Nuclear Instruments and Methods in Physics Research A 662 (2012) S26–S28

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Detecting ultra high energy neutrinos with LOFAR

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A R T I C L E   I N F O

Available online 11 November 2010

Keywords:
Lunar Cherenkov technique
UHE neutrinos
Cosmic rays
LOFAR

A B S T R A C T

The NuMoon project aims to detect signals of Ultra High Energy (UHE) Cosmic Rays with radio telescopes on Earth using the *Lunar Cherenkov technique* at low frequencies ($\sim$ 150 MHz). The advantage of using low frequencies is the much larger effective detecting volume, with as trade-off the cut-off in sensitivity at lower energies. A first upper limit on the UHE neutrino flux from data of the Westerbork Radio Telescope (WSRT) has been published, while a second experiment, using the new LOFAR telescope, is in preparation. The advantages of LOFAR over WSRT are the larger collecting area, the better pointing accuracy and the use of ring buffers, which allow the implementation of a sophisticated self-trigger algorithm. The expected sensitivity of LOFAR reaches flux limits within the range of some theoretical production models.

1. Introduction

The NuMoon project aims to detect the radio signals that are emitted, through the Askaryan effect, when an UHE cosmic ray or neutrino hits the Moon. NuMoon specifically searches for signals in the low frequency range ($\sim$ 150 MHz). An initial measurement has been performed with the low frequency front-ends (LFFEs) of the Westerbork Synthesis Radio Telescope (WSRT), while an experiment with the Low Frequency Array (LOFAR) is in preparation. After a general introduction on the signal efficiency at low frequencies and the presentation of the results of WSRT, we will discuss the specific issues of performing this measurement with the LOFAR telescope.

2. Detection principle

The maximum intensity of the coherent Cherenkov emission is reached at a frequency of about 3 GHz, where the emitted radiation is concentrated in a narrow cone around the Cherenkov angle. The intensity drops at lower frequencies, but the angular spread of the emission increases. For a shower parallel to the surface of the Moon, the Cherenkov angle corresponds to that of total internal reflection. Therefore, for high frequencies, only the few cosmic rays that skim the rim of the Moon, directed towards Earth, can be detected. For lower frequencies (between 100 and 200 MHz), even at large incoming cosmic-ray angles the radiation can escape the surface of the Moon, and as a result, the total surface of the Moon may emit detectable signals [1]. A major advantage of using the Moon for the detection of UHE neutrinos is the rather long attenuation length of $\lambda_r = 9\ \mathrm{m}/\nu$ (GHz) for radio waves, which makes a very large detection volume. As a result the detection efficiency increases with about the third power of the wavelength. A trade-off for the larger detection probability at low frequencies is the lower intensity of the signal and therefore the loss of sensitivity at lower energies.

3. WSRT observations

The emission of 3 m radio waves from impacts of high energy neutrinos on the Moon is exploited in our observations with WSRT and has resulted in the most stringent flux limit at the highest energies [2]. The WSRT consists of an array of 14 parabolic antennas of 25 m diameter. Only 11 of the 12 equally spaced WSRT dishes were used for this experiment. In the observations we employed the LFFEs which cover the frequency range 115–180 MHz with full polarisation sensitivity, sampled as eight sub-bands of 20 MHz each by the Pulsar Machine II (PuMa II) backend [3]. We observed with two different beams aimed at different sides of the Moon, with four frequency bands centred at frequencies of 123, 137, 151 and 165 MHz. This created the possibility of an anti-coincidence trigger

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doi:10.1016/j.nima.2010.11.018

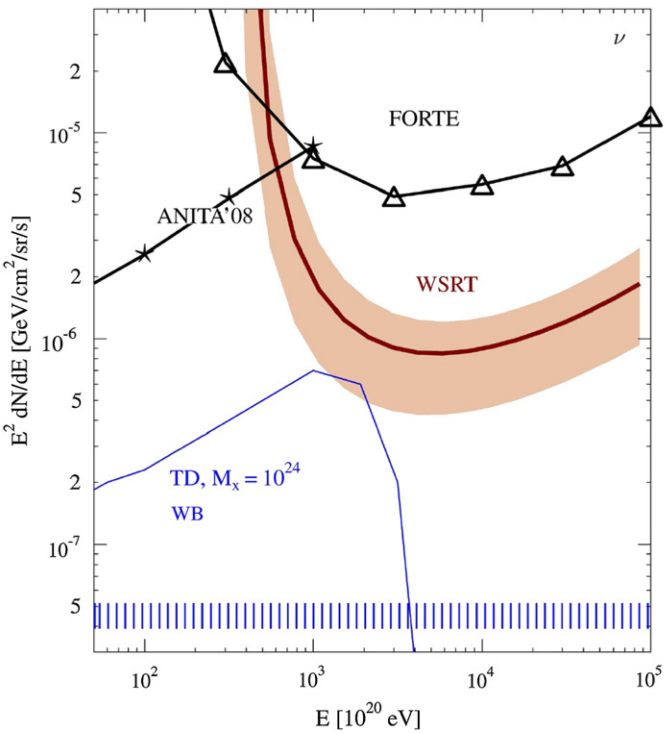

Fig. 1. The limit [2] on the flux of UHE neutrinos obtained from observations with the WSRT is compared with those of other experiments and some model calculations.

since a lunar Cherenkov pulse should only be visible in one of the two beams. The total bandwidth per beam was 65 MHz. The time-series data was recorded for each sub-band with a sampling frequency of 40 MHz. The data was processed in blocks of 0.1 s, where each block was divided into 200 traces of 20,000 time samples.

In an effective observation time of 40 h no pulses were observed above the noise threshold, resulting in the 90% confidence upper limit on the neutrino flux shown in Fig. 1. The limit is almost an order of magnitude better than previous limits in the UHE region set by ANITA [4] and FORTE [5]. The same data has been used to establish an upper limit on the UHE cosmic ray flux [6].

4. LOFAR

We are currently setting up an experiment with the high-band antennas (100–200 MHz) of the LOFAR radio-telescope. LOFAR consists of several stations, which in turn are build up from fields of relatively simple dipole antennas. The central core (24 stations, with a maximum baseline of about 2 km) is located in the northern part of the Netherlands. Also remote (16 stations with baselines of the order of 100 km) and several international stations (~ 1000 km) are either planned or existing already. LOFAR provides many advantages over WSRT. Not only can a higher sensitivity be reached due to the larger collecting area (~ 3 times that of WSRT for the core of LOFAR), but also the pointing accuracy will allow us to determine the location of an event position on the Moon with much better precision, important for RFI discrimination. The multi-beam possibility allows for the formation of sufficiently many coherent beams to cover the complete lunar surface. A third advantage is the Transient Buffer Boards. These will store the raw antenna data for a short time, which allows the implementation of an advanced self-trigger algorithm. Furthermore, once a trigger is issued, the full resolution, full-bandwidth time-series data can be stored for off-line analysis.

In order to considerably reduce the raw data rate of ~ 1 Tb/s, a fast and efficient trigger algorithm is needed. For the trigger itself, only data of the central core stations will be considered. Half the bandwidth of the station data will be send to the Blue-Gene/P supercomputer in Groningen, where the data will be coherently added to form ~ 50 beams to cover the full surface of the Moon. A short time (few ns) peak will be searched for in the time-series data, with the requirement that a peak will only be visible in one or few of the beams. Once a trigger is issued, ~ 1 ms of raw data from all stations will be written to disk for off-line analysis. An important issue, especially at low frequencies, is the frequency-dependent dispersive effect of the ionosphere. At LOFAR-frequencies a typical ionospheric electron content of 10 TEC-units (*TECU*, 10^{16} electrons/m^2) causes a dispersion which spreads the original input signal of a few ns over several time-bins, as illustrated in Fig. 2. In order to still be able to extract the signal the data needs to be de-dispersed. To accomplish this, the absolute electron content of the ionosphere needs to be known online with an accuracy of about 1 TECU.

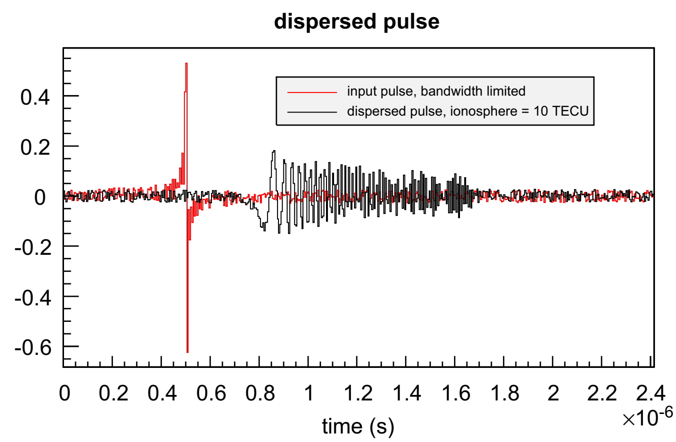

Fig. 2. Time series of a dispersed pulse, for a typical ionosphere of 10 TECU. The original ns bandwidth limited pulse is spread over several bins due to the dispersion.

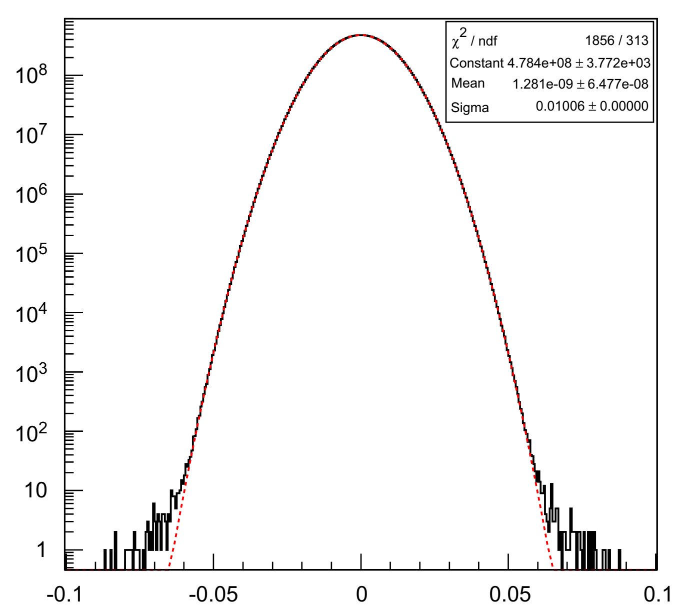

Fig. 3. Histogram of the amplitudes of the time series of a limited test data set. The histogramscontain in total 2 min of beam formed data of six core stations pointing at the Moon. The bandwidth of this data set was limited to about 10 MHz around 145 MHz. The level of non-Gaussian (i.e. transient) noise is small compared to the Gaussian.

This can be improved in the off-line analysis. An interesting approach is measuring the absolute TEC value via the Faraday rotation of polarised light due to ionospheric plasma and the Earth magnetic field. We are currently investigating the possibility to use the polarised light of the rim of the Moon to this extent.

So called *transient noise*, i.e. short-time noise pulses, is of major concern since it may mimic our signal. To reduce the trigger rate and therefore the dead-time of the system, it needs to be identified and ignored with good accuracy in the online trigger. In the off-line analysis noise pulses need to be fully eliminated. We are currently investigating the properties of this noise in test data. Fig. 3 shows the histogram of amplitudes for a test data set of limited bandwidth ($\sim$10 MHz). The histogram contains 2 min of data of six core stations pointing at the Moon. The spectrum is clearly Gaussian on a relatively small non-Gaussian background, which is due to transient noise events. Although the level of transient noise appears to be small from this figure, it is important to realise that these events do result in a trigger, and therefore even these levels of noise need to be suppressed.

We can mimic the behaviour of the online trigger by performing all the online steps in the off-line analysis. Furthermore, since in the off-line analysis we have the full time resolution data of all antennas, we have the freedom to form a beam in any direction and thus determine the origin of the noise. This way, we hope to be able to detect any anisotropy, especially for beams pointing on and off the Moon, in order to see if the noise level is increased e.g. due to reflections from the Moon.

The transient noise level, combined with the allowed trigger-rate, will directly define the trigger threshold and therefore our sensitivity. It is expected that the resolution of LOFAR, which will be even better when the longer baselines are included in the off-line analysis, will be sufficient to discriminate signals from the Moon from man-made noise. Also, specific signatures like the ionospheric dispersion can be used to discriminate between pulses originating from the Moon and those that are Earth-based and possibly reflected.

5. Outlook

In Fig. 4 the neutrino flux sensitivity is indicated that can be reached with one month of observation with LOFAR. The sensitivity is such that one month of accumulated time should result in a large number of observed events for a neutrino flux at the level of the Waxman–Bahcall limit [7]. In the same figure the expected sensitivities of the Square Kilometre Array (SKA) are shown (three months of observing time), both for the low 'LFB' (100–300 MHz band) and intermediate 'MFB' (300–500 MHz) frequencies.

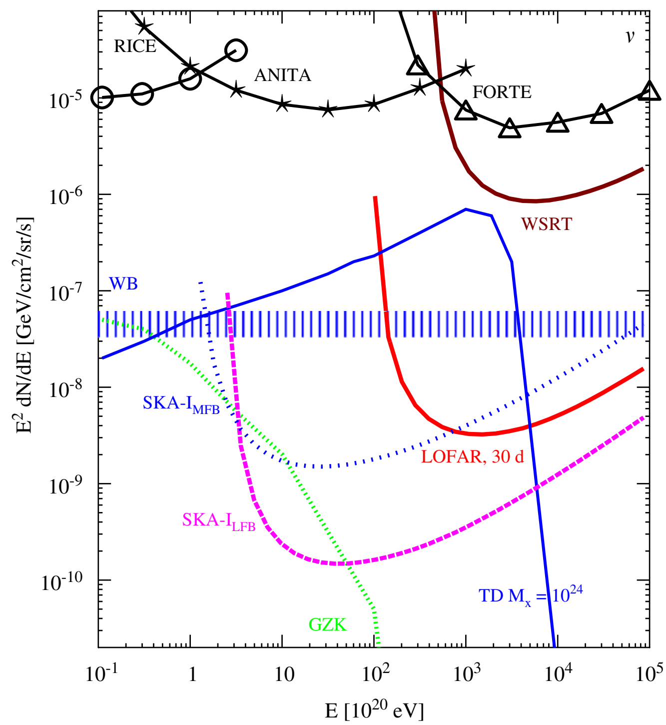

Fig. 4. Expected sensitivities on the neutrino flux of LOFAR and SKA compared to earlier experimental upper limits and some models. The LOFAR sensitivity is shown for 30 days of data taking. Also shown are the expected sensitivity curves of the SKA for low (*LFB*, 100–300 MHz) and intermediate frequencies (*MFB*, 300–500 MHz) after 3 months of observing time.

Expected SKA sensitivities are such that neutrinos from decay products of GZK interactions – using the predictions by Ref. [8] – can be observed.

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