Precision Timing of the ATLAS Level-1 Calorimeter Trigger: From Beam Splashes to High Luminosity Proton-Proton Collisions

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Abstract. The ATLAS Level-1 Calorimeter Trigger uses trigger tower signals from the ATLAS calorimeter as input. In real-time, it identifies high-pT objects, determines total and missing transverse energy sums and assigns bunch-crossing identification. Reliable operation requires collision signals to be synchronised at the nanosecond level. This timing was first established through the analysis of beam splash events and subsequently refined with data from LHC proton-proton collisions. In this contribution, details of the timing synchronization method as well as selected results from the timing adjustments are presented.

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 $10^{34}$ cm$^{-2}$s$^{-1}$. The ATLAS detector [1] measures particles which are created in those collisions and looks for new physics both within and beyond the Standard Model. Online selection of the relevant collision events is performed by a 3-stage trigger system. The hardware-based Level-1 Trigger (L1) operates at 40 MHz, synchronous with the LHC bunch crossings. Within a fixed latency of 2.5 µs, a decision based on fast processing of data with coarsened detector granularity is provided, so that the event is either rejected completely or transferred to the following trigger levels. The decision is generated by the Central Trigger Processor (CTP) which receives information mainly from the Level-1 Calorimeter Trigger (L1Calo) and the Level-1 Muon Trigger (L1Muon). Altogether, the input rate of 40 MHz is reduced to $\lesssim 75$ kHz.

The L1Calo system [4] processes 7168 analogue signals from the Liquid Argon (LAr) and Tile Calorimeters of the ATLAS detector [2] [3]. These signals are created by summing up to 60 calorimeter cells into Trigger Towers (TT) most of which are of size $0.1 \times 0.1$ in $\Delta \eta \times \Delta \phi$

The L1Calo receivers apply a gain, independently adjustable for each TT, to the analogue signals. In the end, each TT is finally calibrated to transverse energy ($E_T$). The signals are then conditioned and digitized in the PreProcessor Module (PPM) with a digitization step of 25 ns. In addition, their bunch-crossing is identified (BCID) and the $E_T$ is determined. This

Here, $\eta = - \ln [\tan (\theta/2)]$ is the pseudorapidity, $\theta$ being the polar angle, and $\phi$ is the azimuthal angle.
information is then processed in parallel by the Cluster Processor (CP) and the Jet/Energy-Processor (JEP) which search for and identify high-$p_T$ electrons/photons, taus/hadrons and jets. The JEP also provides a total and missing $E_T$ measurement. The object multiplicities per threshold are then transmitted to the CTP.

In L1Calo, the timing of the input signal digitization directly affects the identification of the correct bunch-crossing and measured energy. For a stable operation of BCID for non-saturated signals, a sampling of analogue pulses with a precision of ±10 ns is required. Even higher precision is required for an accurate $E_T$ measurement (2%), namely ±5 ns. Within the PPM, the signal digitization can be adjusted for every TT independently with respect to the LHC clock. A TT-specific and individually-adjustable delay register (FIFO) is used for a coarse timing adjustment in steps of 25 ns. The so-called PHOS4 chip allows a finer adjustment in 25 steps of 1 ns. Together, both procedures allow to set the sampling of the analogue TT signal directly to the maximum of the analogue signal peak for the central digitized time-slice. In 2009, LHC splash events were used to cross-check and re-calibrate the initial timing of the L1Calo system. Since the start of proton- proton collision data taking at 7 TeV in 2010, timing calibration has been done with those data.

2. Fit method for L1Calo timing synchronization

Since the analogue pulse shape of the signals is not available in recorded data, a fit of the digitized pulse shape is needed to extract the timing shift. For the fit method, TTs with similar pulse shape features are grouped together according to their calorimeter division. One of such divisions is, for example, the so-called electromagnetic barrel calorimeter (EMB), which is the central part of the electromagnetic calorimeter layer. All divisions and their respective location are listed in Table 1.

Depending on the calorimeter division, TT signals, sampled every 25 ns, are fitted with a combination of a Gaussian and a Landau function (GLu) or of two Landau functions (LLu). Due to the asymmetry of the pulses, combined functions which are joined at the maximum (such as GLu and LLu) have been found to describe the pulses best. The mathematical expression for the GLu fit function is given in equation (1):

$$
\begin{align*}
  f (x \leq x_{max}) &= A \cdot \exp \left( -\frac{(x - x_{max})^2}{2 \cdot \sigma^2_{Gauss}} - \frac{1}{2} \right) + C, \\
  f (x > x_{max}) &= \left( A + e^{+\frac{1}{2} \cdot D} \right) \cdot \exp \left( -\frac{1}{2} \left( \frac{x - x_{max}}{\sigma_{Landau}} + \exp \left( -\frac{x - x_{max}}{\sigma_{Landau}} \right) \right) \right) - D + C.
\end{align*}
$$

Here, $x_{max}$ denotes the maximum position of the signal in units of time and $A$ is the amplitude of the signal fit in the hardware units of digitization, i.e. in ADC counts. $\sigma_{Gauss}$ ($\sigma_{Landau}$) denotes the fit width, in ns, for the rising (trailing) edge of the pulse. $C$ stands for a constant offset or pedestal of the pulse (usually 32 ADC counts), and $D$ allows the fit to fall below its pedestal value. In the LAr calorimeter, the electronic shaping generates a long negative signal part, the so-called undershoot, which reaches, for example in the EMB, a depth of approximately 20% of the positive signal height. For such pulses, the parameter $D$ becomes relevant. The LLu function is obtained from (1) by replacing the Gaussian by another Landau function like the one for the trailing edge, but with parameter $D = 0$.

Table 1 summarizes the fit procedures used for different calorimeter divisions. The choice between GLu and LLu functions is based on their performance and stability. An example of how the fit method works is given in Figure 1. Here is shown a calibration pulse which was sampled with two different digitization settings in the L1Calo PPr system. In Figure 1(a), the pulse is well-timed. Its maximum is unambiguously identifiable and it lies in the central time-slice of
| Calorimeter division | Fraction of TTs [%] | \( \eta \)-range | Fit function | Fit range |
|----------------------|----------------------|------------------|-------------|-----------|
| EMB                  | 25.0                 | \( |\eta| < 1.4 \) | GLu         | 4         |
| emOverlap            | 1.8                  | \( 1.4 < |\eta| < 1.5 \) | GLu / LLu   | 4         |
| EMEC                 | 21.4                 | \( 1.5 < |\eta| < 3.2 \) | LLu         | 4         |
| FCal                 | 3.6                  | \( |\eta| > 3.2 \) | LLu         | 3         |
| Tile                 | 26.8                 | \( |\eta| < 1.4 \) | GLu         | 4         |
| HEC                  | 21.4                 | see EMEC        | LLu         | 4         |

**Table 1.** List of the calorimeter divisions and the fit procedures for the individual calorimeter divisions, including the range of the fit.

![Figure 1(a)](image1a.png) ![Figure 1(b)](image1b.png)

**Figure 1.** Calibration pulse for one EMB TT as recorded by L1Calo for each of two digitization settings, and fitted with the GLu function [6]. The deposited energy (in units of ADC counts) is plotted versus the time, using an arbitrary time origin. (a) A well timed pulse. (b) A pulse with the timing shifted by 12 ns.

The pulse in Figure 1(b) is obviously mistimed, because it shows no clear maximum but rather two values of approximately the same height. This leads to ambiguity in BCID and an \( E_T \) mismeasurement. Here, the timing was shifted by 12 ns.

To both pulses in Figure 1, a GLu fit has been applied. The fit reconstructs the shape and, especially, the maximum position and the amplitude of the original analogue pulse. The challenge of the fit method is to obtain the same pulse shape independent of current digitization settings. In particular, in Figure 1, the signal peak position and the amplitude of both pulses are expected to be identical, apart from a 12 ns shift. Indeed, within small uncertainties, this is the case. Thus, in the timing synchronization procedure, no correction would be required for a pulse like the one in Figure 1(a) and a correction of 12 ns would be needed for a pulse like the one in Figure 1(b).

While for calibration pulses 15 time-slices of a TT pulse are read out from the L1Calo trigger system as displayed in Figure 1, during normal data-taking only 5 time-slices can be handled by the Data Acquisition System (DAQ). Thus, the fit range for GLu and LLu functions is restricted significantly. This is the reason why only 4 or 3 (in FCal) time-slices around the signal peak are used by the fit method (see Table 1). With 6 free parameters, the GLu and LLu are under-constrained, so to reduce the number of degrees of freedom the values of \( \sigma_{\text{Gauss}} \), \( \sigma_{\text{Landau}} \) and the undershoot-to-amplitude ratio \( (D/A) \) are fixed to predefined values derived from calibration data. In addition, the pedestal parameter \( (C) \) is fixed at the TT signal baseline as set in the L1Calo hardware before digitization. Thus, only the maximum position \( x_{\text{max}} \) and the amplitude \( A \) are allowed to vary freely within certain constraints.

The main source of systematic uncertainty of the method comes from the shape differences between the calibration and real physics pulses. They are estimated to be of the order of...
magnitude of 5-15% in the EMEC and in FCal they even reach to some 20-30%. In the application of the fit method to collision data, these shape differences have been corrected for. Overall, however, the timing synchronization determined by the fit method has a $\pm 1\,\text{ns}$ systematic uncertainty and a $\pm 2\,\text{ns}$ statistical uncertainty [6]. With respect to the precision of 1 ns in the digitization point setting in the L1Calo hardware, the method’s accuracy lies well within the targeted precision of 5 ns.

3. Timing calibration with 2009 LHC beam splashes

During autumn 2009, the LHC provided splash events during commissioning, prior to physics (collision) operation. A splash event is produced by beam packets interacting with the collimators located in the beam pipes at $\pm 145\,\text{m}$ from the interaction point at the centre of the ATLAS detector. The timing of such events does not correspond to that of beam collision timing. However, given the distances from collimator to each particular TT, and from that TT to the nominal interaction point, a correction for time-of-flight can be performed to estimate the collision timing. Initially, this has been done with data from Run 140370 (20th November 2009) where 55 of the splash events provided by the LHC were used [5].

Figures 2(a), 2(b) show the fitted signal peak positions which have not been corrected for time-of-flight, while Figures 2(c), 2(d) show the corrected values which were used as the timing corrections with an expected timing accuracy of $\pm 5\,\text{ns}$ (for more details, see [5]).

4. Timing calibration with proton-proton collision data

At the beginning of 2010, the LHC started delivering collision data with a proton-proton centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$. This allowed the possibility of a timing update derived from actual physics data.

4.1. Event and pulse selection

The precise event and pulse selection requirements have evolved, largely to adapt to LHC increases in luminosity. In all cases, events are required to pass certain basic data quality criteria. They have to be taken during stable beam conditions when the detector, especially the calorimetry, is fully operational. A good primary vertex within a maximum displacement along the beam axis, as well as a minimum number of tracks from the vertex are required. These requirements enhance the probability that the signals originate from head-on proton-proton collisions. The pulse selection criteria are mainly there to reduce the number of noise pulses contaminating the analyzed sample. For calorimeter divisions which are especially susceptible to calorimeter noise, e.g. the HEC, a special noise suppression is applied. Also, a minimum transverse energy of approximately 7 GeV in a given TT as measured by L1Calo is required. For details on event and pulse selection, see [6].

4.2. First timing calibration with collision data

The first timing calibration with collision data was done with data from 4-5 July 2010, corresponding to an integrated luminosity of $\approx 30\,\text{nb}^{-1}$. Following the described pulse selection, in each TT, the pulses were fitted with a GLu/LLu function. The differences between the fitted maximum positions and the central time-slice are expected to be gauss-distributed around the best timing correction. Figure 3 shows such a distribution for one of TTs in the EMB and a corresponding gaussian fit. However, the mean value of the distribution itself and not the gaussian fit mean is used as the timing correction, because this has been found to be a more stable procedure.

Figure 4 shows timing corrections for all TTs in both electromagnetic and hadronic layers of the calorimeter determined as described above. Most of the corrections are within $\pm 2\,\text{ns}$ which
Figure 2. (a), (b) $\eta - \phi$ maps of the peak time (ns) plotted on the z-axis, for typical splash events [5]. The peak times ($t_0$) are measured by fitting each trigger tower signal with a GLu/LLu function. The timing reference was taken as 175 ns. In white regions, no reliable fit could be made, hence no correction computed. In (c), (d) the corrected (for time-of-flight) peak time (ns) for each calorimeter layer is plotted. The electromagnetic layer (a), (c) has beam-1 approaching from $+\eta$ direction. The hadronic (b), (d) has beam-2 approaching from $-\eta$ direction.

Figure 3. Distribution of the difference between the fitted maximum position and the middle of the central read-out time-slice for one TT in the EMB from the first physics data based timing synchronization in July 2010 [6]. The mean value of the distribution determined from 523 fits to collision signals indicates a timing correction of 1.8 ns for the given TT. For comparison only, a simple gaussian fit is shown.

Illustrates the consistency of the method. In 2010 and 2011, the L1Calo timing synchronization
was checked nine times using the same method, resulting in six timing adjustments from proton-proton collision data. For a full list of updates, see [6]. The magnitudes of the corrections were usually less than 2 ns.

Figure 4. Timing corrections in ns for the electromagnetic calorimeter layer (a) and the hadronic calorimeter layer (b) [6]. The timing corrections per TT were derived from proton-proton collision data of July 2010.

5. Conclusion
Synchronizing the trigger tower (TT) signals of the Level-1 Calorimeter Trigger (L1Calo) with respect to the LHC clock and with respect to each other, as well as maintaining and refining the timing synchronization, are important to ensure a stable and reliable operation of the ATLAS trigger system. Bunch-crossing identification of signals (BCID) and energy measurement in L1Calo necessitate an accuracy of \( \pm 5 \) ns in the timing synchronization. To accomplish the goal, a special fit method has been developed. It has been applied to beam splash data and to collision data. Over the course of 2010 and 2011, it has been applied nine times to collision data with mean timing corrections of \( \lesssim \pm 1.5 \) ns. The method has demonstrated the stability of the L1Calo timing synchronization to within \( \pm 1 \) ns systematic uncertainty and a \( \pm 2 \) ns statistical uncertainty, as required for reliable trigger operation.

References
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