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Quality factor analysis and optimization of digital filtering signal reconstruction for liquid ionization calorimeters

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ABSTRACT

The Optimal Filtering (OF) reconstruction of the sampled signals from a particle detector such as a liquid ionization calorimeter relies on the knowledge of the normalized pulse shapes. This knowledge is always imprecise, since there are residual differences between the true ionization pulse shapes and the predicted ones, whatever the method used to model or fit the particle-induced signals. The systematic error introduced by the residuals on the signal amplitude estimate is analyzed as well as the effect on the quality factor provided by the OF reconstruction. An analysis method to evaluate the residuals from a sample of signals is developed and tested with a simulation tool. The correction obtained is showed to preserve the original amplitude normalization, while restoring the expected χ^2-like behavior of the quality factor.

1. Introduction

The signals arising from the ATLAS electromagnetic calorimeter (EMC) [1] are shaped by a bipolar filter, then sampled every 25 ns at the LHC bunch crossing frequency and stored in analog buffers. Upon a positive decision from the level-1 trigger, a limited number of these samples (typically 5) are digitized and acquired. The amplitude and timing information of the shaped signals are determined combining the signal pulse samples with a digital filtering technique commonly called Optimal Filtering (OF) [2]: this method is optimized to minimize the noise contribution to the variance of the reconstructed signal amplitude, while guaranteeing that the latter is an unbiased estimator of the true amplitude.

Alongside the amplitude and timing information, the OF reconstruction is designed to produce a quality factor that should allow the discrimination of pathological signals from regular ones. The normalized OF quality factor obtained from regular signals follows a standard χ^2 distribution, while spurious signals generate large quality factor values: these signals could in principle be identified and rejected with a cut on this quantity.

The computation of the Optimal Filtering Coefficients (OFCs) for a given readout cell requires the knowledge of the signal pulse shape and of the (thermal and pileup) noise time autocorrelation [2]. While the latter can be directly measured from dedicated noise calibration runs and minimum bias events, several different approaches have been proposed to predict the ATLAS EMC ionization pulse shapes and their relative amplitudes with respect to the calibration signals used to probe the detector readout properties [3–6]. The precision of these pulse prediction methods is quoted in terms of the difference between the predicted ionization signal and the observed one, the two pulses being normalized to the same amplitude. The vector of differences computed for each digitized sample is commonly called the *residual* vector (defined in Eq. (1)): an accurate prediction method is usually quoted to lead to a difference $<1\%$ at the sample closest to the signal peak, and always between $\pm 2\%$ for the neighboring samples [3–6].

Assuming that such a precision is achieved for the readout cells of the ATLAS EMC using a given pulse prediction scheme, this work aims to study how the unavoidable presence of the residuals systematically affects the signal amplitude reconstruction and its noise variance (Section 4), as well as the relative quality factor distribution, thus impairing the discriminating power of the latter (Section 5).

A technique to optimize the quality factor without spoiling the initial reconstructed amplitude normalization is developed and tested on a reference cell for different possible distributions of the amplitude, which is proportional to the deposited energy. The same technique proves to be a powerful tool to extract from data the ionization pulse shape (up to a normalization factor) when no previous knowledge—even approximate—of it is available (Section 6).

This technique has been developed in the framework of the ATLAS EMC, but it holds for any other detector readout system

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that exploits the OF reconstruction of multiple-sampled signals (e.g. the ATLAS Tile hadronic calorimeter [7]).

2. Notation and nomenclature

In the following a matricial notation will be used in all calculations, N_{samples} being the number of signal samples digitized during the data acquisition, thus the typical size of all vectors and matrices:

$\mathbf{A}$	matrix of size $N_{\text{samples}} \times N_{\text{samples}}$
A_{ij}	(i,j)-th entry of matrix $\mathbf{A}$
$\mathbf{a}$	vector of size N_{samples}
a_i	i-th entry of vector $\mathbf{a}$
$\mathbf{A}^{-1}$	inverse matrix
$\mathbf{A}^{\mathrm{T}}$	transposed matrix
$\mathbf{a}^{\mathrm{T}}$	transposed vector
a	scalar

The following nomenclature is used:

h vector of samples of normalized observed ionization signal
g vector of samples of normalized predicted ionization signal
g′ vector of samples of normalized predicted ionization signal derivative
a vector of amplitude OFCs computed from **g** (and **g′**, if time constraint is included [2])
b vector of time OFCs computed from **g** and **g′**, if time constraint is included
r vector of pulse residuals:

$$\mathbf{r} = \mathbf{h} - \mathbf{g} \tag{1}$$

s vector of observed ionization signal samples for a given pulse amplitude A:

$$\mathbf{s} = A\mathbf{h} + \mathbf{n} \tag{2}$$

n vector of noise contributions to signal samples, having the properties:

$$\langle \mathbf{n} \rangle = \vec{0} \tag{3}$$

$$\langle \mathbf{n}\mathbf{n}^{\mathrm{T}} \rangle = \mathbf{C} \tag{4}$$

C noise covariance matrix:

$$\mathbf{C} = \mathbf{C}^{\mathrm{T}} \tag{5}$$

$$\mathbf{C} = \sigma_n^2 \mathbf{R} \tag{6}$$

R weight matrix, built from the noise autocorrelation function:

$$(\sigma_n^2 \mathbf{R})^{-1} = \frac{1}{\sigma_n^2}\mathbf{R}^{-1} \tag{7}$$

I identity matrix

3. Numerical examples

All the equations derived in this work are illustrated using a simulation tool that can generate pulses **s** for a given signal **h**, noise autocorrelation **R** and width σ_n, and a chosen distribution of amplitudes A. The tool computes OFCs **a** (and **b**) from a given pulse prediction **g** and noise autocorrelation $\mathbf{R}_{\text{OFC}}$ (not necessarily equal to the signal noise autocorrelation), and applies them to the generated samples to obtain the corresponding distribution of amplitude estimates $\tilde{A}$ (and time estimates τ), and the relative quality factors (defined below in Section 5.1).

The test signals **h** and **g** (and their residuals **r**) used in the simulations are plotted in Fig. 1: they correspond to ionization pulse predictions used during the ATLAS EMC Barrel commissioning operations in 2007, namely to the ones corresponding to the middle compartment cells located[1] at $[\eta_{\text{cell}}, \phi_{\text{cell}}] = [20, 50]$ (**h**) and $[\eta_{\text{cell}}, \phi_{\text{cell}}] = [20, 51]$ (**g**). They have been explicitly chosen to be very similar, in order to mimic an optimal situation in which the pulse prediction largely satisfies the precision criteria mentioned in Section 1.

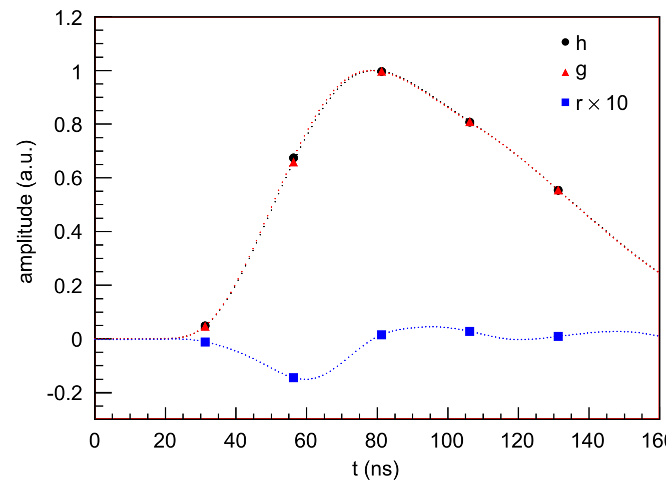

Fig. 1. Signals **h** and **g** and their residuals **r** (magnified by a factor 10) used in the numerical examples.

Table 1
Numerical values used in the simulations.

i	h_i	g_i	r_i	R_{0i}	a_i	b_i
0	0.04761	0.04873	−0.00111	1	0.14516	−7.2531
1	0.65923	0.67365	−0.01442	0.07108	0.22650	−26.9503
2	0.99769	0.99613	0.00156	−0.15330	0.38105	9.1090
3	0.80987	0.80709	0.00279	−0.29747	0.33019	5.9919
4	0.55451	0.55357	0.00095	−0.10336	0.35092	8.3074

The numerical examples correspond to the fixed pulse phase illustrated in Fig. 1, that corresponds to the typical EMC data taking condition at LHC, when $N_{\text{samples}} = 5$ and the signals are digitized so that the third sample is located near the pulse maximum ± 2 ns. The actual values used in the simulations are tabulated in Table 1.

Fig. 2 shows the values of the thermal noise autocorrelation function used to generate the noise affecting the pulses **s**. This is carried out by building the matrix **R** as a Toeplitz matrix based on the relevant autocorrelation function, which in this case was measured in high gain from middle cell at $[\eta_{\text{cell}}, \phi_{\text{cell}}] = [20, 50]$ during the ATLAS EMC Barrel commissioning operations in 2007. The matrix $\mathbf{R}_{\text{OFC}}$, used for computing the OFCs, is based on the measured autocorrelation function from a neighboring cell at $[\eta_{\text{cell}}, \phi_{\text{cell}}] = [20, 51]$. The two autocorrelation functions are quite similar, and previous studies have shown that the residuals obtained are insensitive to details of the autocorrelation function. We thus use $\mathbf{R}_{\text{OFC}}$ and **R** interchangeably. A noise width $\sigma_n = 5$ ADC counts is used, corresponding to a typical value for a EMC Barrel middle compartment in high gain.

[1] The position of ATLAS EMC readout cells is specified by using indexes corresponding to the local granularity in pseudo-rapidity η and azimuthal angle ϕ [1]. In the case of the middle compartment this is $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, implying:

$$\eta = 0.025(\eta_{\text{cell}} + 0.5) \tag{8}$$

$$\phi = 0.025(\phi_{\text{cell}} + 0.5) \tag{9}$$