Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 429–432

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

Implementation of trigger for detection of ultra high energy cosmic rays with LOFAR

K. SINGH[1], L. BÄHREN[2], H. FALCKE[1,2], A. HORNEFFER[1], E. KOOISTRA[2], O. SCHOLTEN[3]
[1]*Department of Astrophysics, Radboud Universiteit, 6535 ED, Nijmegen, The Netherlands*
[2]*ASTRON, 7990 AA, Dwingeloo, The Netherlands*
[3]*KVI, University of Groningen, 9747 AA, Groningen, The Netherlands*
k.singh@astro.ru.nl

Abstract: Using all stations of LOFAR we are planning to investigate the feasibility of using Moon as a detector of Ultra High Energy ($>10^{20}$ eV) cosmic rays. The idea is to cover the whole visible lunar surface and to look for short pulses of Čerenkov radiation emitted of shower induced just below the surface of the moon when the cosmic rays strike it. Our aim is to implement a self-triggering algorithm such that the system can trigger directly on strong and narrow radio pulses without the need of an external particle trigger as is employed presently in the LOPES system. In order to implement this trigger, we need to invert primary signal processing done at LOFAR stations to achieve the required accuracy for triggering the real time signal. Additionally, the pulse will be influenced by the earth's ionosphere; therefore, coherent de-dispersion follow up is essential.

Introduction

The origin and acceleration of high energy cosmic rays well above GZK cutoff [1, 2] is still under debate. This cutoff is due to interactions of cosmic rays with the cosmic microwave background (CMB). Shock wave acceleration by colliding galaxies or Active Galctic Nuclei (AGNs) may produce protons of energies exceeding 0.05 ZeV (GZK cutoff). Energetic protons loose energy through interactions with the cosmic microwave background and produce pions of the same order of energy. Decays of pions further give rise to Ultra High Energy (UHE) neutrinos which may traverse long distances in universe almost unattenuated. In 1989, Dagkesamanskii and Zhelenznykh [3], proposed to detect showers initiated by UHE cosmic ray and neutrinos by measuring coherent Čerenkov radiation emitted just below the surface of the Moon when high energy cosmic rays strike it.

Ultra High Energy ($>10^{20}$ eV) cosmic rays have a flux of about 1 particle per square kilometer per year. This combination of small flux and high energy makes a direct measurement very difficult. Hence, we explore the possibility of detecting extremely high energy particles, which are interacting in the Moon, with the interferometric array of radio telescopes of LOFAR [4].

LOFAR detects the incoming radio signals by using an array of simple omni-directional antennas. A total of seventy seven stations will be build within a circle of 150 kilometers in diameter. There will be 32 core stations together within circle of diameter 3 km with baselines 100m to 2 km. Each station consists of 96 dual polarization Low Band Antenna (LBAs), optimized for 30 to 80 MHz, and 96 High Band Antenna (HBA) tiles for 120-240 MHz. The signals of all the stations are distributed to the central processor, supercomputer "Blue Gene" which is situated in Groningen, Netherlands. The total digitized data rate from the antennas is about 0.5 Tb/sec at each station. Station level signal processing reduces this rate to roughly 2 Gb/sec by combining data from antennas into phased array beams. The remote stations will differ from the core stations by data reduction obtained by enabling only one beam per remote station, which is essential because, the remote stations are further away from the central computer so data transport is more expensive.

For observation of Ultra High Energy Particles, the whole LOFAR is configured into the tied array mode and beams are formed into the direction of the Moon for the frequency range of 120-240 MHz. Unit operated in tied array mode will be constantly tracking the Moon. The field of view should cover a sizable part of the whole lunar surface, whereas the Moon has a field of view of half a degree. The self-triggering requirement would then be that each unit of tied array mode sees a pulse with a power larger than a predefined threshold.

This trigger algorithm should be able to discriminate the real cosmic events from false events to reduce the load on data transmission and storage systems and indeed should be compatible with the requirement of observation and available processing resources.

Signal Processing Sequence

At stations of LOFAR, the analogue signal from antenna is digitized into a 12 bit digital signal at a sampling rate of 200 MHz. Each input is filtered in a polyphase filter (PPF), consisting of FIR (Finite Impulse Response) filter banks of 15th order and an IDFT stage (see fig. 1, [5]). This structure implements a filterbank with arbitrary response for a computational cost that is approximately double that of the FFT alone, for the case where the prototype low pass filter h(n) is an order of magnitude longer than the FFT.

For the above implementation the input and output data rates are identical and there is no difference in the cross multiply load between an FX correlator using this as a filterbank and a traditional FFT FX correlator.

After implementation of polyphase filter bank at station, the observing frequency band is split into 512 frequency subbands, the negative part of the original spectrum, i.e., the other 512 subbands are ignored. Each subband signal is decimated with a factor of 1024 after filtering, therefore, the clock rate after filtering is reduced to (200 MHz /1024) ~ 195 kHz. From the resulting 512 frequency subbands, a number of subbands can be selected depending on the processing power for further processing. The selection of subbands is controlled by Local Control Unit at the stations. To form beams, the antenna signals are combined, this is done with independent beamformers for each subband at station. We can make one beam of 32 MHz, or 8 different beams with each 4 MHz bandwidth. At central processing, these station beams are tied into tied array mode and weights necessary for the beam-former are provided by central processor.

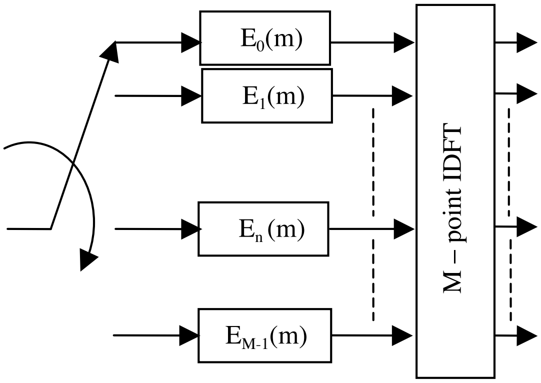

Figure 1: Polyphase filter bank, where $E_i(m)$'s are impulse response of implemented FIR filters (M=1024 in case of LOFAR).

The resulting voltage sum output of each tied array beam is presented as multiple spectral channels, each composed of a time series data with sample rate (195 kHz) set by the inverse of subband bandwidth ~ 5 µsec. Since we are concerned with pulse of temporal width ~ nanosec. Therefore, to search suitable pulses, data has to be transformed back to the time domain to produce high time resolution (~ nanosec). This is achieved by the exact inversion of what has been implemented at station level, more specifically by the inversion of polyphase filters (PPF). The whole concept is known as the reconstruction of signal which is a branch of multi-rate digital signal processing [6]. In Fig. 2, the reconstructed signal is plotted. The input signal is a pulse overriding Gaussian noise plotted in a red curve whereas the reconstructed signal is plotted in green.

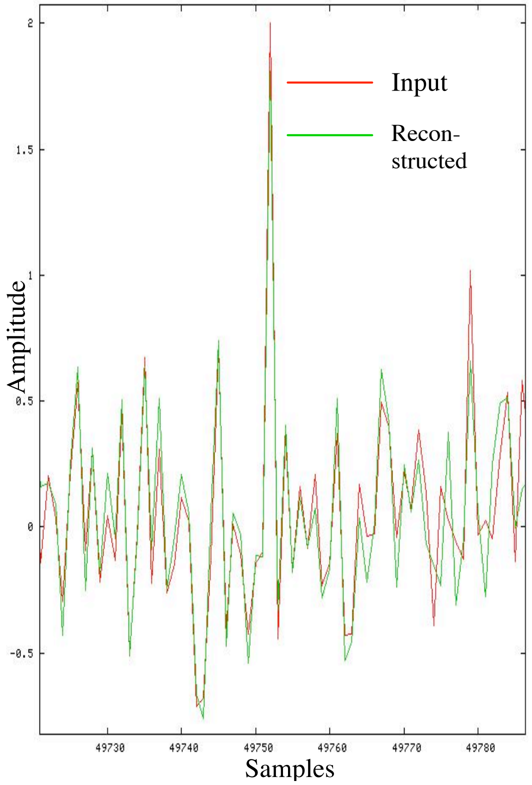

Figure 2: Reconstruction of signal with the inversion of polyphase filter bank.

In parallel with the filtering and beamforming at stations and tied array at central processing, the digitized raw data at station is stored in a transient buffer board (TBBs), which holds raw data for 1 sec that can be accessed for offline processing afterwards upon detection of specific transient events. Hence, the requirement for the generation of this external trigger is basically to define a condition when the data from the TBBs is to be dumped. However, buffering time of buffer boards has posed a serious time constraint of 1 sec.

De-dispersion of signal

The pulse of Čerenkov radiation comes from the moon and hence will be influenced by the earth's ionosphere. When it propagates through an ionized medium and it gets dispersed. The propagation vector of wave propagating through ionospheric plasma will be frequency dependent and can be expressed as,

$$k(f) = \frac{2\pi f}{c}\sqrt{1-\frac{f_p^2}{f^2}} \qquad (1)$$

where, f_p is plasma frequency, f is the frequency of measurement, and c is the velocity of light. Since plasma frequency for earth's ionosphere is maximum for electron density of the F2 layer of ionosphere (NmF2) and is no greater than 3 MHz, however, observation is planned in the frequency range 110-190 MHz, therefore, expansion of $k(f)$ is valid

$$k(f) \approx \frac{2\pi f}{c}[1-\frac{f_p^2}{2f^2}] \qquad (2)$$

on comparison of above expression with plane wave equation, the first term signifies time delay of wave, however, the second term is accountable for an extra phase shift, which will be

$$\phi(f) = 2\pi\frac{1.34\times10^{-7}\,STEC}{f} \qquad (3)$$

where, *STEC* is the Slant Total Electron Content, dependent on the Total Electron Content (TEC), which will be provided by available GPS sources and angle of elevation of the Moon at the time of observation [7]. This is the phase shift which is introduced because the pulse propagated through the dispersive media. It gets dispersed i.e., lower frequencies move faster than higher frequencies as shown in Fig. 3 and hence a delay will be introduced which is frequency dependent. This dispersion is linearly dependent on the specific TEC for the real time observation through GPS.
Therefore, ionospheric correction is done for this dispersion for each station beam at central processor and then they are tied into tied array mode. Further, on the tied array beam, interpolation of signal by inversion of Polyphase filter bank is performed to reach the required accuracy of real time signal.

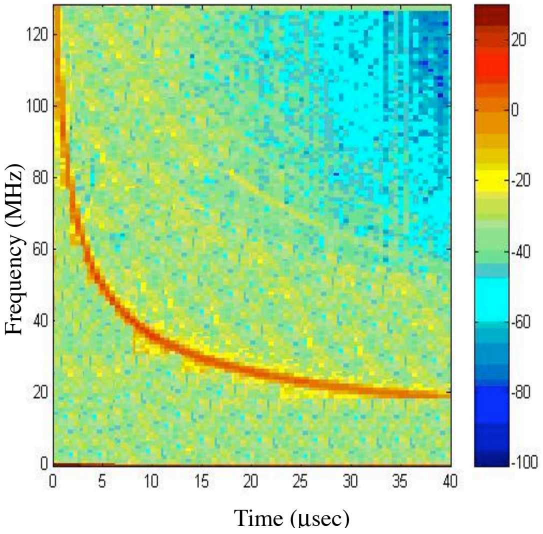

Figure 3: Dispersion of signal because of propagation through ionosphere, for TEC value = 11.5 TECU (1 TECU = 10^{16} electrons / m^2) and the angle of elevation of Moon is 45^0 (calculation is made for optimized frequency of Low Band Antennas of LOFAR)

Strategy of trigger

Core stations of LOFAR will be used for self-triggering for detection of UHE cosmic rays. Beam size using all core stations of LOFAR is 5.2' at 120 MHz and with the available processing power in total 24 beams can be synthesized. Since moon has a field of view of half a degree, therefore, core stations are divided into groups to synthesize beams of the size of nearly half a degree.

These beams from core stations are combined in tied-array mode so that for each sub-division one data stream remains. If a pulse of predefined threshold power is detected in the time series data streams in all the subdivisions, a signal is sent to the transient buffer boards of all stations to freeze the buffer and dump the data.

A coincidence trigger is performed on all beams directed towards the same position of Moon, because a real event should be detected in multiple beams focusing the same position on the lunar surface. In addition of a coincidence trigger an anti-coincidence trigger is performed for beams covering disjunct areas on the lunar surface.

After a trigger is detected the raw time series data of the beam of the last second is stored from the transient buffer boards. For the detection the LOFAR core stations will be used but data of transient buffer board from remote stations will be included in the data analysis to locate the cosmic ray impact site and direction of arrival.

Conclusion

A self sufficient trigger algorithm is essential to reduce the load on data transmission and storage system, which should be well-suited with the time constraint of buffering time of transient buffer boards implemented at LOFAR stations. Furthermore, to correct the ionospheric corruptions of signal, GPS and LOFAR calibrations have to be optimized.

References

[1] K. Greisen, Phys. Rev. Lett., 16, 748, 1966.
[2] G. T. Zatsepin, V. A. Kuzmin, Sov. Phys. JETP Lett., 4, 78, 1966.
[3] R. D. Dagkesamanskii, I. M. Zheleznyk, Sov. Phys. JETP, 50, 233, 1989.
[4] O. Scholten, J. Bacelar, R. Braun, A. G. de Bruyn, H. Falcke, B. Stappers, R. G. Strom, 26, 219, 2006.
[5] Sanjit K. Mitra, Digital Signal Processing, McGraw Hill, 2001.
[6] R. E. Crochiere, L. R. Rabiner, Multirate Digital Signal Processing, Printice Hall, 1983.
[7] R. el Yahyaoui, Masters Thesis, Rijksuniversiteit, Groningen, The Netherlands, 2007.