

# Detecting UHE Cosmics & Neutrinos off the Moon; an Optimal Radio Window.

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**Abstract.** We show that at wavelengths comparable to the length of the shower produced by an Ultra-High Energy cosmic ray or neutrino, radio signals are an extremely efficient way to detect these particles. Through an example it is shown that this new approach offers, for the first time, the realistic possibility of measuring UHE neutrino fluxes below the Waxman-Bahcall limit. It is shown that in only one month of observing with the upcoming LOFAR radio telescope, cosmic-ray events can be measured beyond the GZK-limit, at a sensitivity level of two orders of magnitude below the extrapolated values.

## 1. Introduction

As an efficient method to determine the fluxes of UHE particles we are investigating the production of radio waves when an UHE particle hits the moon. Askaryan predicted as early as 1962 [1] that particle showers in dense media produce coherent pulses of microwave Čerenkov radiation. Recently this prediction was confirmed in experiments at accelerators [2] and extensive calculations have been performed on the development of showers in dense media to yield quantitative predictions for this effect [3]. The Askaryan mechanism lies at the basis of several experiments to detect (UHE) neutrinos using the Čerenkov radiation emitted in ice caps [4, 5], salt layers [6], and the lunar regolith. The pulses from the latter process are detectable at Earth with radio telescopes, an idea first proposed by Dagkesamanskii and Zheleznyk [7] and later by others [8]. Several experiments have since been performed [9, 10] to find evidence for UHE neutrinos. All of these experiments have looked for this coherent radiation near the frequency where the intensity of the emitted radio waves is expected to reach its maximum. Since the typical lateral size of a shower is of the order of 10 cm the peak frequency is of the order of 3 GHz.

We propose a different strategy [11] to look for the radio waves at considerably lower frequencies where the wavelength of the radiation is comparable in magnitude to the typical longitudinal size of showers. We show that the lower intensity of the emitted radiation, which implies a loss in detection efficiency, is compensated by the increase in detection efficiency due

to the near isotropic emission of coherent radiation. The net effect is an increased sensitivity by several orders of magnitude for the detection of UHE cosmic rays and neutrinos at frequencies which are one or two orders of magnitude below that where the intensity reaches its maximum. At lower frequencies the lunar regolith becomes increasingly transparent for radio waves. This implies for the detection of UHE neutrinos that there are two gain factors when going to lower energies; i) Increased transparency of the lunar regolith already stressed in Ref. [12], and ii) Increased angular acceptance, stressed in this work.

In Section 4 we discuss two specific observations, one for an existing facility, the Westerbork Synthesis Radio-Telescope array (WSRT) where we have observation time granted, and one for a facility which will be available in the near future, the Low-Frequency Array (LOFAR).

## 2. Model for Radio Emission

There exist two rather different mechanisms for radio emission from showers triggered by UHE cosmic rays or neutrinos. One is the emission of radio waves from a shower in the terrestrial atmosphere. Here the primary mechanism is the synchrotron acceleration of the electrons and positrons in the shower due to the geomagnetic field, called geosynchrotron radiation [12, 13, 14, 15, 16]. The second mechanism applies to showers in dense media where the front end of the shower has a surplus of electrons. Since this cloud of negative charge is moving with a velocity which exceeds the velocity of light in the medium, Čerenkov radiation is emitted. For a wavelength of the same order of magnitude as the typical size of this cloud, which is in the radio-frequency range, coherence builds up and the intensity of the emitted radiation reaches a maximum. This process, known as the Askaryan effect [1] is the subject of this work.

The intensity of radio emission (expressed in units of Jansky's where  $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2}\text{Hz}^{-1}$ ) from a hadronic shower, with energy  $E_s$ , in the lunar regolith, in a bandwidth  $\Delta\nu$  at a frequency  $\nu$  and an angle  $\theta$ , can be parameterized as [11]

$$F(\theta, \nu, E_s) = 3.86 \times 10^4 e^{-Z^2} \left( \frac{\sin \theta}{\sin \theta_c} \right)^2 \left( \frac{E_s}{10^{20} \text{ eV}} \right)^2 \times \left( \frac{d_{moon}}{d} \right)^2 \left( \frac{\nu}{\nu_0(1 + (\nu/\nu_0)^{1.44})} \right)^2 \left( \frac{\Delta\nu}{100 \text{ MHz}} \right) \text{ Jy}, \quad (1)$$

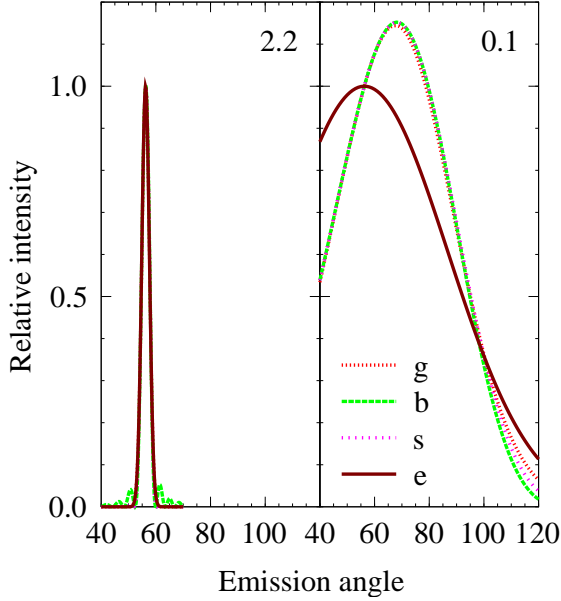
with

$$Z = (\cos \theta - 1/n) \left( \frac{n}{\sqrt{n^2 - 1}} \right) \left( \frac{180}{\pi \Delta_c} \right), \quad (2)$$

where  $\nu_0 = 2.5 \text{ GHz}$  [10],  $d$  is the distance to the observer, and  $d_{moon} = 3.844 \times 10^8 \text{ m}$  is the average Earth-Moon distance. The angle at which the intensity of the radiation reaches a maximum, the Čerenkov angle, is related to the index of refraction ( $n$ ) of the medium,  $\cos \theta_c = 1/n$ . Crucial for our present discussion is the spreading of the radiated intensity around the Čerenkov angle, given by  $\Delta_c$  (in degrees). The  $\sin \theta$  factor in Eq. (1) reflects the projection of the velocity of the charges in the shower on the polarization direction of the emitted Čerenkov radiation. The dependence of  $Z$ , defined in Eq. (2), is suggested by working out some specific cases, as presented in a following paragraph. For small values of  $\Delta_c$  it coincides with the formula found in much of the literature [3, 8, 10] however, Eq. (1) is more accurate for large spreading angles.

The spreading of the radiated intensity around the Čerenkov angle,  $\Delta_c$ , is, on the basis of general physical arguments, inversely proportional to the shower length and the frequency of the emitted radiation. Based on the results given in Ref. [8] it can be parameterized as

$$\Delta_c = 4.32^\circ \left( \frac{1}{\nu [\text{GHz}]} \right) \left( \frac{L(10^{20} \text{ eV})}{L(E_s)} \right), \quad (3)$$



**Figure 1.** The angular spread around the Čerenkov angle for different shower-profile functions (see text) are compared to the parametrization used in this work. The left (right) hand displays the results for 2.2 GHz (100MHz) respectively.

where  $L(E_s)$  is the shower length which depends on the energy. In Ref. [17], values are given for the shower length (in units of radiation lengths, equal to  $22.1 \text{ g/cm}^2$  for lunar regolith). At an energy of  $10^{20}$  eV this corresponds to a shower length of approximately 1.7 m.

Since the angular spread of the intensity of the Čerenkov radiation around the Čerenkov angle for the case  $\lambda \approx L$  is crucial for our considerations, we have derived an analytic formula for the angular distributions for two different shower profiles following the approach given in [5]. For the first one, called the “block” profile, the number of charged particles is constant over the shower length  $L = L_b$ ,  $\rho_b(x) = 1$  for  $0 < x < L_b$ . This profile is not realistic for a shower as the full intensity suddenly appears and disappears. For this reason we have also investigated a second profile where the charge in the shower appears and disappears following a sine profile,  $\rho_s(x) = \sin \pi x / L_s$  with  $0 < x < L_s$ .

For the block longitudinal profile we reproduce the well known intensity distribution found by Tamm [18] for a finite length shower, normalized to unity at the Čerenkov angle,  $I_b(\theta) = \left[ \frac{\sin \theta}{\sin \theta_c} \frac{\sin \pi \chi}{\pi \chi} \right]^2$  with  $\chi = (\cos \theta - 1/n)L/\lambda$ . For the normalized “sine” profile we obtain

$$I_s(\theta) = \left[ \frac{\sin \theta}{\sin \theta_c} \frac{\cos \pi \chi}{(1 - 2\chi)(1 + 2\chi)} \right]^2 \quad (4)$$

The predictions of these two formulas are compared (curves labelled ‘b’ for block and ‘s’ for sine in Fig. 1) with the exponential form used in Monte Carlo simulations [3, 8, 10],  $I_e(\theta) = e^{-((\theta - \theta_c)/\Delta_c)^2}$  with  $\Delta_c$  is given by Eq. (3). The comparison is made for a shower of  $10^{20}$  eV. To reproduce the angular spread of this calculation at 2.2 GHz we choose  $L_b = 2.5$  m and  $L_s = L_b \times 4/3 = 3.4$  m. The results are also compared to those for a gaussian profile, derived in [5],  $I_g(\theta) = \left[ \frac{\sin \theta}{\sin \theta_c} \right]^2 e^{-Z^2}$ , with  $Z$  given by Eq. (2) (curve labelled ‘g’ in Fig. 1). From Fig. 1 it is seen that at 2.2 GHz the simple exponential form is reproduced well by all three analytic forms. The block profile shows the well known secondary interference maxima, due to the sharp edges of the profile, which are not realistic for our case. Keeping parameters fixed the angular distributions are now compared at 100 MHz (right hand panel of Fig. 1). All three analytic forms agree quite accurately but differ considerably from the exponential form. The reason for this difference lies mainly in the pre-factor  $\sin^2 \theta$  which accounts for the radiation

being polarized parallel to the shower which does not allow for emission at  $0^\circ$  and  $180^\circ$ . On the basis of the arguments given above we have used the gaussian parametrization in Eq. (1).

The analytic formulas also work remarkably well at the quantitative level. At an energy of  $10^{20}$  eV the length of the shower is 1.7 m, as found in Ref. [17]. The value for the length used in Eq. (4) is  $L_s = 3.4$  m. For a sine profile the density of charged particles exceeds 70% of the maximum value (the definition of shower length) for only half this distance (i.e. 1.7 m) which is in excellent agreement with the shower length found the Monte-Carlo simulations.

Cosmic-ray-induced showers occur effectively at the lunar surface. For neutrino-induced showers an energy-dependent mean free path has been used,  $\lambda_\nu = 130 \left( \frac{10^{20} \text{ eV}}{E_\nu} \right)^{1/3}$  km. As a mean value for the attenuation length for the radiated power in the regolith we have taken  $\lambda_r = (9/\nu[\text{GHz}])$  m.

A crucial point in the simulation is the refraction of radio waves at the lunar surface as was already stressed in Ref. [3]. Due to internal reflection at the surface the emitted radiation at high frequencies where the Čerenkov cone is rather narrow will be severely diminished. The major advantage of going to lower frequencies is that the spreading increases, allowing for the radiation to escape from the lunar surface. With decreasing frequency the peak intensity of the emitted radiation decreases, however, the peak intensity increases with increased particle energy. The net effect is that at sufficiently high shower energies the aforementioned effect of increased spreading is far more important, resulting in a strong increase in the detection probability.

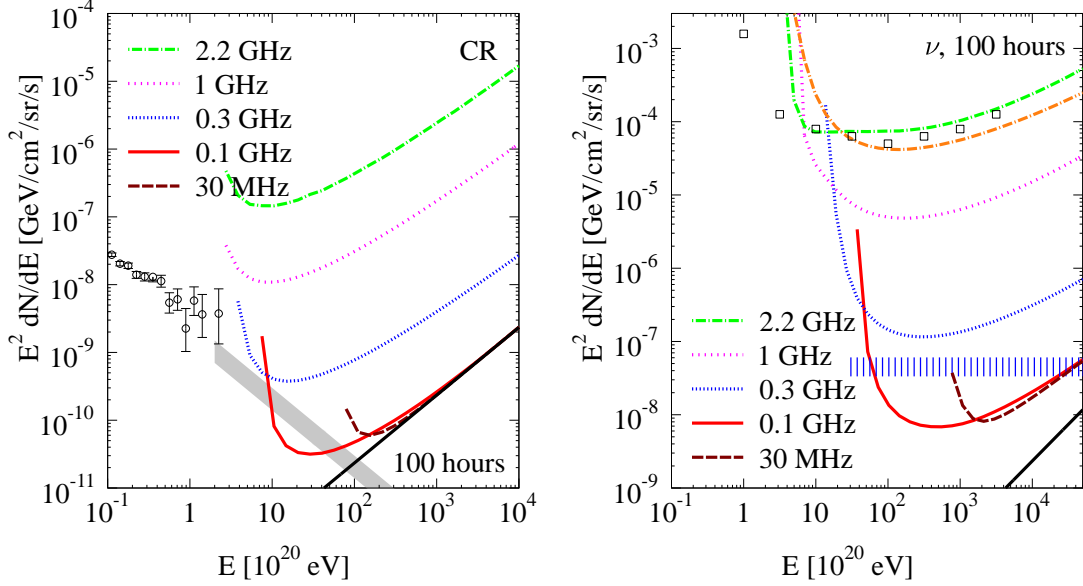
An additional advantage of using lower frequencies is that the sensitivity of the model simulations to large- or small-scale surface roughness is diminished. Since at lower frequencies already a sizable fraction of the radiation penetrates the surface, its roughness will not make a major difference. This is in contrast to high frequencies where most of the radiation is internally reflected when surface roughness is ignored.

### 3. Detection Limits

In Fig. 2 the detection limits for UHE cosmic rays for different radio-frequency ranges are compared with data from the AGASA [19] (points) and a linear extrapolation based on the data from the HiRes experiment [20] (grey bar). We regard an event to be detectable when the power of the signal is 25 times larger than the “noise level” which we take equal to  $F_{noise} = 20$  Jy, using a bandwidth of  $\Delta\nu = 20$  MHz, values typical for LOFAR. It should be noted that for  $\nu = 30$  MHz there is a strong increase in the sky temperature and we have used a ten-fold higher threshold. As a result of the higher detection threshold the flux limit lies considerably higher.

From the l.h.s. of Fig. 2 one clearly sees that with decreasing frequency one loses sensitivity for lower-energy particles. This follows directly from Eq. (1) since with decreasing frequency the maximum signal strength decreases and thus one exceeds the detection threshold only for more energetic particles. If the energy of the cosmic ray is more than a factor 4 above this threshold value the analysis presented in the previous section applies and the detection limit improves rapidly with decreasing radio-frequency until one reaches a frequency of 100 MHz where one obtains the optimum sensitivity. Decreasing the frequency even lower provides no gain since the detection limit has already reached the optimum given by the heavy black line in Fig. 2.

In the r.h.s. of Fig. 2 we compare the detection limits for UHE neutrinos at different frequencies with the results obtained from the GLUE experiment [10]. For neutrino-induced showers only 20% of the initial energy is converted to a hadronic shower, while the remaining 80% is carried off by the lepton. This energetic lepton will not induce a detectable radio shower. One sees similar trends as in the predictions for cosmic rays, in particular the large gain in the determined flux limits with decreasing frequency. At higher energies the limits for neutrinos do not increase as steeply as those for cosmic rays. This is because the neutrino mean-free-path



**Figure 2.** Flux limits (assuming a null observation) for cosmic rays (l.h.s.) and neutrinos (r.h.s.) as can be determined in a 100 hour observation (see text). In the curves for  $\nu = 30$  MHz a ten fold higher detection threshold is used, corresponding to the higher sky temperature at this frequency. The points given in the r.h.s. correspond to the data of the AGASA experiment [19], the grey band is an extrapolation of the HiRes data [20]. The thick black line corresponds to the best possible limit (vanishing detection threshold). The open squares for the neutrino flux are the limits determined from the GLUE experiment [10].

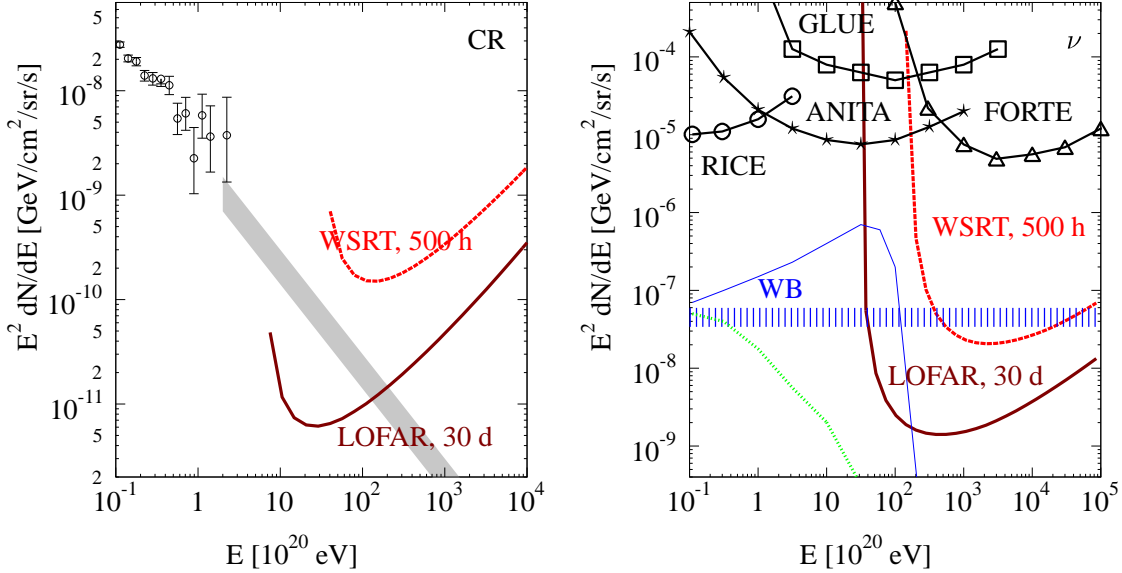
decreases with energy, therefore increasing the probability for the neutrino to initiate a shower close to the surface where the attenuation of the radio waves is small. Our result at 2.2 GHz lies close to that of the GLUE experiment.

#### 4. WSRT & LOFAR predictions

The Westerbork Synthesis Radio Telescope (WSRT) [21] consists of fourteen 25 m parabolic dishes located on an east-west baseline extending over 2.7 km. Elements of the array can be coherently added to provide a response equivalent to that of a single 94 m dish. Observing can be done in frequency bands which range from about 115 to 8600 MHz, with bandwidths of up to 160 MHz. The low frequency band which concerns us here covers 115-170 MHz. In tied-array mode the system noise at low frequencies is  $F_{noise} = 600$  Jy. To observe radio bursts of short duration, the new pulsar backend (PuMa II) will be used. In the configuration which we propose to use, four frequency bands will observe the same part of the moon with the remaining four a different section. In total, coverage of about 50% of the lunar disk can be achieved. We have recently obtained 500 hours observing time of which 200 hours are granted for the first year.

An even more powerful telescope will be the LOFAR array [22]. With a collecting area of about  $0.05 \text{ km}^2$  in the core (which can cover the full moon with an array of beams), LOFAR will have a sensitivity about 25 times better than that of the WSRT. LOFAR will operate in the frequency bands from 30-80 and 115-240 MHz.

Simulations show that a pulse of intensity  $25 \times F_{noise}$ , interfering with the noise background, can be detected with  $3\sigma$  significance at a probability greater than 80%. For this reason we have assumed in the calculations a detection threshold of  $25 \times F_{noise}$  for both the WSRT and the LOFAR telescopes. A simulation for LOFAR, taking  $\nu = 120$  MHz, bandwidth of  $\Delta\nu = 20$  MHz,



**Figure 3.** left: Flux limits on UHE cosmic rays (r.h.s.) and neutrinos (r.h.s.) as can be determined in a 30 day observation with the LOFAR antenna system and a 500 hour observation with WSRT. The data cosmic rays are the same as in Fig. 2. The flux limits on UHE neutrinos are compared with various models, in particular, WB [23] (vertical bars), GZK [24] (dotted thin line), and TD [25, 26] (solid thin line). The experimental limits on the neutrino flux are from the RICE [27], GLUE [10], ANITA [28], and FORTE [5].

a signal-detection threshold of 500 Jy, and an observation time of 30 days is shown in Fig. 3 for cosmic rays and neutrinos. The results are compared with the limits that can be obtained from a presently proposed observation for 500 hours at the WSRT observatory assuming a detection threshold of 15,000 Jy,  $\nu = 140$  MHz, bandwidth of  $\Delta\nu = 20$  MHz, and a 50% Moon coverage.

In Fig. 3 the flux limits are compared to the predictions of several models and with those of other experiments. With the existing WSRT a limit on the neutrino flux can be set which falls just below the WB bound. However, even this will constrain different top-down scenarios, discussed in the literature. With the proposed LOFAR facility this limit can be improved considerably to reach, for the first time, a limit well below the WB bound for neutrinos. In addition one has a good chance to see evidence (in only a 30 day period) of cosmic ray events at an energy one order of magnitude higher than presently observed.

## 5. Summary

We have demonstrated [11] the clear advantage of using radio waves at frequencies well below the Čerenkov maximum. The optimum frequency will be that where the length of the shower, of the order of several meters in the lunar regolith, is of the same order of magnitude as the wavelength of the radio waves where the radio-emission pattern is more isotropic. The gain in efficiency at lower frequencies is such that with the upcoming LOFAR facility one can seriously investigate realistic top-down scenarios for UHE neutrinos and be sensitive to neutrino fluxes well below the Waxman-Bahcall limit. Even now with the existing WSRT, profiting from its capability to measure right in the radio-frequency window where the detection efficiency is highest, one is able to set limits on neutrino fluxes orders of magnitude below the present limit in only a 500 h observation period.

For UHE cosmic rays the LOFAR facility offers, because of the availability of an optimal



radio-frequency window, a very powerful tool to determine the flux beyond the GZK limit. In only a 30 day observing period one is sensitive to a flux which is more than one order of magnitude below the extrapolation of the measured flux from below the GZK limit.

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