Region of Interest (RoI) mechanism. See Figure 2 for the details of the ATLAS data acquisition and trigger system[10].

The RoI comprises a small fraction (2% on average) of the detector accessed at full granularity. The requests are performed by the L2 computer farm (around 500 nodes) following each algorithm needs and the ROD data stored in the Read-out Buffers (ROB) is sent on request to one of the L2 machines to be processed by the algorithms. When an event is accepted by the L2, the contents of all ROBs related to this event are sent to the Event Builder, which will gather the full event data in an unique memory block and will send it to the Even Filter (EF) computer farm (around 1000 nodes). At this stage, much more complex algorithms can be run using calibrations almost as detailed as offline. The L2 average processing time is constrained to be 40 ms to sustain the design load in the data acquisition system, while at the EF, a 4s average time interval is allowed for the full event processing.

![Figure 2. Schematic picture of the ATLAS Trigger and Data Acquisition System.](image)

The L2 and the EF are built with software running in off-the-shelf Linux PCs. These trigger levels are commonly referred to as the ATLAS High-Level Trigger (HLT). A fraction (around 35%) of the total farm is already operational for the commissioning exercises[12].
3.1. High Level Trigger Calorimeter Data Preparation

A common data preparation software layer is used by L2 and EF algorithms to perform unpacking of the readout channels information. The L1 position is used by the different trigger reconstruction algorithms to define (in detector coordinates) the RoI to be unpacked. For instance, a L2 photon algorithm unpacks a $\Delta \eta \times \Delta \phi = 0.4 \times 0.4$, while a L2 jet algorithm requires a bigger region (1.0 x 1.0).

In the L2 case, data is fetched from the network[13, 14]. An internal look-up table is used to find the ROB addresses containing the data fragments related to the RoI, see Figure 3 for the details. For the EF case, this table finds the memory addresses for the different ROB fragments as assembled by the event building process. The unpacking phase converts the raw detector data into physically meaningful objects, like calorimeter cell energies and associates their geometry. This part of the code is sub-detectors specific and re-uses part of the offline data preparation software. In addition decoded ROB data are cached, minimizing the processing time for overlapping RoIs.

Figure 3. Particle identification algorithms which use the HLT calorimeter data preparation layer and a block diagram of this layer describing the different interconnecting blocks that perform the data preparation step.

Since the region of the detector connected to a ROB is defined by hardware considerations, this in general extends beyond what is really needed for a given RoI. To optimize the algorithms access to cells, another lookup table is used to map trigger tower coordinates into the group of cells within these towers. Only the cells in trigger towers within the requested RoI are accessed by the algorithms. In addition, masking of noisy cells is performed by removing specific cells from this map. The known noisy cells are declared in the detector condition database accessed only during the map building stage.

Data is provided to electron, photon, jet, tau identification, missing transverse energy reconstruction and muon isolation algorithms. Different clustering strategies are used depending on the physics goals to be achieved. As an example, the electron and photon (which share common calorimeter reconstruction and are jointly referred to as $e/\gamma$) L2 reconstruction algorithm starts by searching within the RoI for the hottest cell in the EM calorimeter layer where most of the energy of an $e/\gamma$ object is deposited. The cluster position is refined by taking an energy averaged position of the 3 by 7 grid (in $\eta$ by $\phi$) of cells in this same EM layer, centered around the hottest one. The algorithm continues by calculating the total energy including the other layers and calculating the energy in the hadronic calorimeter (referred as hadronic leakage) in the back of the cluster.

4. HLT Calorimeter Performance for Cosmic Rays

After the initial calorimeter assembly, less than 1 per mill cells showed a noise level out of specification. Even in such small numbers, these cells can represent a serious problem for
the calorimeter trigger or offline algorithms as they can dominate completely the cluster search. Furthermore, noisy cells can bias the cluster properties, for instance, its position which is usually based on cell energy as described above in the $e/\gamma$ case. The issue of noisy cells is being addressed in this year shutdown period.

The analogue L1 was designed to be efficient above a few GeV, while the typical signal for the cosmic rays is of the order of 300 MeV for the EM part. Naturally, using this hardware system to search for lower energy objects implies a much noisier mode for the L1 electronics. The additional noise due to this mode of operation can lead to a higher trigger rate than is sustainable by the data acquisition. An efficient online monitoring of rates and trigger uniformity is an important requirement to help finding the sources of problems quickly (within a few minutes) and avoid loosing beam time. Also important is the possibility to cross check a given issue by monitoring different trigger levels and correlating this information with the involved subdetectors monitoring data.

Examples of plots from the online monitoring system are shown in Figure 4. The top plot shows the results of the L2 cluster reconstruction algorithm and shows how often a cluster is reconstructed at a given position in $\eta$, $\phi$. The bottom plot shows the distribution projected onto the $\eta$ axis. The plots show information for clusters passing the 3 GeV and 7 GeV thresholds at L1. As can be seen there are two regions with significantly high noise, one around $\eta$ of 0.5 and another, about 12 times higher, at $\eta = 2.1$ (note that the normalisation has been chosen giving a value of 1 for the noise at 0.5).

![Online monitoring system plot showing noise trigger tower in the L1 system.](image1)

**Figure 4.** Online monitoring system plot showing noise trigger tower in the L1 system. Upper plot is an $\eta \times \phi$ hit map and the bottom one is an $\eta$ projection.

![L1 Trigger Tower could be masked and prescale factor removed. A few noise trigger towers and noisy cells still present but affecting much less the rates.](image2)

**Figure 5.** L1 Trigger Tower could be masked and prescale factor removed. A few noise trigger towers and noisy cells still present but affecting much less the rates.

Detailed analysis showed that the peak around $\eta = 0.5$ is related to two noisy cells firing the L1 7 GeV transverse energy ($E_T$) threshold. The peak at $\eta = 2.1$ was produced mainly by the L1 3 GeV $E_T$ threshold. During this run period a global prescale factor was applied, in such a way that only 1 out of 2000 triggers were being accepted for the L1 3 GeV threshold for the full detector. Even with such a huge prescale factor, the trigger rate was 2 Hz, mostly from that threshold. No prescale factor was used to the L1 7 GeV threshold (every trigger was accepted). Another important feature is that the size of the coloured region of the 2d plot at $(\eta, \phi) = (2.1, 0.6)$ is $0.4 \times 0.4$ in $(\Delta \eta \times \Delta \phi)$ corresponding to the granularity of the L1 algorithm. This indicates that the source of the noise is only one Trigger Tower being input to the L1. As a consequence, the L2 algorithm requests data for this entire region at a high rate. This can
cause an overload of the ROBs serving these requests for data, eventually blocking the data acquisition system.

As soon as a noise problem was identified from the online monitoring, the run was stopped and the L1 calorimeter group acted to mask the problematic trigger tower. A new run was started and since the EM L1 rate had decreased substantially (to 2Hz), it was possible to set the pre-scale factor for these triggers to 1. This demonstrated that the masked trigger tower was the most significant source of problems. As can be seen in Figure 5 (also normalized by the sources of noise at $\eta = 0.5$), other noisy trigger towers appear in $\eta \times \phi$ map. However, since the noise from these trigger towers is at a much lower level, their effect on the whole data acquisition chain was much less important than in the previous run.

Figure 6. Online monitoring system plot from the EM calorimeter, showing two noisy cells being spotted by the sub-detector system in the same places as seen by the High-Level Trigger monitoring.

The other little spots at $\eta = 0.5$ and $\phi = 0.9$ and $\phi = 2.6$ are much smaller, showing us that there is a noise problem at the cell level. In these cases, we could correlate these noisy spots with the ones in the EM calorimeter system. The detector online monitoring produces $\eta \times \phi$ hit maps displaying the average energy per cell. As can be seen in Figure 6, these plots show clearly the same noisy spots, making it obvious that the source of problems was the detector itself. The procedure to mask detector cells is being implemented now.

5. Online Algorithms Processing Performance
As mentioned above, the (L1) trigger uses multiple thresholds. The higher the threshold, the more protected the L2 is from L1 noisy elements as discussed in the previous section. This effect can be seen in the distribution of EM cluster transverse energy calculated by the $e/\gamma$ algorithm at L2 (see Figure 7 - the masking of the L1 noisy trigger tower was active). Distributions are shown for two L1 thresholds, 3 GeV and 7 GeV (the histogram peaking at around 7 GeV).

The peak at low $E_T$ for the 3 GeV threshold is a predominantly due to fake clusters, which are significantly reduced when using the 7 GeV threshold. The high rate of fake clusters with lower threshold is a consequence of the special configuration for cosmic running with very low thresholds at the cell-level. The thresholds applied in normal collision running would remove most of these fake clusters.

Figure 8 shows the energy in the first layer of the hadronic calorimeter. Normally the $e$/gamma selection applies a cut to reject clusters with significant hadronic energy (hadronic isolation cut). This cut was not applied in the cosmic running and so some clusters are
Figure 7. L2 measured EM energy for two different L1 sources (3 and 7 GeV of transverse energy). This plot also indicates that the algorithms is correctly receiving data from the EM calorimeter.

Figure 8. L2 measured Hadronic energy. This shows that the L2 algorithm can receive data from the hadronic calorimeter.

reconstructed with more than 1 GeV of hadronic energy. Although the hadronic energy was not used in this selection, cosmic running provided an important opportunity to test the complete chain including the data preparation layer software for the hadronic parts of the calorimeter.

Another important figure for the trigger is the processing time, especially for the L2 algorithms which are constrained to spend less than 40 ms on average for all the algorithms. The HLT uses a step-wise selection with the faster selection steps performed first, giving the earliest possible rejection. For example, the electron selection first uses only the calorimeter information before reconstructing inner detector tracks and combining the cluster and the track to reach a final decision. The L2 calorimeter trigger therefore runs at the full L1 calorimeter output rate and so it is important for this algorithms to be fast. Figures 9 and 10 show the processing time performance of the L2 jet (averaging in 8.5 ms) and the L2 $e/\gamma$ (3ms) algorithms.

Jets reconstruction algorithms need broader RoI (more time consuming for data unpacking) and loop over more cells to build a Jet cone. The $e/\gamma$ algorithm with a smaller RoI, needs less processing time. The first event in each machine of the L2 processing farm may be slower due to the loading of detector conditions. This can be seen in both figures as higher processing time peaks. We are presently addressing this issue, even though, thanks to the different buffers built into the data acquisition system, these cases can still be correctly handled. Furthermore, when the real physics operation starts, some level of RoIs overlap may be expected and the overall system efficiency may increase due to caching used at different levels (ROB data fetching, data preparation step for each ROB and cluster building results).

6. Conclusions and next steps
The initial cosmic data taking period with the ATLAS detector was an excellent opportunity to exercise the High Level Trigger calorimeter algorithms which identify electrons, photons, taus, jets and the missing energy. Due to the lower energy level usually provided by the cosmic muons, the algorithms were not really used for selecting events, but their performance could be evaluated. The most important aspect is to confirm that the calorimeter data preparation layer, common to the L2 and EF, allows to access data from the different ATLAS calorimeter technologies with the expected performance. For instance, the L2 $e/\gamma$ energy measurement can be compared to the L1 for more energetic shower deposition. For too low L1 thresholds, the
noise level degrades the performance, as expected. The time performance of the algorithms is well within the L2/EF time budget.

The online monitoring system identifies problems in the data taking and their sources (like noisy regions in detectors). Such issues spoiled the data acquisition process, but immediate actions could be taken to avoid lost data acquisition time. This may be a very important procedure to be adopted when the detector receives the first LHC collision events. We are presently improving even further the monitoring to provide enough information to mask not only noise L1 trigger towers but also noisy cells in the HLT Calorimeter data preparation layer.

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