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ATLAS Level-1 Calorimeter Trigger: Status and Development

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The ATLAS Level-1 Calorimeter Trigger seeds all the calorimeter based triggers in the ATLAS experiment at LHC. The inputs to the system are analogue signals of reduced granularity, formed by summing cells from both the ATLAS Liquid Argon and Tile calorimeters. Several stages of analogue then digital processing, largely performed in FPGAs, refine these signals via configurable and flexible algorithms into identified physics objects, for example electron, tau or jet candidates. The complete processing chain is performed in a pipelined system at the LHC bunch-crossing frequency, and with a fixed latency of about 1μs.
The first LHC run from 2009-2013 provided a varied and challenging environment for first level triggers. While the energy and luminosity were below the LHC design, the pile-up conditions were similar to the nominal conditions. The physics ambitions of the experiment also tested the performance of the Level-1 system while keeping within the rate limits set by detector readout. This presentation will show how the Level-1 Calorimeter rose to this challenge, including the rate and efficiency for important physics channels. It will illustrate how the flexibility of FPGAs was utilised to enhance the performance and that there are still more ideas to improve the trigger performance during the current shutdown using the spare capacity and flexibility built into the processing modules along with small hardware additions. Finally, the longer term upgrade plans will also be reviewed.

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[*] Speaker.

[†] I would like to thank my L1Calo colleagues

1. Introduction

Triggering at LHC is difficult. While the total interaction cross section is of the order of 100 mb, the cross section for discovery physics is many orders of magnitude smaller. To cope with this challenge, ATLAS has built a three level trigger system, with two levels (Level-2 and Level-3) implemented in software, and the Level-1 system implemented in custom built hardware. The Level-1 Trigger consists of several components, among them the Level-1 Muon trigger, Level-1 Calorimeter trigger (L1Calo) and Central Trigger Processor.

L1Calo [1] selects events by looking for high transverse momentum final state objects, for example e/γ, τ or jets that lead to localised energy deposits, or for global event properties such as E_T and missing E_T. It is implemented as a pipelined, synchronous system, with fixed latency of about 1 μs[1]. It has several processing stages, and profits from large-scale parallel processing. Most of the electronics is custom made, mainly FPGA based, consisting of around 300 VME modules of 10 types housed in 17 crates. The system was installed at the end of 2007, taking cosmic data for commissioning and detailed checks of L1Calo performance in 2008 and part of 2009, followed by early beam data, taken at the end of 2009. Since early 2010 we have seen a series of rapid steps in delivered luminosity and several step-wise updates of L1Calo calibrations, with stable running during 2012 – 13 data taking period.

2. Calibration of the system

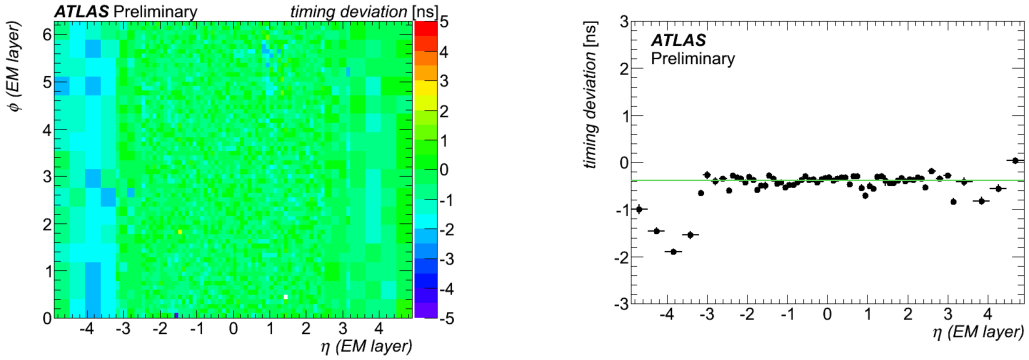

Figure 1: Deviation from ideal timing as measured offline in collision events for EM Trigger Towers as a function of *eta* and *phi*(*left*) and as a function of η (*right*).

Conditioning and calibration of signals in L1Calo is done in several steps. Analogue signals are summed to Trigger Towers (TT) on the detector and then sent on twisted-pair cables to analogue receivers. Here analogue gains are applied, giving the first step in energy calibration. The signals are then digitised and aligned in time, and passed to a digital Finite Impulse Response (FIR) filter. The FIR filter assigns the signal to the correct bunch-crossing, its output is fed into a Look-Up table (LUT), used to perform pedestal subtraction, noise suppression and the final step in energy

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[1] This number refers to L1Calo latency, with maximum overall L1 latency equal to 2.5 μs.

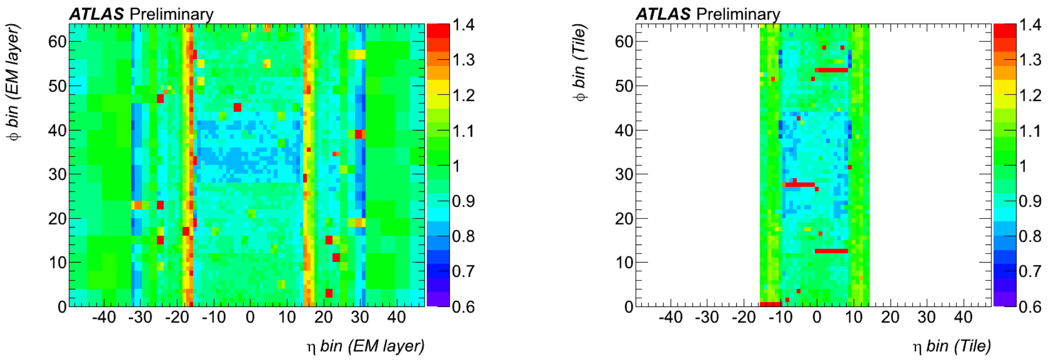

Figure 2: An example of L1Calo receiver gains as used towards the end of 2012 data-taking period for EM LAr calorimeter (*left*) and for HAD Tile calorimeter (*right*).

calibration. For events accepted by the trigger, the information passing through L1Calo is recorded and stored for further analysis. Most of the steps in the calibration procedure are highly interdependent and adjustment of the calibration parameters is an iterative procedure. In the following, input timing and energy calibrations are discussed in more detail.

Analogue Trigger Tower signals are routed from the calorimeter front-end to L1Calo electronics on cables with lengths varying between 30 and 70 meters with the difference in signal propagation times being of the order of 10 bunch crossings (BCs) [2]. To ensure correct operation of L1Calo, it is necessary to align the signals at its input, as large mistiming lead to events being lost and smaller mistiming may lead to energy underestimation. There are several parameters available to adjust input timing. Input delays (implemented in input FIFOs) allow the alignment of signals with a step of 1 BC. Functionality of fine timing is implemented in custom PHOS4 chips and allows the signal digitisation strobe to be adjusted with the precision of 1 ns. Read-out pointers determine which part of the pipeline is accessed for events that were accepted by the trigger.

A first approximation to L1Calo timing has been obtained using calorimeter pulser systems, set up to mimic signals coming from collisions. In a set of dedicated runs, the read-out pointers are adjusted, the signals are aligned in input FIFOs and the fine timing is tuned in such a way that signals are strobed at pulse maximum. The second approximation to timing has been done using splash events, taken at the beginning of 2009 and 2010 data-taking periods. Splash events occur when the LHC beam hits a collimator, leading to large energy deposits in the whole ATLAS detector. These events are ideal for the timing adjustment, although it is necessary to correct for the time-of-flight effects, as the particles do not come from the usual interaction point, but from upstream of the detector.

The final step in timing adjustment is done using collision data. Good events and signals are selected and fitted with a function describing the expected signal shape. The position of the fitted pulse maximum defines the correction that needs to be applied. This procedure is applied in an iterative way, till observed deviations from ideal timing are considered negligible. An example of observed timing deviations after all timing corrections were applied is shown in Fig. 1. In this case

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[2] The time between two LHC bunch crossing is close to 25 ns, equivalent to a frequency of 40 MHz.

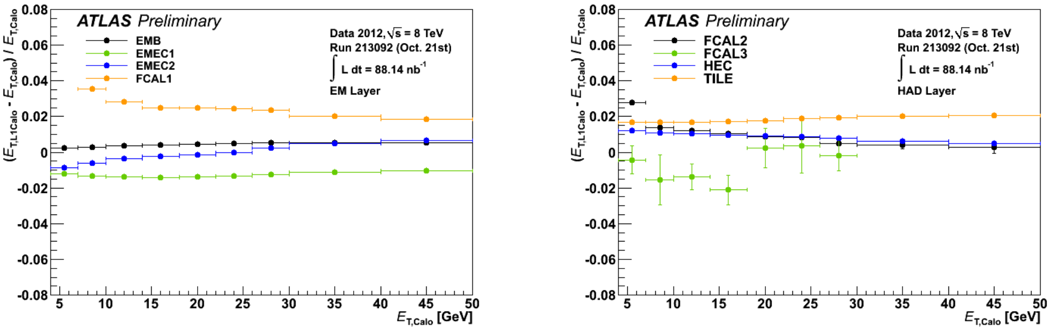

Figure 3: Fractional difference between L1Calo and offline energy for EM calorimeters (*left*) and HAD calorimeters (*right*).

deviations from ideal timing are smaller than ±3 ns in all towers, and better than ±1 ns in the barrel. As correct timing is crucial for correct operation of L1Calo, it is regularly monitored on several levels (on-line during data taking, in off-line monitoring and in dedicated off-line analysis).

The number of ADC counts seen in a trigger tower does not immediately translate to transverse energy in GeV[3]: it is necessary to introduce an energy calibration. Calibration coefficients are implemented mainly in analogue gains in the receivers.

Stability of energy response is controlled with the help of regular calibration (pulser) runs, using the more precise energy measurement in the calorimeters as a reference. Several energy (calibration pulse amplitude) steps are taken in each calibration run and gains are then determined by comparing the energy seen in the calorimeters and in L1Calo. Pulser runs are taken weekly by ATLAS shifters, automatically analysed on ATLAS Calibration Analysis Facility (CAF), compared with current (reference) gains and updated if a difference is seen.

Typical receiver gains, as determined in an analysis of a pulser run are shown in Fig. 2.

As can be seen in the figure, the gains are not uniform over η-ϕ of calorimeters, because they compensate for varying signal attenuation in analogue cables, variations in individual channel response and non-optimally performing hardware. To correct for hardware effects (like dead or disabled noisy cells, malfunctioning drawers or reduced HV), corrections used by calorimeters for

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[3] Although the approximate relation 1 ADC count $\simeq$ 0.25 GeV holds.

energy measurement are picked up during reconstruction of calibration runs. In most cases weekly calibration updates are sufficient to maintain good stability of L1Calo calibration, but occasionally the aim is either higher precision or faster turn-over time than pulser runs offer. A typical example are corrections for reduced HV in LAr calorimeter that can be calculated using dedicated set of scripts and updated at the beginning of next run.

The final E_T scale is determined from an analysis of collision data, where corrections accounting for differences between pulser and physics data (so-called pulser-to-physics corrections) are determined. These corrections are updated typically once in a running period. The quality of the L1Calo energy scale is checked regularly in monitoring and in an offline analysis. As seen in Fig. 3, offline analysis shows that it is better than 2% in all calorimeters, and better in EM barrel.

3. Trigger performance

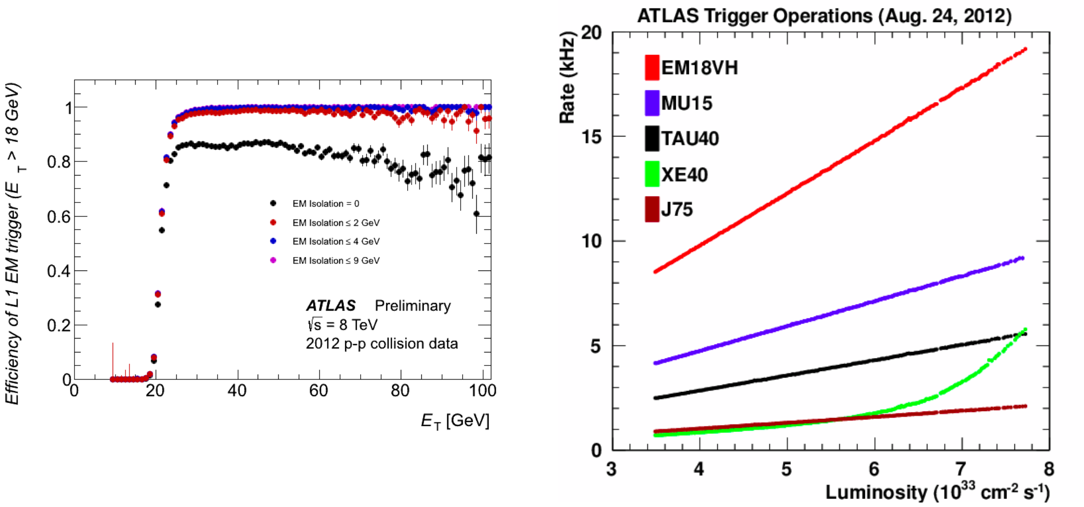

Figure 4: (*left*) Efficiency turn-on for 18 GeV electron trigger. (*right*) Rates of several L1Calo triggers as a function of luminosity.

Good energy scale uniformity leads to a nice, sharp trigger efficiency turn-on (see Fig. 4 left). Figure 4 right shows rates for several L1Calo triggers as a function of luminosity. While rates of local triggers (e/γ, τ, jets) are directly proportional to luminosity, for global triggers (like missing E_T) a clear pile-up dependency is visible. The pile-up effects are especially prominent at high η where large particle occupancy is combined with large tower size and at beginning of bunch trains (see Fig. 5 left). The reason for excessive trigger rates at beginning of bunch trains are signal baseline shifts due to out-of-time pile-up. At the beginning of a train, positive parts of analogue signals overlap, while later in a train positive and negative parts of pulses compensate each other. As a result of this effect, rates of global triggers are very sensitive to noise cuts in forward calorimeters (see Fig. 5 right). During LHC Run 1 noise cuts were the main tool used to keep missing E_T rates under control and were increased several times. For LHC Run 2 additional options, like BC-dependent pedestal correction and usage of pile-up optimised digital filters are under discussion

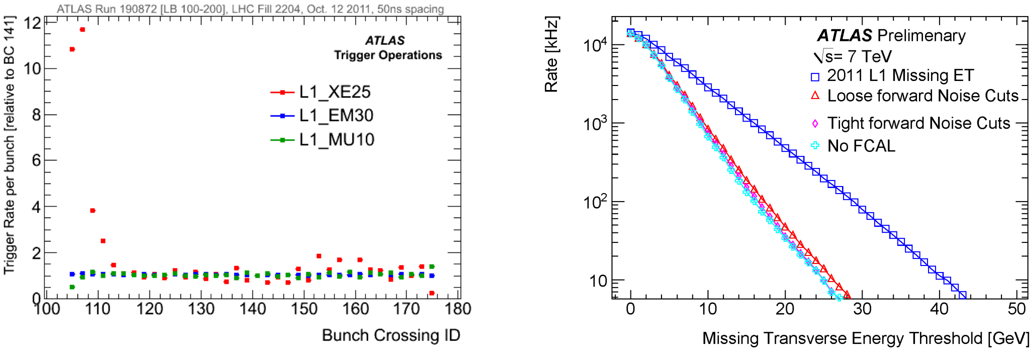

Figure 5: (*left*) Trigger rates of L1 Missing E_T trigger (L1_XE25) as a function of bunch number compared with rates of single electron (L1_EM30) and muon (L1_MU10) triggers. (*right*) Rate of missing E_T trigger for different noise cuts .

4. L1Calo upgrade plans

The rapid increase of the LHC luminosity during Run 1 meant that the ATLAS trigger was permanently under pressure. With LHC upgrades, luminosity will further increase and there is a strong motivation to keep trigger thresholds as low as possible. As a consequence, L1Calo has a rich upgrade program with ultimate goal - digital hardware trigger using full calorimeter signal granularity after Long Shutdown 3 (currently planned around 2022), with partial upgrades during previous shut-downs. In these proceedings I will concentrate on upgrades that are taking place now and will be ready for LHC Run 2 in 2015.

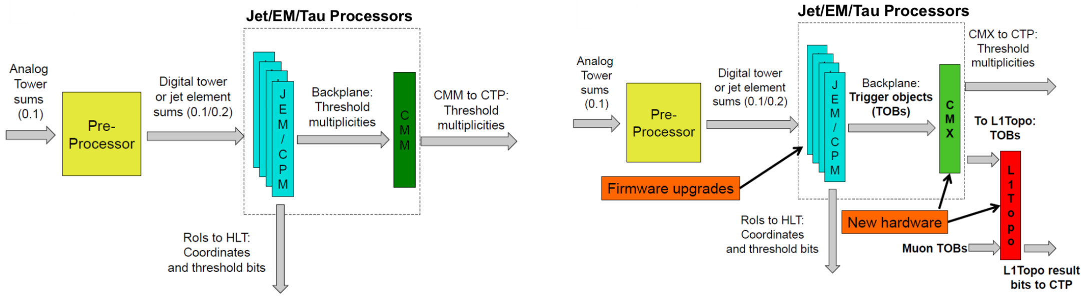

Figure 6: Structure of Run 1(*left*) and Run 2 (*right*) L1Calo system.

In the current, Run 1 system, input signal conditioning, digitisation and digital filtering are all done in daughter-boards on the Pre-Processor, so called Multi-Chip-modules (MCM). Current, ASIC-centred design is going to be replaced with a new design (nMCM), based on FPGA. The nMCM will allow better signal conditioning and BC identification for saturated pulses. It will also help to reduce L1Calo sensitivity to pile-up by performing BC-dependent pedestal subtraction and by making it possible to use pile-up optimised digital filters.

The definition and treatment of L1 trigger objects will change, too. Currently, trigger objects (for example e/γ, τ or jets) are identified in trigger processors. The total count of objects is used in the L1 decision, while detailed position and energy information is used by L2 trigger. After upgrade, both object energy and position will be available for L1 decisions. This is made possible by increasing bandwidth over back-planes in processor crates (see Fig. 6). Processor boards will get new firmware and the information will be processed by new summing modules (CMXs) and send to a new L1 Topology Trigger (L1Topo).

The new structure of L1Calo trigger will bring improvements both to inclusive, single-object and multi-object triggers. Already during Run 1 the firmware in jet and electron processor boards was updated to make possible to adjust cluster thresholds with fine (0.1 for e/γ and τ, 0.2 for jets) granularity in η. For Run 2 the treatment of EM isolation will improve (by using LUT instead of fixed-value cut), too. L1Topo will make it possible to apply cuts on quantities like $\delta\phi$ or $\delta\eta$ between trigger objects as identified by L1Calo and L1 muon systems. It will also make it possible to trigger on quantities like transverse mass and improve treatment of global quantities.

Acknowledgments

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References

[1] R. Achenbach et al. The ATLAS Level-1 Calorimeter Trigger. *JINST*, 3:3001, 2008.