PUBLISHED BY INSTITUTE OF PHYSICS PUBLISHING AND SISSA

RECEIVED: *October 16, 2006*
REVISED: *December 13, 2006*
ACCEPTED: *January 18, 2007*
PUBLISHED: *February 12, 2007*

**TECHNICAL REPORT**

# Algorithms for the ROD DSP of the ATLAS Hadronic Tile Calorimeter

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ABSTRACT: In this paper we present the performance of two algorithms currently running in the Tile Calorimeter Read-Out Driver boards for the commissioning of ATLAS. The first algorithm presented is the so called Optimal Filtering. It reconstructs the deposited energy in the Tile Calorimeter and the arrival time of the data. The second algorithm is the MTag which tags low transverse momentum muons that may escape the ATLAS muon spectrometer first level trigger.
Comparisons between online (inside the Read-Out Drivers) and offline implementations are done with an agreement around 99% for the reconstruction of the amplitude using the Optimal Filtering algorithm and a coincidende of 93% between the offline and online tagged muons for the MTag algorithm. The processing time is measured for both algorithms running together with a resulting time of 59.2 $\mu s$ which, although above the 10 $\mu s$ of the first level trigger, it fulfills the requirements of the commissioning trigger ($\sim$ 1 Hz). We expect further optimizations of the algorithms which will reduce their processing time below 10 $\mu$s.

KEYWORDS: Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases); Data processing methods; Digital signal processing (DSP); Analysis and statistical methods.

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## Contents



## 1. Introduction

The ATLAS detector (see figure 1) is a general purpose experiment designed to exploit the physics discovery potential of the next proton-proton collider at CERN, the Large Hadron Collider (LHC).

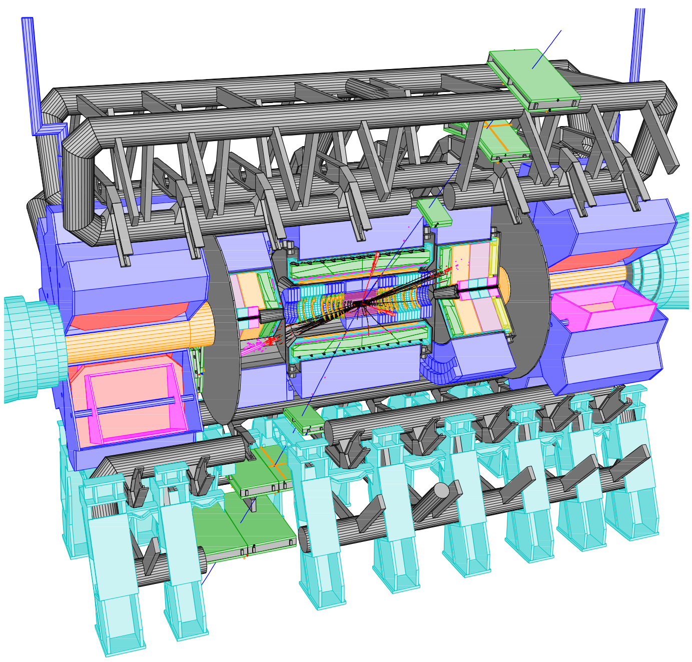

**Figure 1.** ATLAS detector.

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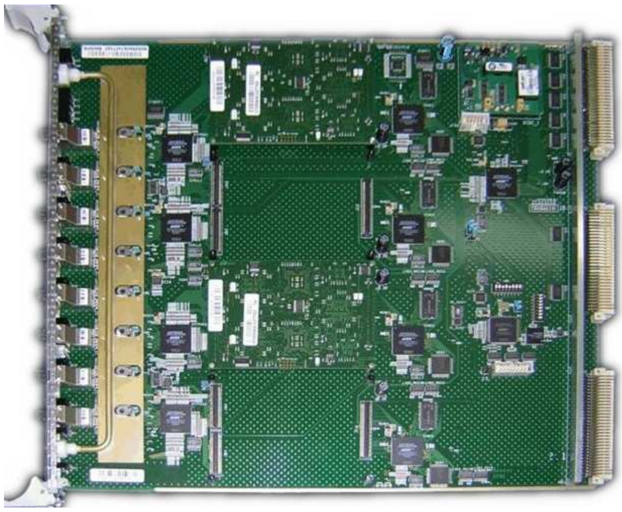

**Figure 2.** TileCal Read-Out Driver board.

The ATLAS hadronic Tile Calorimeter (TileCal) [1] is a sampling calorimeter made out of iron as absorber material and plastic scintillating plates as active medium. The light produced in the scintillating tiles is collected through wavelength shifting fibers and read-out by photomultipliers. The analogue electrical signal of the photomultipliers is digitized in several samples of 10 bits taken each 25 ns, the latency between two consecutive LHC bunch crossings. Therefore, the $\sim 10\,000$ photomultipliers of the calorimeter produce up to $\sim 164$ Gbps of data that is read-out by the TileCal back-end electronics. This data rate is set by the interface cards which are part of the front-end electronics. These cards output up to 16 bits at 40 MHz in two redundant fibers.

The main element of the back-end electronics is the Read-Out System [2]. This system is composed of 32 Read-Out Driver (ROD) boards (see figure 2). The RODs are based on a custom 9U VME64x board equipped with up to four Processing Units (PUs) which are pluggable mezzanine boards. The PUs process in pipeline mode the data coming from the TileCal front-end electronics to feed the second level trigger with information of energy deposited in the calorimeter and other relevant quantities.

The PUs are equipped with the TMS320C6414x$^{\mathrm{TM}}$ Digital Signal Processors (DSPs) of Texas Instruments in order to execute reconstruction algorithms in real time. The latency of the first level trigger is $10\mu$s which sets stringent requirements on the processing time of the reconstruction algorithms. The choice of DSPs over similar devices, e.g FPGAs, is justified by several reasons. First, the DSPs can apply different algorithms depending on the trigger type of the data: physics, pedestal, laser, charge injection... second, they can be programmed in high level languages, such as C language, which are simpler to maintain and to adapt to the detector requirements. This is needed because the selected device should be flexible to change the reconstruction algorithms depending on the LHC conditions which may vary along its life. Moreover, the commercial DSPs implement easily MAC (Multiply-Accumulative) instructions which are the base of standard data filtering algorithms. They have also an internal local memory where input and output data is stored using a circular buffer. Another useful feature of the DSPs is the access through a host port interface and



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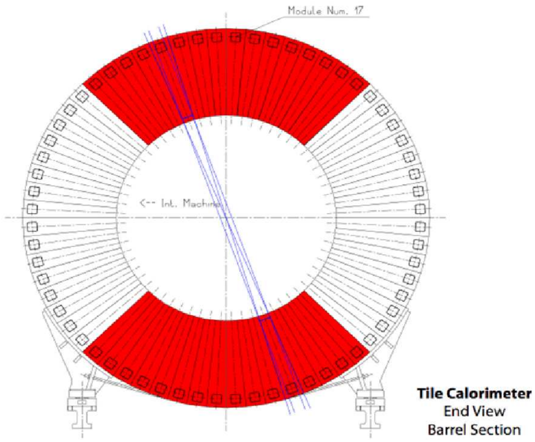


**Figure 3.** TileCal cosmic muon trigger.

a serial port, which allows us to re-configure the DSP at running time, read histograms from the device and load new calibration constants. Furthermore, the PUs of the Read-Out Drivers are also equipped with FPGAs which perform pre-processing and quality checks of the data.

In this paper we present the performance of two algorithms implemented in the DSPs. We propose an algorithm for the energy reconstruction, the so called Optimal Filtering (OF) [3], which reconstructs the amplitude and time of the photomultiplier signal by means of weighted sums of the digital samples. Additionally, we propose a fast muon tag algorithm, named MTag, to identify low transverse momentum ($p_T$) muons that may escape the muon spectrometer. The tagging of these muons helps to trigger interesting B-physics channels.

Both algorithms have been tested online in the ATLAS commissioning with cosmic rays runs. The performance of both algorithms and the processing time required is presented in this paper.

## 2. Experimental setup

Until 2007 the ATLAS detector is being commissioned in the ATLAS cavern. During this period all subdetectors will be progressively integrated into the final ATLAS Trigger and Data Acquisition system.

During 2005 and 2006, TileCal has been fully assembled in the underground experimental hall UX15. A program of cosmic rays data acquisition has been planned for TileCal in standalone mode. The trigger signal was provided by the TileCal trigger electronics, using custom coincidence boards which take as input up to 192 TileCal trigger tower analog signals [4]; half in the top part and half in the bottom part. A signal coincidence in the upper and lower part of the calorimeter triggers the data acquisition (see figure 3).

The cosmic muon trigger is not synchronized with the data acquisition system and thus the arrival time of the events follows a distribution in a wide time window of up to 200 ns.

Our goal is to satisfactorily reconstruct the energy deposited by the muons and to check the online performance of the MTag algorithm.

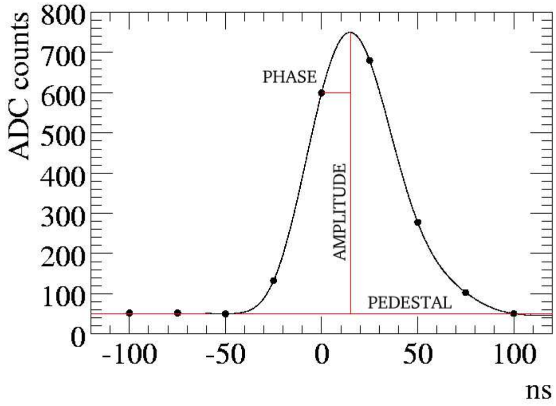


**Figure 4.** Definition of amplitude, phase and pedestal.

## 3. Algorithms

Both the Optimal Filtering and the MTag algorithms are implemented in the ROD DSPs which are the Texas Instruments TMS320C6414x$^{\text{TM}}$ DSPs. They are fixed-point processors which perform up to 32-bit data MAC instructions. Their CPU contains only multiplier and ALU units; therefore divisions are not allowed and they are implemented as shift instructions, to divide in powers of 2, and with the use of 16-bit look-up tables to implement more complex operations. Consequently, the algorithms inside the DSP should reach a compromise between simplicity and accuracy.

### 3.1 Optimal filtering

The Optimal Filtering algorithm reconstructs the amplitude and phase of a digitized signal by a linear combination of its digital samples (see eq. (3.1) and eq. (3.2)):

$$A = \sum_{i=1}^{n} a_i S_i, \tag{3.1}$$

$$\tau = \frac{1}{A}\sum_{i=1}^{n} b_i S_i, \tag{3.2}$$

where $S_i$ represents the digital sample $i$ and $n$ is the total number of samples. We define the pedestal as the baseline of the signal. The amplitude, $A$, is the distance from the pedestal to the peak and the phase, $\tau$, is defined as the time between the central sample and the peak of the pulse (see figure 4).

The weights, $\boldsymbol{a}$ and $\boldsymbol{b}$, are obtained from the pulse shape of the photomultipliers and the noise autocorrelation matrix. The process to calculate them minimizes the effect of the noise in the amplitude and time reconstruction [5]. They are calculated to avoid pedestal subtraction in the samples.

These weights are estimated assuming small phases, which means that increasing $\tau$ the quality of the reconstruction decreases. This occurs during the TileCal commissioning since the data is not synchronized with the trigger clock. In order to properly calculate the energy deposited in



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the calorimeter during the commissioning phase we introduce iterations in the OF algorithm to estimate the arrival time of the data, although this increases the processing time. Anyway, the expected trigger rate is $\sim$ 1 Hz which reduces the time restrictions.

The initial phase ($\tau_0$) is estimated as the time between the maximum and the central sample in units of 25 ns, then the amplitude and phase are calculated in each iteration as:

$$A_k = \sum_{i=1}^{n} a_i \Big|_{\tau_{k-1}} S_i, \tag{3.3}$$

$$\tau_k = \frac{1}{A_k} \sum_{i=1}^{n} b_i \Big|_{\tau_{k-1}} S_i, \tag{3.4}$$

where $k$ is the iteration index and runs from 1 to 3. It is being observed that the amplitude converges with three iterations.

Weights calculated for phases between -80 ns and 80 ns are stored in the ROD DSPs memory in order to use them during the iteration mechanism and to scope the time window of the arrival of the events. The result of the third iteration, $A_3$ and $\tau_3$, is used as input by the MTag algorithm.

### 3.2 Muon tag

The primary goal of the MTag algorithm [6, 7] is to search for muons taking into account the energy deposited in each layer of TileCal. Figure 5 shows the TileCal cell structure with 3 layers (A, BC and D cells) and with a projective geometry in $\eta$. In order to identify the muons, the typical energy deposition in each cell is limited by a high and a low threshold:

$$thr_i^{\text{low}} \leq E_i \leq thr_i^{\text{high}} \quad i = 1,2,3 \tag{3.5}$$

If this condition is fulfilled in each of the 3 layers with a projective pattern in $\eta$, the muon is tagged. In order to be efficient on events in where the muon loses a considerable fraction of its energy in one of the layers, muons are also tagged if eq. (3.5) is fulfilled in two layers while in the third layer the energy deposition is above the low threshold.

The low energy threshold is meant to cut electronic noise and minimum bias pile-up events. In this algorithm, all cells have the same low energy threshold values. The high energy thresholds are meant to delimit the maximum muon energy deposition while eliminating hadronic showers and tails. These thresholds are determined for each individual cell, depending on the pseudorapidity of the muon trajectory.

The output of the MTag algorithm is the number of muons inside a TileCal module and the pseudorapidity where they were found.

## 4. Results

Since July 2006 several runs of cosmic rays were acquired and reconstructed online in the ROD DSPs. Figure 6 shows the histogram of the reconstructed amplitude in the ROD DSPs (online) and the offline reconstruction for all the operative channels during the acquisition. The large tail corresponds to energy deposited by cosmic muons, while the peak around zero corresponds mostly to electronic noise. The agreement between both reconstructions is around 99% for amplitudes

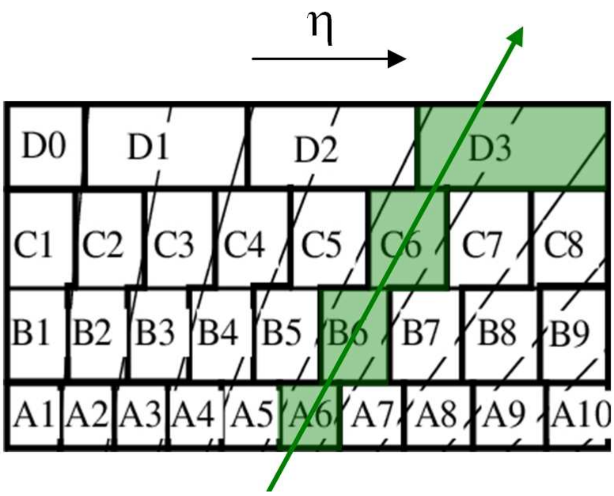


**Figure 5.** Muon path going through a tower in $\eta$.

above $3\sigma$ of the noise, see figure 7. For amplitudes smaller than $3\sigma$ the difference between the online and offline reconstruction is expected to be larger due to the low signal to noise ratio and the use of the look-up table. Eq. (3.4) shows that in order to calculate the phase we need to divide by the amplitude. In the ROD DSPs, this implementation is carried out by the use of a look-up table which degrades the resolution of the phase for amplitudes close to zero.

Figure 8 shows the online and offline phase reconstruction for amplitudes larger than $3\sigma$. The relative error of the phase reconstruction is larger than the relative error of the amplitude. This is due again to the use of look-up tables. The difference for amplitudes above $3\sigma$ of the noise is around 0.25 ns, see figure 9.

Figure 10 shows the energy distribution of the online tagged muons in the ROD DSPs using Optimal Filtering for the energy reconstruction. The results are compared with the distribution of the offline MTag algorithm using the Fit method for the energy reconstruction which is the standard offline algorithm. Even though the energy taken as input of the offline MTag is slightly different from the online, up to 93% of the offline tagged muons are also tagged in the ROD DSPs.

The processing time of the online algorithms is a very important issue, since the latency of the first level trigger is 10 $\mu$s. Although our future goal is to achieve a processing time below 10 $\mu$s, the cosmic muon acquisition rate is around 1 Hz and during the first years of the LHC operation the first level trigger rate will be set to 50 KHz.

The DSP processing time has been measured in our laboratory (see table 1). This time is estimated with a scope. The scope measures the time between the start of the reconstruction routine, when a pin in the DSP is set up, and the end of the routine, after sending the reconstructed quantities and the original samples, when the pin goes down. For every channel there is a threshold below which the algorithm does not implement iterations. Therefore, the processing time changes event by event. The time shown in table 1 is an upper limit of the processing time. This time is consistent with the estimated time provided by the simulation using the Code Composer Studio software from Texas Instruments. It has being also verified by the observation of busies when changing the input

| Algorithm | Time ($\mu$s) |
|---|---|
| *OF* | 54.4 |
| *OF and MTag* | 59.2 |

**Table 1.** ROD DSP processing time.

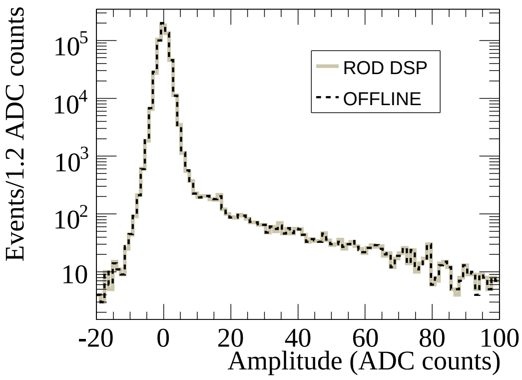


**Figure 6.** Histogram of the reconstructed amplitude using Optimal Filtering, offline (black dashed line) and inside the ROD DSPs (grey solid line).

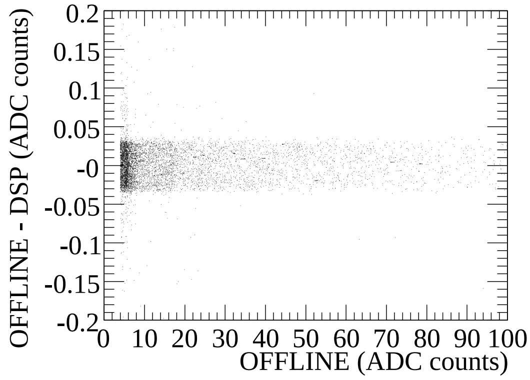


**Figure 7.** Scattered plot of the difference between the online and offline amplitude reconstruction versus the offline amplitude.

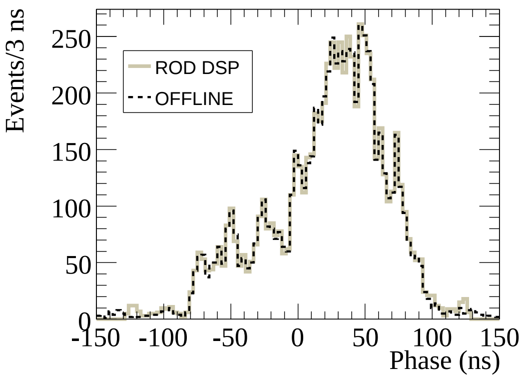


**Figure 8.** Histogram of the reconstructed phase using Optimal Filtering, offline (black dashed line) and inside the ROD DSPs (grey solid line).

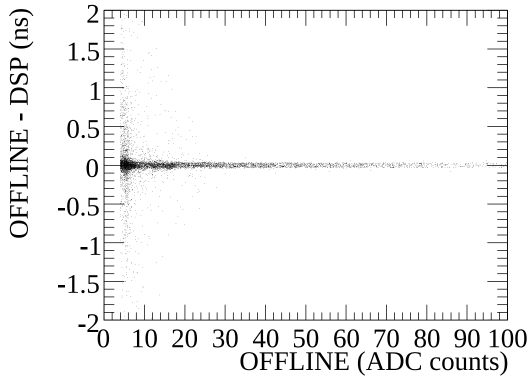


**Figure 9.** Scattered plot of the difference between the online and offline phase reconstruction versus the offline amplitude.

data rate. Globally these times are well above to 10 $\mu$s, however, the current implementation is coded in C and a great improvement is expected after migrating to assembler. Furthermore, the OF algorithm is adapted to the commissioning conditions and makes use of iterations. Nevertheless, in the final configuration, when timing is fixed with the LHC clock no iterations will be needed and the processing time will be reduced.

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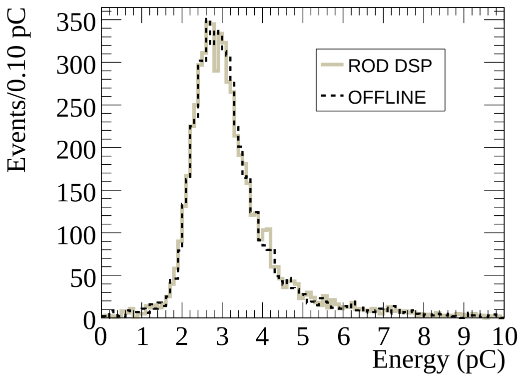


**Figure 10.** Histogram of the energy distribution of the tagged muons, offline (black dashed line) and inside the ROD DSPs (grey solid line).

## 5. Conclusions

Since July 2006 the Optimal Filtering and the MTag algorithms are being tested within the ATLAS commissioning environment. The results of their implementation in the ROD DSPs (online) and offline are shown. For the Optimal Filtering algorithm the agreement with the offline amplitude reconstruction is better that 99%. Concerning the phase reconstruction, differences from offline around 0.25 ns are shown for events with amplitudes larger than $3\sigma$ of the noise. The decrease of the online resolution for small amplitudes is due to the use of look-up tables in order to implement the division by the amplitude in the phase reconstruction. The result of the MTag algorithm analysis shows that up to 93% of the offline tagged muons are also tagged in the ROD DSPs, even though the reconstruction algorithms are different.

The processing time was also measured for both algorithms running together with a result of 59.2 $\mu$s which fulfills the requirements of the ATLAS commissioning which is $\sim 1$ Hz. In a close future our goal is to reach 10 $\mu$s which is the requirement of the ATLAS first level trigger.

## Acknowledgments

The authors acknowledge the help of Oleg Solovyanov, Giulio Usai, Sasha Solodkov, Tomas Davidek and the whole TileCal community.

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