Ultra-High Energy Cosmic Ray and Neutrino Detection with LOFAR

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Abstract. **Askaryan predicted that a particle shower in a dense medium, such as the lunar regolith, produces a coherent pulse of microwave Cherenkov radiation. At wavelengths comparable to the size of the shower (a few meters), the emission becomes nearly isotropic, which makes the detection of the pulse efficient. Our plan is to search at low frequencies (100-200 MHz) for these short radio pulses coming out of the lunar surface when a high-energy particle strikes the surface. To capture these pulses we observe the visible lunar surface with several coherent beams from the LOFAR (Low Frequency Array) antenna array. To reduce the load on data transmission lines and storage devices, we will implement an online trigger.**

***Keywords*: Ultra-High Energy Cosmic Rays, LOFAR, Radio Detection.**

I. Introduction

When an ultra-high energy (UHE) cosmic ray, $E > 10^{20}$ eV, impinges on a dielectric a particle shower is created with particles moving at almost the light velocity c. Since the velocity of these charged particles is larger than the propagation speed of electromagnetic waves $c_d = c/n$, where n is the index of refraction, coherent Cherenkov radiation will be emitted. This is known as the Askaryan effect [1]. In 1989, Dagkesamanskii and Zhelenznykh [2] proposed to use this effect to measure the flux of UHE neutrinos when they interact in the surface of the Moon. The Moon offers a large collecting area which allows for sensitive measurements of the flux of these UHE neutrinos and cosmic rays.

Based on this concept, experiments have been carried out at the Parkes and the Goldstone telescopes [3], [4]. These experiments have looked for radiation near the frequency where the intensity is expected to reach its maximum. For lower frequencies, however, the angular spread of the emission around the Cherenkov angle increases [5]. This results in a large increase of the detection efficiency for UHE particles. It was shown that the optimum window for these kind of observations lies around 100-200 MHz. With the Westerbork Synthesis Radio Telescope (WSRT) we have made observations in a frequency window around 150 MHz, where we have been able to improve the flux limit for UHE neutrinos by about an order of magnitude [6], [7]. With a larger collecting area and a wider frequency range for observations LOFAR [5], [8], [9] will have a much higher sensitivity for UHE neutrino detection than WSRT.

LOFAR (Low Frequency Array), an array of simple dipoles, is the largest radio telescope currently under construction. There are three observation modes for the detection of cosmic rays of three different energy ranges [9], [10]. For the lower energy range, typically from 10^{15} eV to 10^{17} eV, digital beams are formed from antennas near the point of impact to achieve the appropriate sensitivity. To observe the cosmic rays in the energy range from 10^{17} eV to 5×10^{18} eV, we will look for sharp radio pulses in single antennas. The individual antenna signals will be searched for the occurrence of correlated pulses in a set of antennas within a preselected time window. And this will act as triggers to download and store the recent voltage time series of individual antennas. However, the highest energy mode of LOFAR is observation of UHECRs. For this mode of observation the digital beams will be formed using all antennas of LOFAR to achieve enough signal to noise ratio. Beams will be pointing towards the Moon and we will look for radio pulses within the beam from inside the lunar surface. The triggering will be performed for the occurrence of correlated pulses in a number of beams.

II. LOFAR

The central area LOFAR will consist of 5,000 small antennas, distributed over 36 antenna fields (stations) in the North East of the Netherlands. The interferometric array will operate at the frequencies between 10 and 240 MHz. The plan is to have 18 antenna fields densely populated in the core with a diameter of 2km. In addition to the core stations, 18 remote stations are planned further away from the central core within 100 km [8]. Each station will have 96 dual polarized Low-Band Antennas (LBAs), optimised for 30 to 80 MHz, and 48 High-Band Antennas (HBA tiles) for 120-240 MHz. The HBA tiles consist of 16 bowtie-shaped fat dipoles (Fig. 1) and measures 5×5 m. The HBAs at each station are grouped into two sub-fields, at a distance of about 30 m, each with 24 tiles [9]. A remote station consists of 48 tiles and a diameter of about 41 m. A European

Fig. 1. LOFAR - High Band Antenna (HBA) tile.

station consists of 96 tiles and has a diameter of about 57 m.

In addition to this there will be stations located in various other countries such as Germany, the UK, France, Sweden, Poland, and Italy to make it European LOFAR (E-LOFAR). The interferometric baselines within Netherlands are of the order of 100 km and 1000 km for E-LOFAR.

The electric signals from the antennas will be transported to a series of electronic boards where appropriate phase delays will be applied so that station beams on the sky can be formed in a predetermined direction. Thus, every station will be digitally synthesized as a dish of a traditional telescope. Each of the station has 4 Gb/sec connection to the central processor which is an IBM Blue/Gene. In addition to this, beams of several stations will be tied together online at the central processor. This will improve the pointing resolution of the tied array beams. In parallel to this processing, the digitized raw data of antennas will be stored in a ring buffer at the stations which can be accessed for off-line processing. The buffer boards can hold raw data from 8 dual polarized antennas for a storage time of 1 sec.

III. Experimental Method

The HBAs of LOFAR will be used for the observation of UHE neutrinos and cosmic rays. For this observation mode the HBAs antennas will be used. The A/D converter will convert the analogue signals into a 12 bit digital signal at a maximum sampling rate of 200 MHz as shown in (Fig. 2). Each (digital) Receiver Signal Processing (RSP) board receives signals from 4 dual polarized antennas. On the RSP board, each input signal will be filtered in a polyphase filter. From the resulting 512 subbands, 258 subbands will be selected (preferably RFI free) for beamforming. The weights necessary for the beam-former are calculated in Local Control Units (LCU). Since we are looking for pulses that pass through the Earth's ionosphere we will first correct for ionospheric dispersion before transferring the station beams to the Central Processor (CEP). There the station beams from all stations will be added coherently to form tied array beams to cover the aperture of the Moon in the frequency range of 100-200 MHz using the HBAs of the core stations only. Each beams will be covering a different patch on the visible lunar surface. Each beam will be then transformed back to the time domain and will be searched for suitable pulses, and when found, a trigger signal will be send to read out the relevant part of the information of the ring buffers at the core stations, as well as at the remote E-LOFAR stations. Since the remote stations are further away from the central processor it will be a challenge to transport the data within the buffering time limit. We need a number of tied array beams to cover the visible lunar surface. A real cosmic ray or neutrino event can be discriminated from pulsed noise by performing an online anti-coincidence check on a number of beams (Fig. 2).

Using remote stations as we all as international stations for off-line analysis we will strongly enhance the sensitivity for the detection of UHE particles. One reason is the the signal-over-background ratio is improved by increasing

the collecting area of the telescope array. The recent observations with the WSRT, which is a path finder of LOFAR [6], [7] have shown that it is crucial to control the pulsed noise. The source of this pulsed noise is not known. It was shown that noise can efficiently be suppressed by requiring that the signal of interest comes from a confined area of the Moon and thus the signal of the interest should be present in only a single tied-array beam (or a few near ones). Therefore, adding international stations with interferometric baselines of the order of few hundred kilometers will be extremely useful to improve the pointing resolution and therefore the sensitivity.

The field of view (FoV) of the core stations within a diameter of 2 km is 4.8×10^{-3} sq.deg. Including remote stations LOFAR has longest baseline of 80 km and therefore the FoV is $2.72 \times^{-6}$ sq.deg., however, European stations will make the resolution much better by adding baselines of the order of a few hundreds of km, at 500 km baseline the FoV is $3.87 \times^{-10}$ sq.deg. Therefore, 52 tied array beams needs to be synthesized out of the 18 core stations, to cover the visible lunar surface which has a FoV 0.25 sq.deg. Beam forming with remote stations and European stations is not possible online, therefore, only core stations will be configured in tied array mode for online triggering.

IV. Results and Discussion

The System Equivalent Flux density (or sensitivity) is defined as

$$S_{sys} = \frac{2\eta k}{A_{eff}} T_{sys} \tag{1}$$

where k denotes Boltzman's constant, η denotes the system efficiency factor $(= 1.0)$, T_{sys} denotes the system noise temperature which is sum of sky temperature and instrument temperature. The sensitivity of core stations at 150 MHz is 113 Jy, while the sensitivity of core and remote stations is 45 Jy. Including European stations will results in a sensitivity of 24 Jy. During an observation of 90 days, statistically one expects no pulse above

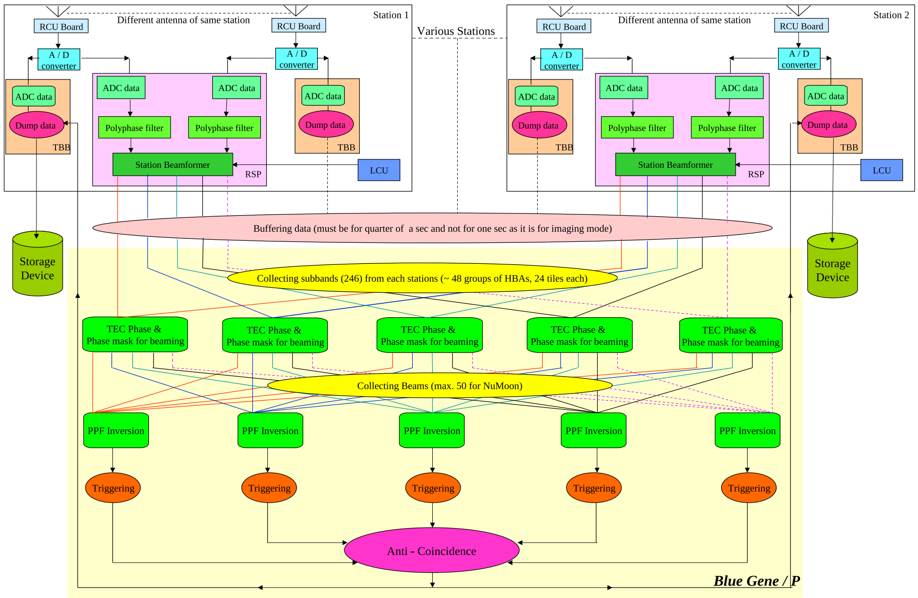

Fig. 2. Online data processing for UHE neutrinos and cosmic rays at LOFAR.

a detection threshold of $25 \times S_{sys}$ except for pulses generated from the impact of UHE particles on the moon. Not observing a pulse allows thus for setting limits on the flux of UHE particles as indicated in (Fig. 3) for cosmics and in (Fig. 4) for neutrinos. The limits are determined on the basis of a simulation done for a central frequency of $\nu = 150$ MHz and a bandwidth of $\Delta\nu = 50$ MHz. It is assumed that triggering is done on core stations and that data from remote stations and European stations will also be available for off-line processing. In addition, due to the sharp position resolution with the European stations we are able to reduce pulsed noise by two orders of magnitude.

To estimate the efficiency to observe UHE cosmic rays the Pierre Auger data [11] is plotted in (Fig. 3). The sensitivity limit is calculated for 90 days of accumulated observing time. A power-law with spectral index 3.3 is plotted which meets the expected sensitivity. For a power-law with spectral index 4.4, appropriate for energies above 4×10^{19} eV, we would not be able to observe any event. Although, in the presence of local sources one may expect a lower value for the spectral index at the highest energies.

In Fig. 4 the sensitivity for neutrino flux detection is compared with other experiments such as ANITA [12], FORTE [13], and GLUE [4] and theoretical models [14]. With 90 days of observation we will be able to improve the limit on the neutrino flux by three orders of magnitude compared to the FORTE limit [13]. With WSRT a flux limit has been achieved which is an order of magnitude lower than the current FORTE limit [6], [7]. With LOFAR the neutrino flux limit will reach well below the Waxman-Bahcall bound for neutrinos [15]. The removal of pulsed noise by better pointing resolution on the Moon will lower the detectable energy threshold of Neutrinos and may reach 10^{21} eV.

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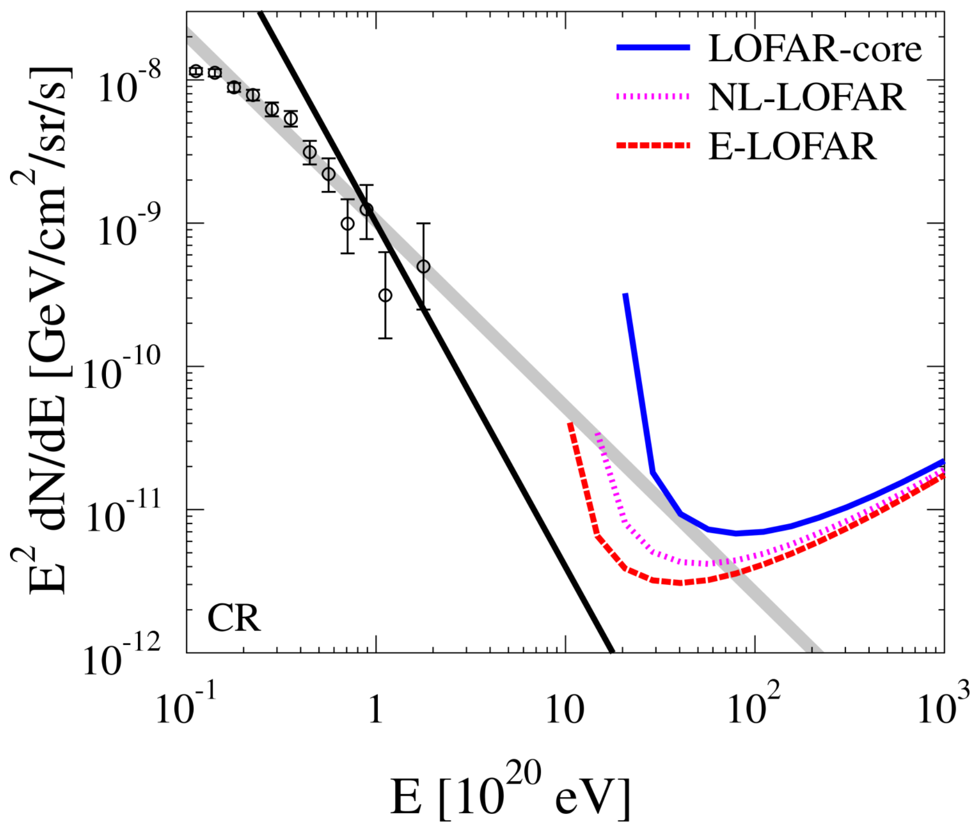

Fig. 3. Expected detection limits on cosmic ray flux with LOFAR for a 90 days observation.

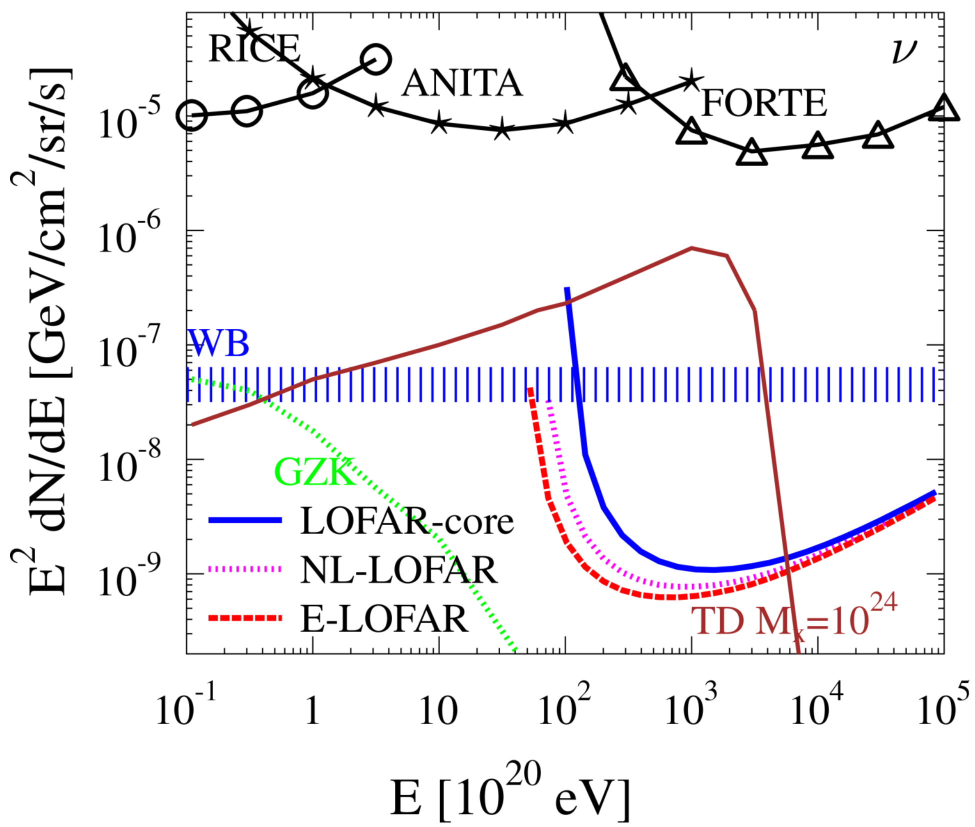

Fig. 4. Sensitivity limit expected for detection of Ultra-High Energy Neutrinos within 90 days.