First Results from the FPGA/NIOS Adaptive FIR Filter Using Linear Prediction Implemented in the Auger Engineering Radio Array

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Abstract—In this paper we present first results of the efficiency of the adaptive FIR filter based on the linear prediction (LP) for a suppression of radio frequency interference (RFI), deployed in real AERA (Auger Engineering Radio Array) station on pampas, with a comparison to the currently used UR notch filter with constant coefficients. The filter has been installed in several radio stations in the AERA experiment. AERA observes coherent radio emission from particle air showers induced by ultra-high-energy cosmic rays to make a detailed study of the development of the electromagnetic part of air showers. Radio signals provide complementary information to that obtained from Auger surface detectors, which are predominantly sensitive to the particle content of an air shower at the surface. The radio signals from air showers are caused by the coherent emission due to geomagnetic and charge-excess processes. These emissions can be observed in the frequency band between 10 - 100 MHz. However, this frequency range is significantly contaminated by narrow-band RFI and other human-made distortions. A FIR filter implemented in the FPGA logic of the front-end electronics of a radio sensor significantly improves the signal-to-noise ratio. Theoretical calculations show a high efficiency of this filter for mono-carrier as well as for standard FM radio contaminations. The laboratory tests, performed on an Altera development kit confirmed the theoretical expectations. The coefficients for the linear predictor are dynamically refreshed and calculated in a Voicpex PXA270M ARM processor, which is operated on a daughter-board placed in the same digital unit as the FPGA. Laboratory tests confirms the stability of the filter. Using constant LP coefficients the suppression efficiency remains the same for hours, which corresponds to more than 10^12 clock cycles. We compare in real conditions several variants of the LP FIR filter with various lengths and various coefficients widths (due to fixed-point representations in the FPGA logic) with the aim to minimise the power consumption for the radio station while keeping sufficient accuracy for noise reduction.

Index Terms—AERA, cosmic rays, FIR, FPGA, linear predictor, Pierre Auger observatory, RFI.

I. INTRODUCTION

RECENTLY radio detection of cosmic-ray air showers re-"ives a renaissance, mainly thanks to a huge progress of the powerful digital signal processing techniques in experiments such as LOPES [1], CODALEMA [2] or the Auger Engineering Radio Array (AERA) [3], which is situated within the Pierre Auger Observatory [4].

Results from the Pierre Auger Observatory, point to the need for very large aperture detection systems for ultra-high energy cosmic rays. With its nearly 100% duty cycle, its high angular resolution, and its sensitivity to the longitudinal air-shower evolution, the radio technique is particularly well-suited for detection of ultra-high energy cosmic rays (UHECRs) in large-scale arrays [5]. AERA has been enlarged to 124 radio detector stations (RDSs), covering an area of 6.5 km², therefore allowing the detection of UHECRs.

Since the 1960 s we know that the radio emission from air showers is strongly correlated with the local geomagnetic field [6]. In addition to the geomagnetic effect that can be described macroscopically [7], Askaryan [8], [9] predicted that there should be an emission component related to the time-variation of the negative net charge excess in air showers. Both [1] and [2] confirmed these effects. Using the AERA setup, the Auger collaboration quantified the relative strength of these effects [10].

The observation of air showers with radio-detection techniques can be done at almost all times. Moreover, radio signals are sensitive to the development of the electromagnetic component of particle showers in the atmosphere. In the last 10 years the radio-detection technique in the MHz region has been revived and the present radio-detector arrays for cosmic-ray research are equipped with low-noise and high-rate digital samplers. Simultaneously, the number of stations within these arrays has grown from less than ten to more than one thousand. The question to be addressed in the VHF band (MHz-range) is not whether extensive air showers emit radiation. At this moment the main question to answer is: can we use radio signals to determine the primary energy, the arrival direction, and the mass of cosmic rays with accuracies which are close to or better than...
II. RFI Suppression for Real AERA Data

Triggering directly on the radio signal of the air showers (instead of using particle detectors as a trigger) poses some challenges for the data acquisition, due to man-made radio-frequency interference (RFI). The continuous background level is set by the radio emission from the Galactic plane, but any man-made narrow band transmitters add to the level above which one must detect air-shower pulses. Additionally, man-made pulsed RFI (from sparking electrical equipment, airplanes, etc.) can mimic the short pulsed signal from cosmic rays. Since the bandwidth and computational resources at each triggering level are limited, one of the technical focuses for the first stage of the array has been to develop various methods to reject RFI in order to minimize efficiency losses from bandwidth saturation.

The energy threshold for radio detection of cosmic rays is limited by the considerable radio background and noise. The very high level of RFI in the FM and short wave band has to be eliminated by a band pass filter. Within the remaining receiver frequency range between 30 to 80 MHz the noise at the quiet-rural environment of the Pierre Auger Observatory is dominated by the frequency dependent galactic noise [11] with noise temperature of 5000 K at 60 MHz. Without an effective trigger, a stable and low level energy threshold is not guaranteed. Furthermore, the data rate for communication of the triggered data to the central DAQ would exceed the available bandwidth.

Two types of the RFI filter were already developed and used in the radio stations in Argentinean pampas:
1) Adaptive filter based on the FFT - cleaning the RFI peaks in the frequency domain,
2) Non-adaptive IIR notch filter suppressing 4 arbitrarily selected frequencies.

The proposed FIR filter based on the linear prediction is a new alternative to the previous ones.

A. Linear Predictor

Linear prediction is a mathematical operation where future values of a discrete-time signal are estimated as a linear function of previous samples [12]. This method is widely used in audio signal processing and speech processing for representing the spectral envelope of a digital signal of speech in compressed form, using the information of a linear predictive model [13]. With the advent of faster signal processing techniques in FPGAs it is now possible to apply similar techniques to the real-time processing of radio signals in the 10-100 MHz region [14][15].

In the LP method the covariances for 1024 ADC samples can be calculated in the FPGA fast logic block. Either the NIOS soft-core processor [16] or the external ARM-processor, solves the matrix of 32 or 64 linear equations and provides coefficients needed for the FIR filter. The calculated coefficients are next transferred to the fast logic block, updating appropriate registers. They are used as the FIR coefficients in the ADC data filtering. Finally, the predicted and delayed data (expected background) are subtracted from the ADC data to clean the signal from periodic contaminations (Fig. 1).

Comparison of graphs in [17] indicates that the LP approach can eliminate RFI narrow frequency contaminations as efficient as notch and FFT filters.

B. FFT+ Median filter +iFFT

For self-triggered measurements, the data will be digitized and processed in real time by a powerful FPGA chip. The narrow peaks in the frequency domain due to radio frequency interferences have to be strongly suppressed before building a trigger. These peaks are removed in several stations, digitizing at 180 MHz, using a median filter. The filter works in the frequency domain using an FFT routine provided by Altera. The median FPGA filter eliminates mono-frequency carriers, but broadband radio pulses from cosmic showers are not affected. After a second inverse FFT, signals are converted back to the time domain (Fig. 3) [18].

The amplitude of the de-convoluted signal increases by about 20% compared to the input signal. Since the galactic and electronic noise is completely uncorrelated, the S/N ratio increases by the same amount.

The FFT approach is generally very power consuming. This is a factor for a system supplied from solar panels.

C. IIR Notch Filter

As stated earlier, before triggering on a radio pulse it is advantageous to increase the signal-to-noise ratio by filtering out any narrow band transmitters from the digitized antenna signals. In stations digitizing at 200 MHz, this is accomplished in a computationally efficient manner by using a series of IIR notch filters.
2-channel 14-bits 250 MSPs ADC (ADS4249). Both modules were connected through the Altera HSMC-ADC-Bridge providing LVDS data transmission (Fig. 16).

At first the filter was tested for a mono-carrier drifting the frequency from 50.0 MHz to 50.2 MHz in 120 s. The LP coefficients were calculated: either by the NIOS soft processor implemented in the same FPGA parallel to a fast logic [16] (Fig. 1) (in laboratory tests) or in a Voipac PXA270M ARM processor, which is implemented on a daughter-board placed in the same digital unit as the FPGA (real tests in radio stations on pampas). Thus, these LP coefficients were used for the data cleaning in several tens of minutes (which corresponds to more than $10^{12}$ clock cycles). Fig. 8 shows a perfect long-term stability of the filter. If the generator driving the filter uses the frequency for which the LP coefficients were originally calculated, the suppression is almost total. Therefore, LP coefficients do not need to be refreshed very frequently.

Secondly, we checked the Hi-Fi FM configuration (75 kHz deviation of the 50 MHz carrier with the maximal acoustic 15 kHz modulation). This is a very restrictive condition, which actually should not appear in real conditions in Argentina. The band 30 - 80 MHz is used rather by narrow-band transmitters, while the FM Hi-Fi transmission is selected for the band of 88 - 108 MHz, cut-off by the band-pass analog filter. Nevertheless, even these critical contaminations were successfully suppressed (Fig. 9).

We also tested the suppression efficiency (in the Fourier space) in the presence of relatively strong white noise (Fig. 11). Two pure carriers with 27.12 and 57.9 MHz were wired mixed with noise. Fig. 10 shows that even when the noise level reaches the signal level the suppression factor remains on a level of 5-10 (for signals 50 mV and 200 mV contaminated by 50 mV and 200 mV of a noise). When the noise is small, the suppression factor reaches values up to 35. However, a strong asymmetry is observed. The strong signal (i.e. 200 mV of 27.12 MHz is
suppressed with a very high factor (35) while a 4 times smaller signal (57.9 MHz) is almost not suppressed at all. For versa configuration the suppression structure remains the same.

V. COMPARISON TO CURRENTLY USED IIR-NOTCH FILTER

We compared suppression characteristics of the FIR filter based on the linear prediction with the currently used IIR-notch filter with 4 band-reject bands. Fig. 12 shows amplitudes of the 13th frequency bin in the Fourier space corresponding to a contribution of the 1st carrier contamination with various frequencies in the range 27.00 - 27.24 MHz for a small (10 mV - upper graph) and significant (100 mV - lower graph) noise. It is well visible that the efficiency of the IIR filter is very high and, as expected, only around the reject frequency (27.12 MHz) of the filter. Higher noise (comparison 100 mV vs. 10 mV) reduces the efficiency only slightly, thereby extending the width of the rejection band (from ~ ±20 kHz to ~ ±30 kHz).

Fig. 13 shows the 283th (55.2 MHz) and 296th (57.9 MHz) Fourier modules vs. various frequencies in the 1st channel contamination (27.00 - 27.24 MHz). As expected, the suppression of the IIR filter outside the reject band is negligible. Note that for structured contaminations (two mono-carriers with frequencies equal exactly the reject frequencies of the IIR-filter) the efficiency of the FIR filter is comparable with the efficiency of the IIR one, provided the background noise level is low in comparison to the contamination.

Fig. 12 and 13 justify testing the FIR filter based on the linear predictor as an adaptive filter, adjusting the suppression characteristics to changing RFI conditions in the field.

VI. POWER CONSUMPTION

The power consumption is an important factor for systems supplied from solar panels. More sophisticated filter provides
a better accuracy of data processing. However, the power efficiency may significantly decrease. We measured the power consumption for all developed FIR variants and compared with the currently used IIR filter. Fig. 14 shows results for the current consumption with the NIOS processor (left panel) and with temporary blocked NIOS (right panel). The NIOS processor was used for the calculation of LP coefficients for the FIR filter and for data transmission via UART to the PC for both filters.

From Fig. 14 it is visible that the FIR filter with 32 stages and only 14-bit coefficients is at least power efficient in comparison to the IIR. Longer FIR filters consume much more power and could be used exceptionally in extremely contaminated environment, where the suppression efficiency becomes the more important factor than the power efficiency.

VII. DATA FROM PAMPAS

We have implemented the 32-stage LP filter (with D = 128) in the AERA radio station LS009. Fig. 15 show a suppression of the RFI in the higher frequency range. In comparison to Fig. 4(b) the suppression efficiency is lower, however, in current environment the huge contribution of non-stationary RFI was observed. In presence of variable RFI the efficiency of the LP filter is not so high as for mono-carriers contamination. Fig. 15 shows the
The current consumption vs. input signal (amplitudes in mV) for two types of configurations: 14 × 18 and 14 × 14) for several tested variants of the FIR filter with a comparison to the currently used IIR one. It is worth noticing that 14 × 14 configuration (14-bit ADC data and 14-bit FIR coefficients - right panel) is much more energy efficient than 14 × 18 configuration (14-bit ADC data and 18-bit FIR coefficients - left panel). 14 × 18 configuration utilizes only 2 DSP blocks in the FPGA. Measurements show that reduced size of FIR coefficients provides still a very good accuracy in the RFI cleaning processes.

The laboratory measurement setup with the Altera DK-DEV-5C5N7 Development Kit with Cyclone V FPGA and Texas Instruments ADS4249EVM Evaluation Module with 2-channel 14-bit 250MSps ADC (ADS4249). Both modules were connected by the Altera HSMC-ADC-BRIDGE providing the LVDS data transmission. Tektronix AFG3252 C 2-channel generator provides 2 sine waveforms, Agilent 33250 A provides noise signal.

the noise suppression for the EW polarization is almost negligible.

VIII. CONCLUSIONS

Analytical calculations (Fig. 4–5) show that a very high efficiency of the LP filter can be obtained. The laboratory measurements confirmed that when the data is contaminated by monocarriers, the suppression factor is very high. However, the environmental RFI as encountered in the Pierre Auger Observatory has a much more sophisticated structure. Therefore, the efficiency of the LP-filter significantly decreases.

Nevertheless, in each radio station the filter setup can be calculated, thereby optimizing the suppression factor, depending on the location of each station and the type of RFI contamination compared to the IIR filter that is fixed.

In AERA the Cyclone IV FPGA EP4CE75F291I7 is currently in use. The laboratory tests provide input for an optimization of the RFI cleaning for the next generation of the AERA Front-End based on Cyclone V with Hardware Processor System (HPS) and System on Chip (SoC). Altera documentation [20] shows that Cyclone V (anticipated for the next generation) consumes ~40% less power in comparison to Cyclone IV. With Cyclone V we would have higher flexibility in a filter length implementation. Longer (and much more efficient) filter can be dynamically turned on for stations reported really high level of the RFI.

REFERENCES


