Matched DDWT ROI Compression Engine for the Imaging Particle Detector

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Abstract: A new multirate DDWT (Double Density Wavelet Transform) matched filter ROI (region of interest) processor for the ICARUS (Imaging Cosmic And Rare Underground Signals) particle detector [Amerio(2004)] has been designed. The ROI extraction engine is based on matched and unmatched Wiener filtering using coupled DWT and DDWT processing. High through-put image-like ICARUS detector data (160MBps data rate per crate) is able to be compressed 600 times using multi-stage compression with ROI extraction. The 32-channel (160MBps data rate) processor has been fully implemented in a low cost FPGA device thanks to Fast Integer Arithmetic Wavelet Transform (FIAWT) [Półchłopek(2006)] algorithm implementation.

Keywords: signal detection, signal processing algorithms, Wiener filters, spectral transformations, discrete-time systems

1. INTRODUCTION

The T600 ICARUS Detector [Amerio(2004), Ankowski(2010)] is the large scale (dual 300 ton liquid Argon) electronic bubble-chamber with the total data throughput of several GB per second. The signals (see fig. 1) gathered in the chamber are of low S/N ratio because of the special signal conditions (charge collected in a very large volume form the ionized liquid Argon caused by the low energy particles as neutrinos). The important data occupies as low as 0.5% of the total collected volume. The typical low amplitude signal is shown in figure 1. The typical ICARUS signals can be fitted with 5 parameter function *f(t)* [Amerio(2004)]:

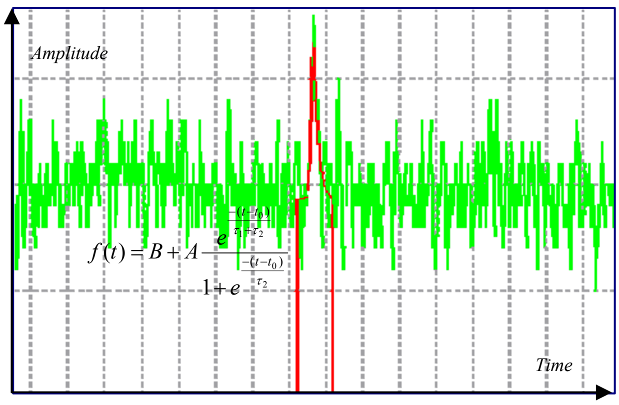

Fig. 1. Typical signal from ICARUS detector (green) and fitted signal (red)

$$f(t) = B + A\frac{e^{\frac{-(t-t_0)}{\tau_1+\tau_2}}}{1+e^{\frac{-(t-t_0)}{\tau_2}}} \tag{1.1}$$

The time domain signal detector DAEDALUS [Arneodo et al. (1998)] designed for the 50l prototype was unable to handle with low SNR (close to 0dB) signals from 600 ton ICARUS module (T600), because was designed to operate with at least 20dB SNR signals. The only solution was to design time-frequency signal detector with time resolution at least of 32 samples which was the maximum decimation factor due to ROI window of 64 samples.

2. T600 SIGNAL AND NOISE ANALYSIS (WIENER SOLUTION)

The ICARUS detector test runs revealed much lower than expected SNR of the signals and presence of various stationary and non-stationary noises and interferences. The noise analysis was presented in [Gibin(2003)] is shown in figure 2 (power spectral density function of signals were obtained with fitting procedure of detected signals with function (1.1)). The analysis will lead to the statistically optimal Wiener solution using PSD of signals $S_s(f)$ and noise $S_n(f)$ [Wiener(1950)],[Miller(2004)]:

$$|H(f)|^2 = \frac{S_s(f)}{S_s(f)+S_n(f)} \tag{2.1}$$

which could be well fitted with exponent function of three parameters [10]:

$$|H_{fit}(f)|^2 = \left(\frac{1}{1+e^{\frac{f-b}{a}}}e^{\frac{f}{c}}\right)^2 \tag{2.2}$$

The fitting function was chosen because of CDF [Cohen(1992), Donoho(1992)] spectral response similarity. The $H_{fit}(f)$ function with parameters $a=0.33\cdot b$; $c=2.5\cdot b$ well approximates CDF(2,2) spectral response (see fig. 2). The procedure assumes linear phase filters, which can be used in lifting application biorthogonal wavelets transform CDF.

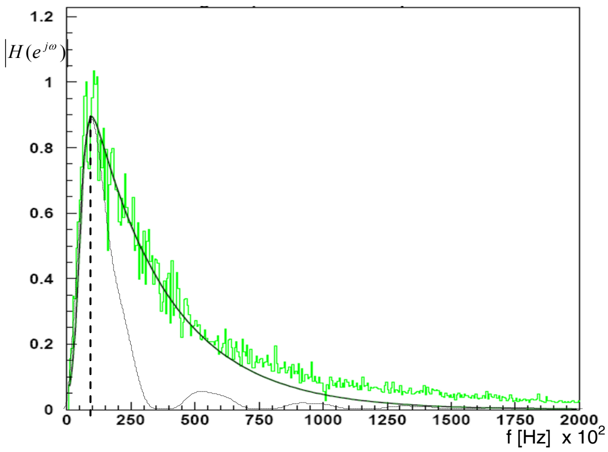

Fig. 2. Wiener filter frequency response for ICARUS signals (eq. 1.3) – green, fitted with function $H_{fit}(f)$ [Gibin(2003)] and CDF(2,2) synthesis wavelet (scale 32) amplitude spectrum.

3. WAVELET SCHEME DETECTION OF THE SIGNALS

The procedure of detection described in [Batko (1999)] which uses Continuous Wavelet Transform can be well adapted to the ICARUS signals. The Continuous Wavelet Transform:

$$C_{a,b} = \int_{-\infty}^{+\infty} f(t) \cdot \psi\left(\frac{t-b}{a}\right) dt \qquad (3.1)$$

of the signal is checked for local maxima and found maximum index b_{max} produces one dimensional function (see fig. 3) with one parameter b_{max}. The shape of this function is then checked for correlation with noise free signal shapes. This procedure uses CWT approximation which is

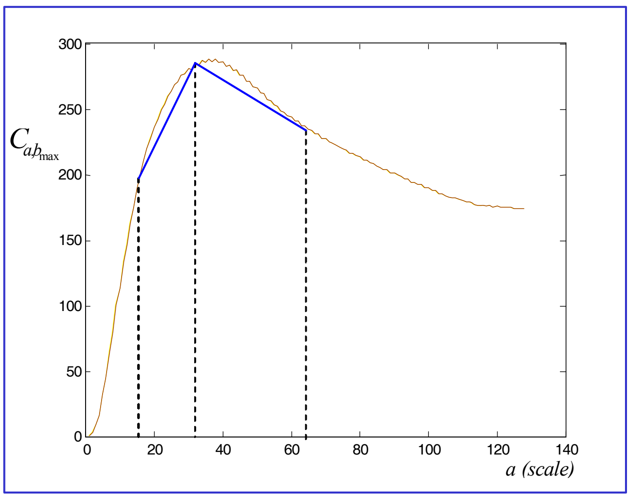

Fig. 3. Maximum (b_{max}) coefficients of CWT.

computationally complex and thus impossible to implement in the real-time ICARUS DAQ system.

4. DDWT DETECTION BASED ON WIENER SOLUTION FILTERS

The real-time solution is possibile only with DDWT approximation of CWT. The shape of $C_{a,bmax}$ function is then reduced to a three point approximation DWT (and for better time resolution DDWT). The DDWT approximation of CWT is efficient only when the middle filter is matched (scale 32 - see figures 2 and 3) with optimal Wiener filter, and the two other filters are unmatched (scales 16 and 64 - see figure 3). This solution need six stages of DDWT decomposition which has been applied using DDWT FIAWT [Półchłopek (2002a),(2002b),(2006)] algorithm. The matched filter output (details on 5-th stage of decomposition) is then followed by over-threshold checking procedure. The two unmatched DDWT outputs are compared with dynamic threshold (their amplitude must be lower than matched filter output).

5. ROI ENCODING AND COMPRESSION RESULTS

The initial state simulations were done in the Matlab® environment. Compression results were obtained via C++ data analysis program called Qscan with compression and ROI extraction interface. This application is designed for processing the ICARUS raw data files.

Table 1. ROI extraction and compression results comparison.

	Time analysis	DDWT unmatched	DDWT matched
ROI blocks detected (left chamber – low SNR) total/per channel	16017,15 /2,80	5526,83 /0,96	5918,07 **/1,03**
ROI blocks detected (right chamber – better SNR) total/per channel	5257,55 /0,92	4768,64 /0,83	5885,82 **/1,03**
Compression ratio (64 samples window)	**34,46**	**71,21**	**62,11**
Compression ratio with additional lossless FIAWT wavelet compression	**172**	**356**	**310**
Compression ratio with additional high quality lossy FIAWT wavelet compression	**344**	**712**	**620**
False detection ratio (left chamber - low SNR)	**67,18%**	**13,72%**	**0,54%**

Final ROI extraction and compression results are shown in the table 1. DDWT matched filter procedure shows high robustness to the noise and low false detection grade. Two dimensional image-like views (fig. 4) show algorithms sensitivities with small amplitude and low SNR (0dB and less) and confirms the best matched DDWT algorithm performance.