

# Signal reconstruction performance with the ATLAS Hadronic Tile Calorimeter

**Pawel Klimek, on behalf of the ATLAS Tile Calorimeter group**

Stockholm University, Sweden

E-mail: `pawel.klimek@cern.ch`

**Abstract.** The Tile Calorimeter (TileCal) is the central section of the hadronic calorimeter of ATLAS. It is a key detector for the reconstruction of hadrons, jets, taus and missing transverse energy. TileCal is a sampling calorimeter with steel as absorber and scintillators as active medium. The scintillators are read-out by wavelength shifting fibers coupled to photomultiplier tubes (PMTs). The analogue signals from the PMTs are amplified, shaped and digitized by sampling the signal every 25 ns. The read out system is designed to reconstruct the data in real time fulfilling the tight constraints imposed by the ATLAS first level trigger rate (100 kHz). The signal amplitude for each channel and their phase are measured using Optimal Filtering techniques both at online and offline level. We present the performance of these techniques on the data collected in the proton-proton collisions at center-of-mass energy equal to 7 TeV. We will address the performance for the measurement on high pile-up environment and on various physics and calibration signals.

## 1. Introduction

ATLAS [1] is a general-purpose experiment, whose goal is to cover a broad range of experimental particle physics phenomena, with the long sought Higgs boson and supersymmetry on top of the wanted list. The Tile Calorimeter [2] is the hadronic calorimeter of ATLAS in the region  $|\eta| < 1.7$ . The purpose of TileCal is to identify hadronic jets and measure their energy and direction. It also provides vital information for the first level trigger, the measurement of the missing energy due to non-interacting particles and the identification of electrons and photons. It uses steel as absorber and scintillating plastic tiles as active material.

## 2. Read out architecture

Photomultiplier tubes (PMTs) read out the light from the scintillating tiles using wavelength shifting fibers. The fibers are grouped to segment the calorimeter in cells with a granularity  $\Delta\phi \times \Delta\eta \sim 0.1 \times 0.1$  and 3 radial layers. Each cell is read out by two PMTs, corresponding to two independent electronic channels. The PMT output is a current pulse with its amplitude proportional to the energy deposited in the associated cell. Electronics mounted on the PMT amplifies and shapes the output current pulse. Pulse shaping forms the signal width to 50 ns at half-maximum. In order to effectively extend the dynamic range a bigain read out is used with a ratio between the two of 64. The two analogue pulses (high gain and low gain) are digitized by two 10-bit ADCs at 40 MHz. The high gain chain is used until it saturate at about 12 GeV, for higher energies the low gain is used [3]. The analogue pulse is digitized by 10-bit analogue to

digital converters with 7 samples at 25 ns intervals which are read out upon a trigger accept from the first level trigger and sent to the back-end electronics in a counting room 100 m off detector, the Read Out Drivers (ROD). The RODs use Digital Signal Processors (DSP) to compute the pulse amplitude, phase and quality factor.

### 3. Optimal Filtering algorithm

The goal of the energy reconstruction algorithms is to compute the energy deposited in a TileCal cell from the number of ADC counts measured in each of the two corresponding read out channels. The samples are referred to as  $S_i$  with  $i = 1 - 7$  and are in units of ADC counts. The energy reconstruction combines the  $S_i$  to first obtain the amplitude in ADC counts and thereafter applies a calibration constant in MeV per ADC count. The  $S_i$  are linearly combined to provide the pulse amplitude  $A$ , the phase  $t$  with respect to the 40 MHz clock and the electronic pedestal  $P$  (figure 1 left panel). The quality factor  $QF$  is also computed to verify that the computed amplitude, phase, pedestal and the known pulse shape  $g(t)$  are compatible with the observed data points  $S_i$ . In case of deviation between the actual shape and the expected shape, the quality factor takes large values which can be used to detect problems in the reconstruction procedure. These quantities are calculated as follows [4]:

$$A = \sum_{i=1}^7 a_i \cdot S_i, \quad t = \frac{1}{A} \sum_{i=1}^7 b_i \cdot S_i, \quad P = \sum_{i=1}^7 c_i \cdot S_i, \quad QF = \sqrt{\sum_{i=1}^7 \left( S_i - (A \cdot g_i - A \cdot t \cdot g'_i - P) \right)^2}$$

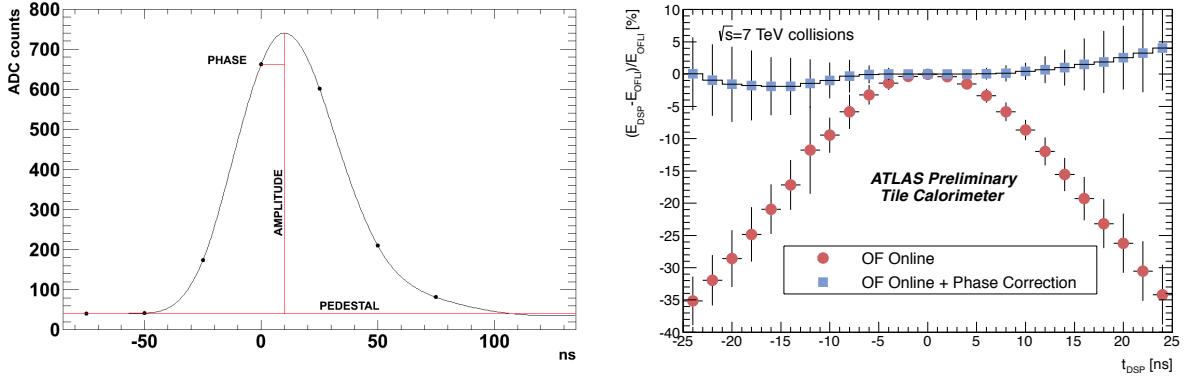
This method is called Optimal Filtering. Prior knowledge of the normalized pulse shape function is required to determine the constants  $a_i$ ,  $b_i$ ,  $c_i$ . The pulse shape was precisely measured in test beam and it was verified with data from the full installed TileCal that this function could be used for all channels. The linear coefficients are optimized, using the autocorrelation matrix, to minimize the effect of the noise on the reconstructed quantities. The coefficients are functions of the phase of the pulse with respect to the 40 MHz electronic clock. The pulse shape function and the linear constants are stored in a dedicated database for calibration constants.

Offline reconstruction can be performed with iterations (Iterative Optimal Filtering) and without iterations (Non-Iterative Optimal Filtering). In the iterative method the quantities are calculated with an initial assumed value of the phase, equal to the time of the maximum of the  $S_i$ . In later iterations, the phase is taken to be equal to  $t$  from the previous iteration. In absence of out-of-time pile-up the iterative algorithm always converges to the true value of the phase with an accuracy better than 0.5 ns. The iterative method is slower and more sensitive to out-of-time pile-up. In the non-iterative method the phase used is the best signal phase known, retrieved from the database for each channel. In this case no further iterations are performed.

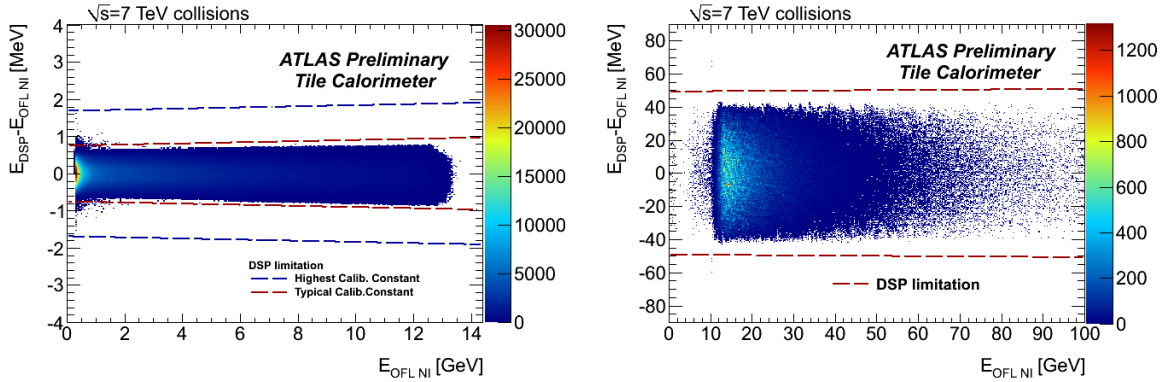
The Optimal Filtering reconstruction is also performed online by the DSP which perform the above linear combinations in real time. Above a trigger rate of 30 kHz the Optimal Filtering must be performed without iterations due to the processing time in the DSP exceeding the limit allowed by the data acquisition system. The DSP reconstruction is limited by use of fixed point arithmetic and the internal precision available to describe the linear coefficients and calibration factors. Since the division is a time consuming operation in the DSP the phase is computed using a look-up table with the energy reciprocal pre-defined and stored in the DSP memory.

### 4. Validation

The ROD can be configured to transmit both the reconstructed quantities and the raw data samples  $S_i$ . Due to the limited bandwidth digital samples are transmitted only for pulses above a programmable threshold (currently  $S_{max} - S_{min} > 5$  ADC counts). The raw data obtained in this way can be reconstructed using well tested offline algorithms and can be used to validate the reconstruction in DSP.

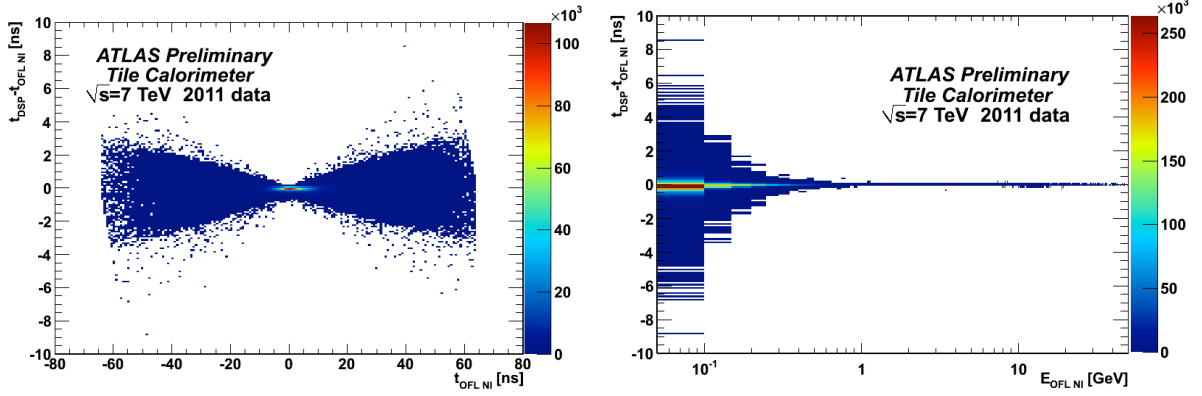


**Figure 1.** Left: Sketch of a typical Tile Calorimeter pulse shape with the ADC samples (dots) and the illustration of Optimal Filtering reconstructed quantities. Right: Relative difference between the energy reconstructed with DSP ( $E_{DSP}$ ) and offline Iterative Optimal Filtering method ( $E_{OFLI}$ ) as a function of the phase reconstructed by DSP ( $t_{DSP}$ ) in collision data at 7 TeV. There is a bias in the energy reconstructed online with Optimal Filtering method (OF Online) due to phase variation (circles). The bias can be reduced applying a second order correction using the phase of the pulse (squares). The vertical error bars correspond to the RMS of the distributions.

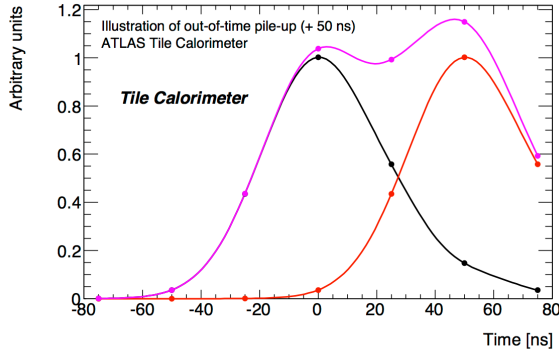


**Figure 2.** Absolute difference between the energy reconstructed with DSP ( $E_{DSP}$ ) and offline Non-Iterative Optimal Filtering method ( $E_{OFLNI}$ ) as a function of the energy reconstructed offline in collision data at 7 TeV in high gain (left) and low gain (right).

In order to validate the DSP results the consistency of online and offline implementations is checked. Figure 1 right panel shows performance of energy reconstruction with DSP in collision data at 7 TeV. In-time and out-of-time collision events populate the plot in order to evaluate the DSP reconstruction performance on a wide time window. Most of the pulses are in the time range  $[-5, 5]$  ns. The circle points show the relative difference between the energy reconstructed with DSP and offline with Iterative Optimal Filtering method. The variation in the phase of pulses leads to an underestimation of the amplitude reconstructed online. This bias is parametrized by second order polynomial and reduced thanks to an amplitude correction function of the phase. The square points show the relative difference after the correction. In the time range  $[-10, 10]$



**Figure 3.** Left: Absolute difference between phase reconstructed with DSP ( $t_{DSP}$ ) and offline with Non-Iterative Optimal Filtering method ( $t_{OFLNI}$ ) as a function of phase reconstructed offline in collision data at 7 TeV. Right: Absolute difference between phase reconstructed with DSP and offline with Non-Iterative Optimal Filtering method as a function of energy reconstructed offline ( $E_{OFLNI}$ ) in collision data at 7 TeV.

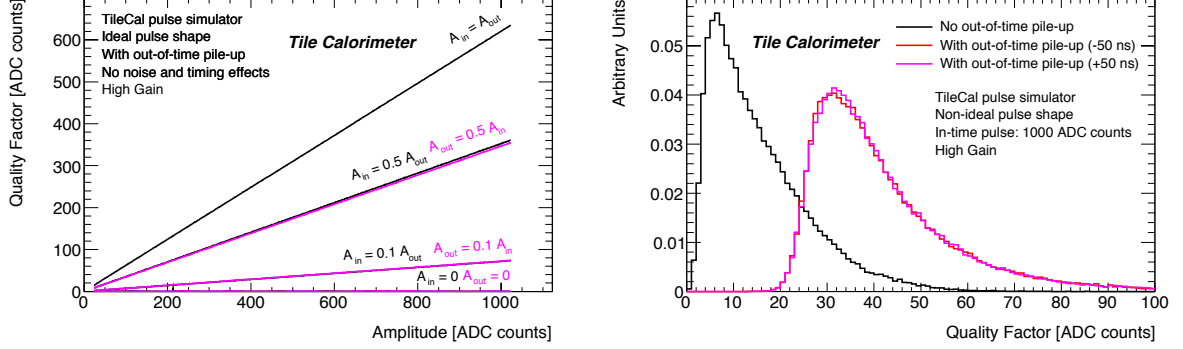


**Figure 4.** Illustration of out-of-time pile-up (+50 ns) in ATLAS Tile Calorimeter with pulse shapes obtained with the TileCal simulation [5].

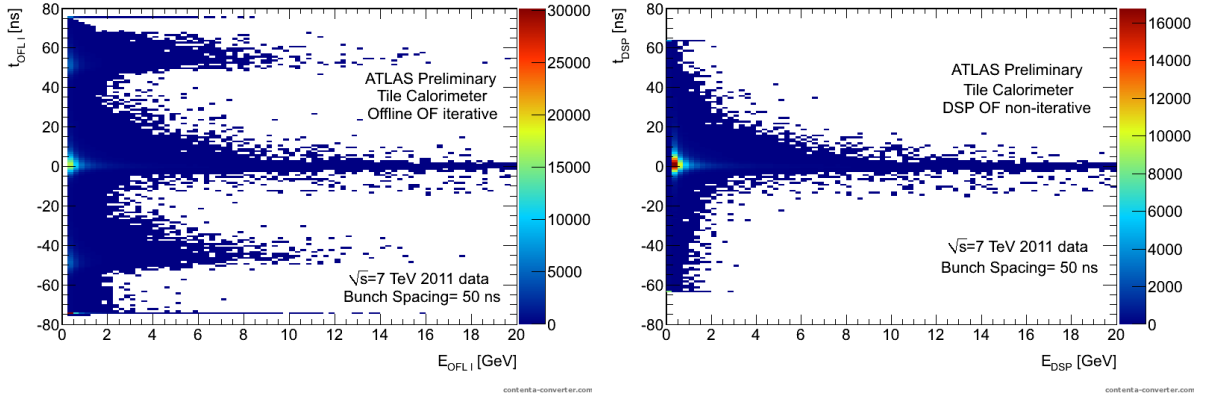
ns the average difference between the offline and online reconstruction, after the correction, is smaller than 1%.

Figure 2 shows the residuals after applying the parabolic correction between the energy reconstructed with DSP and offline with Non-Iterative Optimal Filtering method in high gain (left panel) and low gain (right panel) in collision data at 7 TeV. The performance is slightly energy dependent. The maximum expected difference due to fixed point arithmetic is proportional to the calibration constant ADC to MeV and therefore changes from channel to channel. The worst cases arise in a few PMTs with abnormal high voltage settings. The response needs to be amplified by a large factor to compensate for the gain deficit. In left panel of figure 2 the red dashed lines indicate the maximum expected precision for standard functioning channels of about 1 MeV and contain 99% of the channels while the blue lines indicate the expected precision for the highest calibration constant of about 2 MeV. For comparison the electronic noise RMS level is about 30 MeV. In right panel of figure 2 the blue lines indicate the precision of about 50 MeV. This is fully adequate in the range where signals are larger than approximately 8 GeV.

Figure 3 shows the absolute difference between phase reconstructed in DSP and offline with Non-Iterative Optimal Filtering as a function of offline reconstructed phase (left panel) and



**Figure 5.** Left: Quality factor as a function of the amplitude in different pile-up scenarios obtained with the TileCal pulse simulation.  $A_{in}$  ( $A_{out}$ ) is the amplitude of the in-time (out-of-time) pulse. The x-axis shows the amplitude in ADC counts before cell-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. Right: Normalized distributions of quality factor in TileCal simulator with non-ideal pulse shape. Generated amplitude of in-time pulse is 12 GeV. Amplitude of the out-of-time pulse follows the distribution in ZeroBias trigger with a cut on 34 ADC counts [5].



**Figure 6.** Left: The phase reconstructed offline with Iterative Optimal Filtering method as a function of the energy reconstructed offline in collision data at 7 TeV. Right: The phase reconstructed with DSP (Non-Iterative Optimal Filtering method) as a function of energy reconstructed with DSP in collision data at 7 TeV. A data sample with presence of out-of-time pile-up (bunch spacing 50 ns) is used.

energy (right panel) in collision data at 7 TeV. Since the same non-iterative algorithm is used online and offline the expected difference is due to fixed point arithmetic and the precision of the look up table (LUT) used in the DSP. The LUT effect is enhanced for larger phases but differences between phases reconstructed in DSP and offline are within 1.5 ns in the  $[-25, +25]$  ns range.

## 5. Out-of-time pile-up

Signal pulses coming from different LHC bunch crossing (bunch spacing of 50 ns) can be measured in the readout windows used of  $\pm 75$  ns. The out-of-time pile-up results in the

superposition of pulses shifted in time resulting in anomalous pulse shapes which can be detected thanks to large values of  $QF$  [5]. Figure 4 shows an illustration of an out-of-time pile-up pulse at +50 ns, in the case where the in-time and out-of-time pulses have the same amplitude.

Figure 5 left panel shows the dependence of the quality factor  $QF$  as a function of the in-time pulse amplitude  $A_{in}$  and the out-of-time pulse amplitude  $A_{out}$  for different values of the ratio between the in-time and out-of-time pulse amplitude. A Monte Carlo simulation is used for this study. Data samples are generated according to the expected pulse shape. The lines correspond to a linear fit to the mean value of the quality factor. It shows two important features, first that for a given ratio of  $A_{out}/A_{in}$ , the quality factor increases linearly with the amplitude of the in-time pulse, and second that the dependence on the amplitude  $A_{in}$  gets steeper when the ratio  $A_{out}/A_{in}$  gets closer to one. The worst case scenario occurs for in-time and out-of-time pulses of equal amplitude, in that case the quality factor becomes maximal. The introduction of an out-of-time pile-up pulse is equivalent to introducing a deviation between the ideal pulse shape and the real pulse shape.

Figure 5 right panel illustrates that for significant out-of-time pile-up pulses the distribution of quality factor is quite different in case of out-of-time compared to no out-of-time pile-up. A Monte Carlo simulation is used for this study. Data samples are generated according to the expected pulse shape with emulation of electronic noise, pulse shape and phase variation. There is a clear separation between the two cases. The effect of an out-of-time pulse at -50 ns is nearly equivalent to the effect of an out-of-time pulse at +50 ns. Based on these studies possible identify to select pile-up channels can be proposed.

Figure 6 shows the reconstructed phase as a function of energy reconstructed offline with Iterative Optimal Filtering method (left panel) and in DSP with Non-Iterative Optimal Filtering method (right panel) in collision data at 7 TeV. A run with train of bunches crossing every 50 ns was used. The iterative method is able to reconstruct signals generated by a different bunch crossings (peaks at 0 ns and  $\pm 50$  ns on left panel of figure 6). The non-iterative algorithm as implemented in the DSP uses a well defined phase of triggered event. The reconstructed phases correspond to in-time pulses (peak at 0 ns only on right panel of figure 6). Therefore, this algorithm is robust against out-of-time pile-up.

## 6. Conclusions

The TileCal online signal reconstruction performed in the DSP has been validated with the LHC collision data at 7 TeV reconstructed offline. The results are compatible with the expected differences between the fixed point arithmetic used in the DSP and the floating point arithmetic used for the offline reconstruction. Currently LHC operates with 50 ns bunch spacing causing out-of-time pile-up signals. The Non-Iterative Optimal Filtering method is to a certain extent robust against out-of-time signals. It is shown that the quality factor is very sensitive to differences between expected and real pulses in the detector and that the quality factor can be used to flag cells with presence of pile-up.

## References

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- [5] Clement C and Klimek P 2011 Identification of Pile-up Using the Quality Factor of Pulse Shapes in the ATLAS Tile Calorimeter *Proc. IEEE NSS MIC* (Valencia)