Time Calibration of the ATLAS Tile Calorimeter using an Integrated Laser System

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Abstract. The ATLAS hadronic Tile Calorimeter is ready for data taking with proton-proton collisions provided by the Large Hadron Collider (LHC). The Tile Calorimeter is a sampling calorimeter with iron absorbers and scintillators as active medium. The scintillators are read out by wave length shifting fibers (WLS) and photomultipliers (PMTs). The LHC provides collisions every 25 ns, putting very stringent requirements on the synchronization of the ATLAS triggering systems and the read out of the on-detector electronics. More than 99% of the read out channels of the Tile Calorimeter have been time calibrated using laser pulses sent directly to the PMTs. Timing calibration constants can be calculated after corrections for differences in laser light paths to the different parts of the calorimeter. The calibration consists of two parts: programmable corrections implemented in the on-detector electronics, and residual deviations from perfect timing stored in a database used during the offline reconstruction of the Tile Calorimeter data. Data taken during long ATLAS cosmic runs and during LHC beam time in September 2008 has confirmed a timing uniformity of 2 ns in each of the four calorimeter sections. The remaining offsets between the four calorimeter sections, have been measured in two ways. First by using the laser pulses interleaved with cosmic triggers inside a global ATLAS run. The second method uses the real LHC events acquired during the 2008 beam time. Both methods give consistent results. The main limitations on the precision of the time calibration are presented.

1. Introduction
The Large Hadron Collider (LHC) at CERN will extend the frontiers of particle physics with its unprecedented high energy and luminosity. Inside the LHC, bunches of up to $10^{11}$ protons will collide 40 million times per second to provide 14 TeV proton-proton collisions at a design luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. The high interaction rates, radiation doses, particle multiplicities and energies, as well as the requirements for precision measurements have set new standards for the design of particle detectors. The ATLAS detector [1], located at one of the four LHC collision points, is a general purpose detector designed to fully explore the wide range of possible new physics provided by the LHC at the next high-energy frontier.

This paper summarizes the synchronization of the readout electronics of the ATLAS hadronic Tile Calorimeter, using laser pulses sent directly into the PMTs. The full details of this work can be found in Ref. [2].

In section 2 the mechanical, optical and electronical characteristics of the calorimeter is outlined and a brief overview of the different timing issues is given. Section 3 focuses on the laser calibration system which has been used to perform this work. In sections 4 and 5 the method of time calibration using laser pulses is outlined. In section 6 the different sources of systematical uncertainties present in the study are briefly discussed.
2. The Tile Calorimeter

The ATLAS hadronic Tile Calorimeter [1] [3], also referred as TileCal, is a scintillating sampling calorimeter [4] named after its layers of scintillating plastic tiles and steel absorber plates. Its main task is to identify jets and perform measurements of their energy and direction, as well as to contribute to the measurement of missing transverse energy. TileCal is also capable of measuring the time of flight [5] of particles crossing it. TileCal plays an important role in the ATLAS first level trigger [6].

TileCal has a cylindrical structure (Fig. 1 left) divided into a 5.64 m “long-barrel” (LB) and two 2.65 m “extended-barrels” (EB), with an inner radius of 2.28 m and an outer radius of 4.23 m. The long barrel itself is divided into two electronically independent sections, or an A- and an C-side, called LBA and LBC respectively. Each of the extended barrels makes up its own section, EBA and EBC respectively. Each section is sub-divided into 64 azimuthally oriented wedge shaped modules (Fig. 1 right), making a total of 256 TileCal modules.

![Figure 1.](image.png)

Figure 1. Left: the ATLAS Tile Calorimeter with its four sections. Right: a wedge shaped TileCal module. A module consists of alternating layers of scintillators and absorbers. WLS fibers collect the scintillating light and distributes it into PMTs. The drawer, located on top of the module, contains the PMTs and all the front-end electronics.

The scintillating light produced by charged particles inside a hadronic shower is collected by WLS fibers and distributed to PMTs. The PMTs are located in a removable mechanical structure (called a drawer) at the back of each module, together with the front-end and read-out electronics. Each barrel module contains 45 PMTs and an extended barrel module contains 32 PMTs (or 30 PMTs for two special modules), making it a total of 9852 PMTs.

The tiles are arranged in cells as shown in Fig. 2. The WLS fibers from all tiles within one cell are organized in two bundles, one from each side of the cell. The bundles are in turn connected to two different PMTs placed in the drawer. Also as shown in Fig. 2 the tiles are grouped into readout cells organized into 3 different radial depths: A-cells closest to the beam line (z-direction), D-cells furthest away from the beam line and so called BC-cells in the intermediate region. The three sampling depths are staggered in z in order to obtain a projective tower geometry (pointing towards the interaction point).

2.1. TileCal Electronics and Readout

The PMTs together with the front-end electronics [7] are mounted inside the drawers which are located at the back of each module (Fig. 1 right). The analogue signals from the PMTs are shaped and amplified by a so-called 3-in-1 card attached to the PMT base. The 3-in-1 card has four signal outputs: one for the first level trigger, one for calibration purpose and two outputs to the digitizer board described in
Figure 2. Sketch of the Tile Calorimeter showing cell structure and cell numbers. The left side of the figure shows a barrel module (such as LBA or LBC) and the right side shows an extended barrel module (such as EBA or EBC). The three readout depths: A-, BC- and D-cells are displayed.

section 2.1.1. The last two have different amplifications in order to be sensitive to a wide range of signal strengths.

2.1.1. The Digitizer Board  The purpose of the TileCal digitizer system [8] is to sample and digitize the analogue signals coming from the PMTs via the 3-in-1 cards. The digitizer board has two 12-bit Analogue to Digital Converters (ADCs), two for each PMT, reading the two different outputs. The ADCs sample the analogue signals from the 3-in-1 card every 25 ns. The sampled values are buffered in a local pipeline memory while awaiting the first level trigger accept. The digitizer board also contains one Timing Trigger and Control receiver chip (TTCrx) described in section 2.1.3 and two TileDMUs described in section 2.1.4. One digitizer board reads out and digitizes the analogue signals from up to six PMTs. One barrel drawer has eight digitizers boards while an extended barrel drawers has only six.

2.1.2. ATLAS Timing, Trigger and Control  The ATLAS Timing, Trigger and Control (TTC) system [9] is a multipurpose, optical fiber based, distribution system that has been developed for the four LHC experiments. The TTC system distributes timing, trigger and control information, trigger accepts, bunch crossing counters, orbit signals, trigger type, counter resets, and configuration and test commands. The trigger accepts are generated by the ATLAS Central Trigger Processor (CTP) when TileCal is operated within an ATLAS run, or otherwise from a Local Trigger Processor. The TTC system also distributes the 40 MHz system clock that is synchronized with the protons bunches during LHC collisions.

2.1.3. TTC Receiver Chip  The TTC receiver chip [10] (TTCrx) is an interface between the TTC optical system and the front-end electronics. It receives the optical signals and converts them into electrical signals. The TTCrx receives the central 40 MHz system clock and distributes a synchronous clock referred to as \( \text{clock40\_des2} \), or sampling clock, to the ADCs.

The sampling clock determines when the ADC should sample the physical signals. The \( \text{clock40\_des2} \) clock can be delayed to allow for optimal sampling of the physical pulse due to charged particles traversing the calorimeter. A fine programmable delay, referred to as \( \text{dskew2} \), allows one to delay the \( \text{clock40\_des2} \) clock by up to 25 ns, in steps of 0.104 ns. In this work, the \( \text{dskew2} \) delays are used to compensate for different arrival times of the 40 MHz system clock to different parts of TileCal front-end electronics.
2.1.4. TileDMU  The TileDMU [11] (Data Management Unit) chip, located on the digitizer board, is a readout- and digitizer-control system. It contains the pipeline memory which stores the sampled data for up to 6.4 $\mu$s, while waiting for the trigger accept. When the first level trigger decides to keep an event, a trigger accept signal is sent to the TileDMU from the ATLAS CTP via the optical TTC system and the TTCrx. The TileDMU then reads out 7 consecutive samples from the pipeline memory. The pipeline memory can be set such that the readout starts one or several samples later or earlier. This provides a handle for coarse timing in multiples of 25 ns (Fig. 3b and 3c). This setting can be seen effectively as a programmable timing correction which is referred to as $\Delta p$ in the rest of this work.

![Diagram of TileDMU](image)

**Figure 3.** The figure shows the effect of changing the digitizer pipeline memory offset $\Delta p$ and the $dskew2$, on the calculated time $T_{fit}$, between the pulse peak and the 4th sample. The numbered circles indicate the seven consecutive samples taken by the ADC and read out. (a) The pulse is sampled too early by the ADC, hence $T_{fit} > 0$. (b and c) The pipeline memory setting $\Delta p$ is changed by -1 (b) and +1 (c) respectively. This has the effect of changing the 1st sample to be read out (circle numbered 1). (d) The position of the samples can be finely adjusted to achieve $T_{fit} = 0$ by setting $dskew2$ to an appropriate value.

2.2. TileCal Timing

During LHC operation the so called Optimal Filtering (OF) algorithm [12] will be used to reconstruct the energy of the TileCal events. The OF is known to have its best performance when the ADCs sample within 2-3 ns from the peak of the analogue pulses and the residual offset, measured beforehand with a precision of $\lesssim 1$ ns, are given as input to the algorithm. An offline correction has been developed [13] to correct for any timing caused energy reconstruction of up to 7%, provided that the time is off by $< 10$ ns. This however can not be used to correct the online reconstructed energy provided to the 2nd level trigger. Therefore it is necessary that the timing offset after calibration is small and that its residual value is precisely measured.

The quantity measuring the time difference between the fourth sample and the pulse maximum is called “the calculated time” or $T_{fit}$ (illustrated in Fig. 3). $T_{fit}$ is calculated by the TileCal reconstruction.
using the so-called fit method [14] described in section 3.4. $T_{fit}$ is defined as

$$T_{fit} \equiv t_{peak} - t_{4th},$$

where $t_{4th}$ is the time of the 4th sample of the pulse. The sign of $T_{fit}$ can be interpreted in terms of late or early sampling of the pulse, in the following way:

$$T_{fit} \begin{cases} > 0 & \Rightarrow \text{The sampling of the pulse by the ADC starts too early} \\ < 0 & \Rightarrow \text{The sampling of the pulse by the ADC starts too late} \end{cases}$$

In the ideal situation $T_{fit} = 0$ for all channels. However, there are a number of reasons why this is not the case a priori:

- The 40 MHz system clock is provided to each digitizer board by the TTC system. The signal enters each drawer via an interface card placed at the center of each barrel drawer or at one side of each extended barrel drawer. Thereafter the signal propagates through adjacent boards on its way through the drawer (see Fig. 4), delaying the arrival of the system clock up to about 10 ns to the outermost digitizers. A late arrival of the system clock means that the ADC will also sample the pulse late, if not corrected for.

- The TTC fibers running from the counting room to each drawer (see Fig. 4) can have significantly different lengths, due to the large size of TileCal. In the most extreme cases the difference in TTC fiber length is more than 7 m, corresponding to a time difference of up to about 40 ns. A long TTC fiber means late arrival of the system clock compared to a drawer with a short fiber. Hence the ADCs will sample late if this effect is not corrected for.

- The time of flight for particles to different regions of the calorimeter differs as well as the length of the light collecting WLS fibers. This has to be corrected for before real physics data is taken. However, this issue is not addressed in this paper, since the WLS fibers are completely separated from the laser light distribution path. Instead time of flight and WLS corrections will be applied on top of the timing corrections discussed in this work.

The TileDMU is clocked by the 40 MHz system clock, while the ADCs are clocked by the clock40des2 clock. Both clocks are obtained from the TTCrx. The system clock is fixed (and synchronized with the LHC bunch crossings). The clock40des2 is synchronous with the system clock but can be delayed by a constant phase. This allows for fine tuning of the ADCs in order to sample as near the PMT pulse peak as possible and to obtain a uniform $T_{fit}$.

The clock40des2 clock can be delayed by up to 25 ns, with respect to the system clock. The delay is set in units of dskew2 counts, where 1 count = 0.104 ns (240 counts represents 25 ns). Six consecutive channels share the same digitizer board (see Fig. 4) and the same TTCrx, therefore the TTCrx cannot compensate for delays among the six channels it is connected to.

3. The Laser System

In order to calibrate and monitor the time and energy response of the TileCal PMTs an integrated laser system [15] has been developed. Laser pulses with a wavelength of 532 nm and a pulse width of 15 ns from a single laser source are distributed directly into each of TileCal’s nearly 10000 PMTs via a chain of optical fibers. In the present work, the laser system is used for the time calibration of TileCal.

3.1. Laser Distribution System

A sketch of the laser system is displayed in Fig. 4. The laser is located in an underground counting room about 100 m away from the ATLAS detector. So-called laser fibers, each about 110 m (120 m) long in the barrel (extended barrel) lead the laser light to each of the Tile Calorimeter modules. Each laser fiber connects to a distribution connector located in the drawer and whose output is a bundle of so-called clear fibers. The clear fibers distributes the light directly into each PMT. The arrangement is such that it takes two laser fibers to distribute light to one module (odd and even numbered PMTs respectively). The WLS fibers, connecting the tiles to the PMTs, are not part of the laser path.
Figure 4. Propagation of the TTC signals inside a TileCal barrel drawer, from the interface card to the digitizer boards. The figure also shows the laser distribution system. Note that it takes two laser fibers to distribute light to odd and even PMTs in one drawer.

3.2. Lengths of the Clear and Laser Fibers
The clear fibers (section 3.1) are of different lengths and these are taken into account in the intra-module time equalization described in section 4.1. There is a strong indication that the precision of the cutting of the laser fibers leads to a smearing of the laser pulse arrival time. Measurements of the time difference between mean time in even and odd PMTs in the long barrel drawers suggest that this smearing is of the order of 1.2 ns. Since the even and odd PMTs are fed with two different laser fibers, whose length should be the same, the spread of this distribution gives an estimate of the accuracy of the laser fiber cutting.

3.3. Speed of Light in the Clear and Laser Fibers
In order to exploit the laser calibration data to derive timing corrections between channels and sections, it is necessary to know the velocity of light in the optical fibers that make up the TileCal laser distribution systems, for the wavelength (532 nm) used by the laser system. The clear and laser fibers are of the same type and thus have the same velocity of light, which are denoted $v_{CF}$. There are several available measurements of $v_{CF}$. From the manufacturer it is specified that $v_{CF} = 20.1 \text{ cm/ns}$ for a wavelength of 650 nm. There is also a “direct measurement” of $v_{CF}$ using an OTDR (Optical Time Domain Reflectometer) device which gives $v_{CF} = 19.7 \text{ cm/ns}$ for the same wavelength. The difference of $v_{CF}$ between this specified wavelength and the operational wavelength of the laser system should nevertheless be of the order of a few percents. The value of $v_{CF} = 22.5 \text{ cm/ns}$, used prior to the 2008 LHC beam, was derived with a different “iterative method” method, presented in [2]. This value is now believed to be an overestimate of the actual $v_{CF}$.

3.4. Signal Reconstruction
The pulse phase and amplitude of calorimeter laser events are reconstructed with the linearized method known as the fit method [14]. The fit method uses prior knowledge of the pulse shape in order to reconstruct the pulse and suppress the noise. For each channel a fit to the function

$$f(t) = Ag(t - \tau) + c$$

is performed, where $A$ is the amplitude, $g$ is the normalized pulse shape function, $\tau$ parameterizes the peak position in time and $c$ is the pedestal value. The pulse shape function has to be derived separately for physics and calibration data, and is stored for later retrieval by the algorithm.
4. Time Calibration of the Tile Calorimeter

A “laser run” corresponds to a set of TileCal data taken while the laser is pulsing. From the observed $T_{fit}$ values in a laser run, one can derive programmable delays $d_{skew2}$ and pipeline memory settings $\Delta p$, so that $T_{fit}$ is made uniform over the entire calorimeter for a hypothetical light pulse arriving simultaneously to all PMTs. Once the WLS fiber lengths corrections are also applied, this corresponds to a uniform $T_{fit}$ for a simultaneous energy deposition in all cells.

4.1. Intra-module Synchronization

Intra-module synchronization refers to the equalization of $T_{fit}$ within each drawer. In a TileCal drawer the signals of the 40 MHz system clock propagate from the digitizers closest to the drawer interface card to the ones furthest away, as illustrated in Fig. 4. Hence the PMTs pulses are sampled earlier the closer to the interface card they are, as illustrated in Fig. 3.

The clock signal propagation results in groups of 6 PMTs belonging to the same digitizer to appear as displaced in time with respect to PMTs from the other digitizers (see Fig. 5a). The time difference between two neighboring digitizers are typically of the order of 2-4 ns.

The goal is to delay the “early” digitizers, the digitizers first receiving the clock signal, in such a way that all digitizers within the drawer sample the PMTs pulses simultaneously. This is done by setting the $\text{clock40des2}$ TTCrx chip delay on the digitizer boards, to an appropriate phase relative to the system clock, hence delaying the time of the samples, again illustrated in Fig. 3. The result is shown in Fig. 5b. Note that the variations among channels of the same digitizer will still remain after implementing the $\text{clock40des2}$ delays.

![Figure 5. Time vs PMT number, before (a) and after (b) implementing the $d_{skew2}$ timing corrections.](image)

4.2. Inter-module Synchronization

Inter-module synchronization refers to the equalization of $T_{fit}$ among the 64 different drawers inside each of the four TileCal sections. Since the TTC fiber lengths differ from drawer to drawer, different drawers receive the clock signals at different times. This changes the phase between the system clock and the PMTs pulses. During the TTC fiber routing, often the shortest possible fiber length was used. Since TileCal is a large detector this means that the fibers can vary over many meters in length from one drawer to another, generating correspondingly large time differences. Without adjustment the drawer to drawer difference would be as high as 40 ns.

The method consists of choosing a reference drawer in each section and shift the $\text{clock40des2}$ and/or pipeline memory settings of all other drawers such that they all align with the section reference drawer. Figure 6 shows the distribution of $T_{fit}$ for more than 99% of all channels with respect to each sections reference drawer after intra and inter-module synchronization. The width of the fitted function provides a measure of the statistical limit of the time calibration method.
4.3. Inter-section Synchronization

The timing offsets between the different sections arise from:

- Different TTC fiber lengths to the four sections, yielding different phases between the physics pulses and the system clock.
- Different read out pipelines.
- Different cable lengths between the ATLAS Central Trigger Processor and the various TileCal TTC crates
- and possibly, different cable lengths among TTC modules inside the TTC crates.

Since in earlier sections it has been shown that the timing can be equalized within each TileCal section, what remains to be equalized is the pulse peak to clock phase among the reference drawers of the four sections. The calculation of timing corrections between the reference drawers and their compensation is referred to as the inter-section synchronization.

The offsets between the reference drawers can be derived using the laser events. Special runs are used where the laser system is firing during so-called calibration triggers inside a physics or combined ATLAS run. In this way the section offsets is measured with the exact same setup as during an ATLAS physics run. This is particularly important as in TileCal standalone and other type of runs, the trigger latencies are not necessarily the same as for an ATLAS combined / physics run, which can therefore require different TileCal pipeline settings.

The measured offsets is biased by the large differences in laser fiber lengths between sections. The actual, measured, laser fiber lengths are used to correct for this effect.

Figure 7 shows the offset of the reference drawers with respect to LBC, which is the calorimeter section taken as reference. The circles (triangles) show the resulting section offsets measured with the laser system, using $v_{CF} = 22.5$ cm/ns ($v_{CF} = 21.0$ cm/ns). The squared markers are the section offsets resulting from actual beam events, where muons in the LHC beam halo crossed TileCal, traveling parallel to the beam axis. The later measurement is independent of $v_{CF}$ since it does not rely on the laser system. The best agreement with the beam measurement is achieved with 21.0 cm/ns.

5. Offline Residuals

It has been outlined how to use the offsets measured between the different TileCal channels to derive programmable delays and pipeline settings to program the TTCrx chips on the digitizer boards, to equalize the measured pulse times over TileCal. After this online equalization, one can remeasure the spread in time over TileCal with a new laser run. There is a residual spread among channels due to:
Figure 7. The offset between the different TileCal sections obtained using laser events inside an ATLAS combined run with $v_{CF} = 22.5$ cm/ns (circles) and $v_{CF} = 21$ cm/ns (triangles). The result from the laser is compared to the section offsets derived from events triggered by muons from the LHC beam halo (squares).

- One TTCrx chip serves 6 channels, therefore the time spread among the channels belonging to the same TTCrx chip cannot be reduced online,
- If the online constants for timing equalization are not perfect in any way, this will appear in any laser run as a non uniform $T_{fit}$.

5.1. Derivation of the Offline Residuals

The data from a laser run, taken after implementation of the online programmable delays, can be used to measure the departure of the actual TileCal timing from the perfect TileCal timing. During collisions, the clock is synchronized with the collisions, and the perfect TileCal timing is defined as the set of online constants giving a uniform $T_{fit}=0$ over all TileCal for all particles traveling with the speed of light and coming from the ATLAS interaction region. In the case of a laser run, the perfect timing is achieved if for a given laser pulse, $T_{fit}$ corrected for laser and clear fiber lengths is constant over all TileCal channels, equal to the $T_{fit}$ in a reference channel.

The offline residuals are additional corrections, which are added offline to the $T_{fit}$’s in each channel, in such a way that $T_{fit}$ is constant over the entire TileCal, giving the perfect timing for laser runs. If the programmable dskew2 delays are accurate, then the offline residuals will be small. For drawers where the online programmable corrections could not be computed, the offline residuals will in general be large. In the current TileCal setup which was also used for ATLAS data taking with the first LHC beam, the offline residuals are known for 99% of the TileCal PMTs and their standard deviation is 0.6 ns. These offline residuals can be used as input for the energy reconstruction algorithm, up to a global constant equal to the phase in a reference PMT, between the pulse maximum and the clock synchronized to the beam. These offline residuals are remeasured after each modification of the online programmable corrections and stored in the TileCal offline conditions database.

6. Uncertainties

The most important sources of systematic uncertainties and their respective estimated magnitudes are listed in table 1. Apart from the uncertainties already discussed in section 3.2 and 3.3 there is also a possible estimated bias from the pulse shape function used by the fit method (section 3.4), time resolution of the fit method and a possible different clear fibers routing scheme in part of the drawers.
Table 1. Significant systematic uncertainties affecting TileCal timing.

| Source of uncertainty                          | Value    |
|------------------------------------------------|----------|
| Laser fiber lengths                            | ±1.2 ns  |
| Pulse shape                                     | ±0.4 ns  |
| Fit method time resolution                      | ±0.35 ns |
| Clear fiber routing                             | ±0.5 ns  |
| $v_{CF}$ contribution to intra-module           | <0.1 ns  |
| $v_{CF}$ contribution to inter-section          | O(5 ns)  |

7. Conclusion

A method to equalize the PMT pulse times measured in all TileCal drawers has been developed and applied to about 99% of the TileCal channels. The residual spread for simultaneous laser pulses is of the order of 0.6 ns in each TileCal section. The laser system was also used to derive the global offset among TileCal sections, but suffers from the uncertainty on the laser fiber length. Nevertheless a combination of the laser data and beam data can be used to calibrate the lengths of the laser fibers. Finally the main sources of uncertainties on the TileCal timing are presented. The leading source of uncertainty is the laser fiber length, which should ultimately be calibrated with beam data and which would allow one to independently measure the TileCal timing using beam or laser events.

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