

# Energy reconstruction of the ATLAS Tile Calorimeter under high pile-up conditions using the Wiener filter

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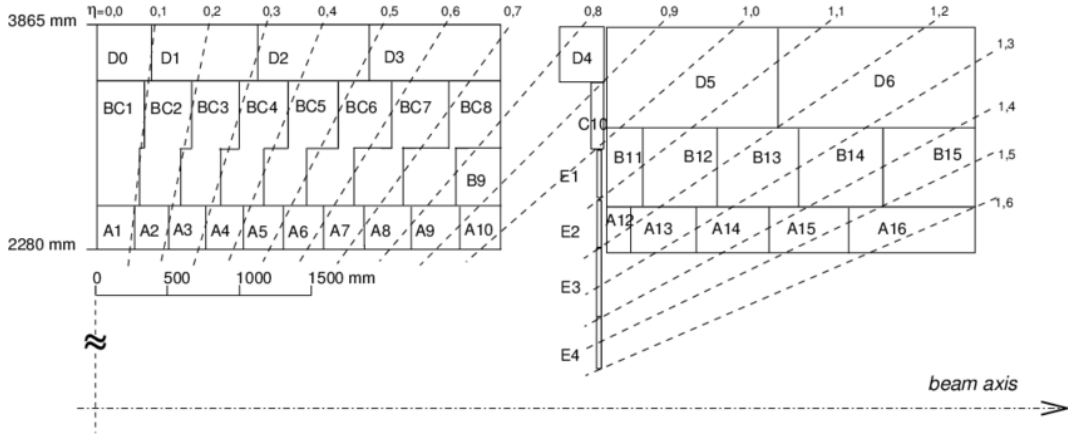
## **Abstract.**

The ATLAS experiment records data from the proton-proton collisions produced by the Large Hadron Collider (LHC). The Tile Calorimeter is the hadronic sampling calorimeter of ATLAS in the region  $|\eta| < 1.7$ . It uses iron absorbers and scintillators as active material. Jointly with the other calorimeters it is designed for reconstruction of hadrons, jets,  $\tau$ -lepton and missing transverse energy. It also assists in muon identification. The energy deposited by the particles in the Tile Calorimeter is read out by approximately 10,000 channels. The signal provided by the readout electronics for each channel is digitized at 40 MHz and its amplitude is estimated by an optimal filtering algorithm. The increase of LHC luminosity leads to signal pile-up that deforms the signal of interest and compromises the amplitude estimation performance. This work presents the proposed algorithm, based on the Wiener filter theory, for energy estimation in the Tile Calorimeter under high pile-up conditions during LHC Run 3. The performance of the proposed method is studied under various pile-up conditions and compared with the current optimal filtering method using proton-proton collision data.

## **1. Introduction**

The ATLAS [1] Tile Calorimeter (TileCal) [2] is a sampling device that uses steel as absorber material and scintillating tiles as active material [3] to provide precise measurements of hadrons,  $\tau$ -lepton, jets and missing transverse energy from the proton-proton collisions at the Large Hadron Collider (LHC) [4]. It comprises a central barrel and two extended barrels, the Extended Barrel A (EBA) and the Extended Barrel C, covering most central part of the ATLAS detector ( $|\eta| < 1.7$ ). The energy deposited by the particles is read out by approximately 5000 cells and 10000 channels, as most of the cells are composed of two read out channels. The TileCal is segmented in depth in three layers, as illustrated in Figure 1. An E layer, located only in the extended barrels, is composed of four scintillator plates per module.

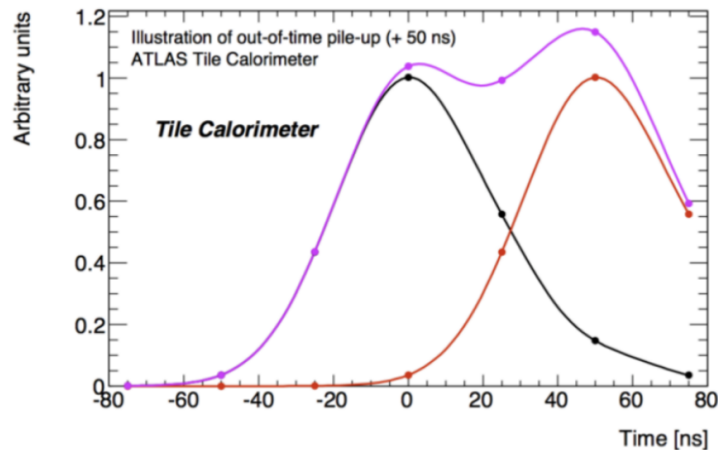
The light produced in the scintillating tiles for each cell is sent along optical fibers to the TileCal readout electronics [5], where it is converted into a digital signal at 40 MHz and its amplitude is estimated by an optimal filtering algorithm. Because of hardware limitations, the TileCal front-end electronics requires a simple and fast online energy estimation method, such as the Optimal Filter (OF) [6]. The OF method is the method currently used in TileCal. It assumes a single input signal with a well-defined shape embedded in a Gaussian electronic noise



**Figure 1.** TileCal cell segmentation for half barrel and one extended partition [7].

and it uses the deterministic pulse shape and the noise covariance matrix to calculate the filter weights.

The TileCal pulse shape is wider in time than LHC bunch spacing. In high occupancy channels, such as the ones in the E layer, adjacent collisions are therefore observed within the same readout window, causing signal pile-up. The pile-up deforms the signal of interest and compromises the amplitude estimation performance. Figure 2 illustrates the readout window with the resultant signal (magenta line) acquired by the front-end electronics. The pulse in black corresponds to the expected signal pulse shape, and the red line corresponds to an out-of-time signal. The pile-up effect is expected to be accentuated during LHC Run 3 in 2023, when the LHC luminosity is going to be increased.



**Figure 2.** Illustration of the pile-up effect in TileCal (magenta line). The pulse in black is the expected signal pulse shape, and the red line corresponds to an out-of-time signal [7].

This work presents a proposed algorithm, based on the Wiener filter, for energy estimation in the Tile Calorimeter under high pile-up conditions during LHC Run 3. Sections 2 and 3 describe the current TileCal energy estimation algorithm and the proposed estimation method. Section 4 shows the results using a proton-proton collision data set, where the Wiener Filter is

evaluated and its efficiency is compared with the current optimal filtering method. Finally, the conclusions are presented in Section 5.

## 2. TileCal energy estimation

The Optimal Filtering algorithm is the method used in ATLAS calorimeters for energy reconstruction. This technique uses the autocorrelation function of the noise samples to minimize the variance estimator in order to determine the time origin and the amplitude of the signal. The OF algorithm version presented here, named Optimal Filtering 2 (OF2) [6], is currently being used in TileCal for energy estimation. The method is based on a weighted sum of digitized samples. The estimate of the amplitude can be calculated as

$$\hat{A} = \sum_{i=1}^N s_i w_i \quad (1)$$

The vectors  $\mathbf{s}$  and  $\mathbf{w}$  correspond to the received ADC samples and the OF weights, respectively. The parameter  $N$  is the number of samples, which is fixed to  $N=7$  for TileCal.

The variance to be minimized can be calculated as:

$$\text{var}(\hat{A}) = \mathbf{w}^T \mathbf{C} \mathbf{w} \quad (2)$$

where  $\mathbf{C}$  is the background covariance matrix.

The minimization must be performed under some constraints:

$$\sum_{i=1}^N g_i w_i = 1 \quad (3)$$

$$\sum_{i=1}^N g'_i w_i = 0 \quad (4)$$

$$\sum_{i=1}^N w_i = 0 \quad (5)$$

where  $g_i$  is the TileCal normalized reference pulse shape vector and  $g'_i$  is its time derivative. The first constraint (Equation 3) was added to provide unbiased estimations, while both second and third constraints (Equations 4 and 5) assure the algorithm immunity against phase and baseline fluctuations.

With these conditions and using the Lagrange multipliers method, the weights  $w_i$  can be calculated by solving the following system:

$$\begin{pmatrix} C_{1,1} & \cdots & C_{1,7} & -g_1 & -g'_1 & -1 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \\ C_{7,1} & \cdots & C_{7,7} & -g_7 & -g'_7 & -1 \\ g_1 & \cdots & g_7 & 0 & 0 & 0 \\ g'_1 & \cdots & g'_7 & 0 & 0 & 0 \\ 1 & \cdots & 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} w_1 \\ \vdots \\ w_7 \\ \lambda \\ \xi \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad (6)$$

where  $\lambda$ ,  $\xi$ ,  $v$  are the Lagrange multipliers.

The covariance matrix  $\mathbf{C}$  can be written as a diagonal matrix if the noise can be modeled as an uncorrelated Gaussian process. The weights are calculated offline and implemented on

Digital Signal Processors (DSPs), which provide the online amplitude estimation for the selected events.

The pile-up introduces higher-order statistics to the noise (non-Gaussian), and the signal model used by OF2 may no longer be reliable. Hence, its performance is significantly degraded, especially for the TileCal E cells where the occupancy is high. Therefore, a different method, described in the next section, has been proposed to improve the TileCal energy estimation under such harsh conditions.

### 3. Proposed energy estimation method

The proposed method is based on the Wiener-Hopf filter [8]. This technique makes use of both signal and noise statistical properties to come up with a set of optimum weights that estimates the signal from a noisy data stream. Therefore, the weights are calculated with the aim of minimizing the expected value of the squared error, given by

$$J = E[(\hat{A} - A)^2] \quad (7)$$

Using the linear model for  $\hat{A}$  given by the Equation 1, the error will be minimized when the derivative of function J is equal to zero. The algebraic solution leads to the following equation:

$$\mathbf{w}\mathbf{R} = \mathbf{p} \quad (8)$$

where  $\mathbf{w}$  corresponds to the filter weights, the matrix  $\mathbf{R}$  is the autocorrelation matrix for the input signals, and the vector  $\mathbf{p}$  corresponds to the cross-correlation matrix between the input signals and the vector of vector of desired amplitude values.

Equation 8 can be rewritten as

$$\mathbf{w} = \mathbf{R}^{-1}\mathbf{p} \quad (9)$$

In order to absorb bias (mean of the error), an element equal to 1 can be added to each input signal, as the last element. Thus, the amplitude estimate by the proposed algorithm is given by

$$\hat{A} = \sum_{i=1}^N s_i w_i + w_{N+1} \quad (10)$$

where the vector  $\mathbf{s}$  corresponds to the received ADC samples and  $w_{N+1}$  is the bias that is subtracted from each estimate.

## 4. Results

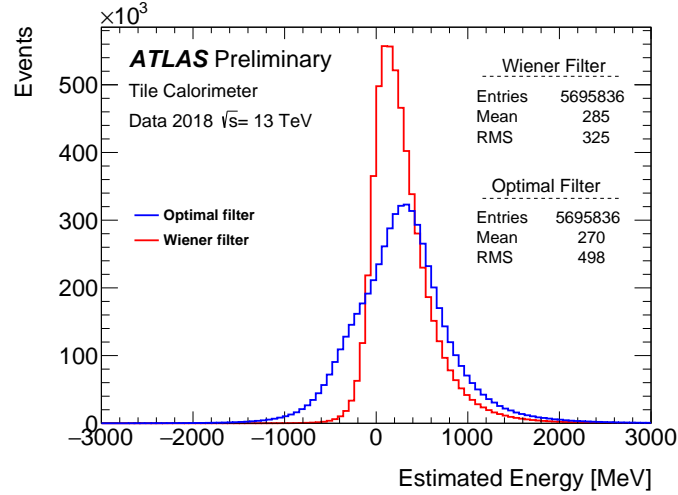
This section presents the data set used and the algorithm's performance, as evaluated through the comparison between the energy distributions estimated by both OF2 and Wiener methods.

### 4.1. Data set

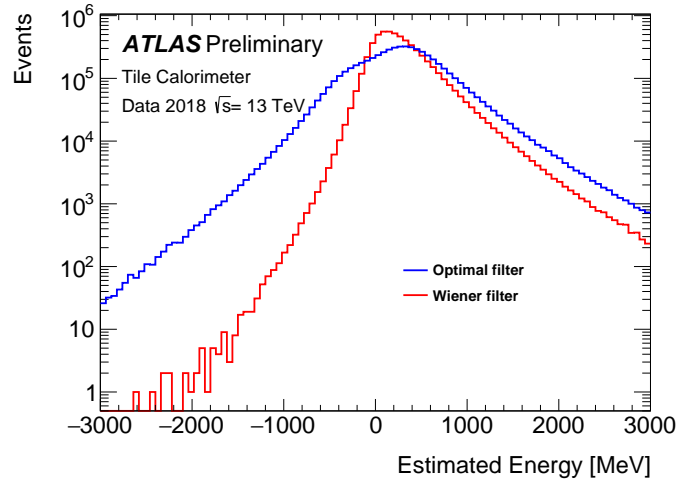
The data set consists of approximately 5,700,000 events for the TileCal E4 ( $1.4 < |\eta| < 1.6$ ) cell, which is one of the highest occupancy cells in TileCal. The events are proton-proton collision data from a special high- $\mu$  run with peak  $\langle \mu \rangle = 90$  at 13 TeV collected in October 2018. A total of 64 modules in  $\phi$  are used while known pathological channels were excluded.

#### 4.2. Performance evaluation

The OF2 and Wiener filter were applied to the data set previously described. Since the events used in this studies are from proton-proton collision data, it is expected the energy estimation will not to be centered at zero, but the number of negative-energy cells should be as small as possible. The distribution of the EBA E4 ( $1.4 < |\eta| < 1.6$ ) Tile calorimeter cells energy (in MeV), in linear scale (a) and logarithmic scale (b), estimated by the Wiener filter and OF2 algorithms is illustrated in Figure 3.



(a)



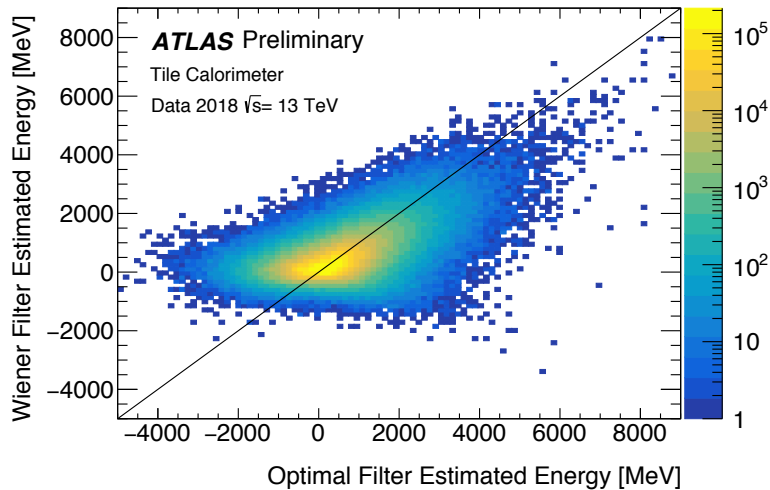
(b)

**Figure 3.** Distribution of the EBA E4 ( $1.4 < |\eta| < 1.6$ ) Tile calorimeter cells energy (in MeV) estimated by the Wiener filter and OF2 algorithms, in linear scale (a) and logarithmic scale (b) [7].

It can be noticed that the energy distribution estimated by the Wiener Filter has a smaller negative tail compared with the one estimated by the OF2. This negative tail corresponds to the out-of-time pileup that the OF2 algorithm is not able to deal with. Therefore, the Wiener Filter shows the best performance in terms of out-of-time pileup suppression.

Figure 4 shows the correlation between the EBA E4 Tile calorimeter cells energy (in MeV)

estimated by the Wiener and the OF2 algorithms. As expected, the OF2 shows a greater dispersion in the negative region of the correlation graph, confirming the predominant efficiency of the Wiener Filter method to reduce the out-of-time pile-up. Although the Wiener Filter has superior performance compared with OF2, it does not treat noise optimally, since higher order statistics are not absorbed (linear method). However, the Wiener method is simple and fast to operate online and offline, which makes it very attractive to be implemented in TileCal.



**Figure 4.** Correlation between the EBA E4 ( $1.4 < |\eta| < 1.6$ ) Tile Calorimeter cells energy (in MeV) estimated by the Wiener Filter and by the Optimal Filter algorithms [7].

## 5. Conclusions

This work presented a performance study of a proposed algorithm, namely the Wiener filter, to estimate energy in the ATLAS Tile Calorimeter under high pile-up conditions during LHC Run 3. The results show that the Wiener Filter reduces the negative tail due to the out-of-time pileup in the energy distribution reconstructed using proton-proton collision data in EBA E4 Tile calorimeter cells. The bias constant, inserted in the filter design, makes the filter unbiased with respect to luminosity variation. Therefore, the Wiener Filter approach has shown to be a promising alternative to estimate the energy in high occupancy cells.

## Acknowledgments

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