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PeVatron Search Using Radio Measurements of Extensive Air Showers at the South Pole

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Abstract. The Galactic Center is visible from the South Pole throughout the year, at an inclination of 61°. High energy gamma-rays arriving at the South Pole from this direction, will produce inclined air showers in the atmosphere. Since radio emission of inclined showers leaves a large footprint on the ground, a measurement of the electromagnetic shower component using the radio technique is possible. It is already known that radio detection of air showers helps in the reconstruction of the shower maximum and the energy of the air shower with a very good accuracy. Using radio detectors along with particle detectors enhances the detection accuracy of the air shower events and helps in separating the gamma-ray induced events. IceCube-Gen2, the proposed extension of the IceCube Neutrino Observatory, will enhance both the surface and in-ice capabilities of the facility. Ideas for adding surface radio antennas are under discussion in addition to the upgrade and extension of the IceTop surface array using scintillator detectors. While the scintillators will primarily be used for improving the calibration and lowering the veto energy threshold for distinguishing cosmic ray from astrophysical neutrino events, they can also be used with radio antennas to search for photons of PeV energies from the Galactic Center. Using such a setup at the South Pole can help in the identification of the Galactic Center as a PeVatron. In particular, the key for such a search is to use frequencies higher than the standard frequencies used by air-shower radio experiments, which thereby lowers the energy threshold.

1. Introduction

Recent observations from H.E.S.S. indicate the existence of a PeVatron at the center of our Galaxy [1]. The Cherenkov telescope was able to observe gamma-rays near to the location of Sgr A* with energies up to ≈ 40 TeV. The spectrum of these gamma-rays were not seen to have a cut-off in the observed energies. The extent of hardness of the spectrum upon extending it to PeV energies is unknown. The number of gamma-rays from the PeVatron at these energies could be non-zero. We devise a possible way to search for PeV gamma-rays from the Galactic Center.

A possible experimental location to conduct this search is that of the IceCube Neutrino Observatory. IceCube is a neutrino detector with a cubic-kilometer volume, located at the South Pole [2]. It has a complete temporal and spatial exposure to the Galactic Center, which always lies at a zenith angle of 61° at the South Pole. IceTop, the surface array of cosmic ray detectors at IceCube, is composed of ice-Cherenkov tanks [3]. The cosmic-ray setup is planned to be enhanced using an array of scintillators [4]. Apart from this, a large surface array of scintillators is also expected to be a part of IceCube-Gen2 [5]. It is also possible to include a radio antenna array along with this, forming a hybrid array of cosmic air-shower detectors. Such a hybrid array can help us in measuring the different components of the air showers (electromagnetic and muonic). This setup can be used to search for gamma-rays with PeV energy coming from the Galactic Center.

Gamma-rays will produce air showers upon entering the Earth's atmosphere. Since the gamma-rays from the Galactic Center arrive at the South Pole with a zenith angle of 61°, these PeV air showers will be inclined in nature. Hence, the particle content of these showers will be very low as the shower reaches the ground, which leaves fewer signals on the particle detectors. The radio signal from these showers, on the other hand, will reach the ground unimpeded and thus gives us a higher chance in detecting these gamma-rays.

Recent studies by the Auger Engineering Radio Array (AERA) have experimentally proven that inclined air-showers will leave a large radio footprint on the ground [6]. So a large radio footprint with a diameter of several 100 m can be expected from an air shower produced by a gamma-ray approaching the IceCube Observatory from the Galactic Center. This footprint will then be elliptical in shape due to the inclined nature of the shower.

We describe studies made on the detectability of radio signals from PeV gamma-ray showers, focusing in particular on the improvement of the signal-to-noise ratio in order to lower the energy threshold of detection to the PeV range. For this CORSIKA [7] simulations with the CoREAS [8] plugin are used to obtain the radio signals from air showers. The simulations use SIBYLL-2.1 [9] as the high energy hadronic interaction model. The radio signals obtained are convolved with the response of a a dipole antenna simulated using NEC2++ [10]. The simulations assume an antenna array where one antenna is placed at the position of each IceTop station, giving 81 antennas in total. The simulated air-showers have a fixed azimuth angle, and are oriented such that the shower axis is anti-parallel to the Magnetic North. Since the Earth's magnetic field is inclined at an angle of only 18° with respect to the vertical axis, the variation of the observed radio signal on the azimuth can be safely neglected.

2. Radio detection of inclined PeV showers

The emission of the radio signal in air showers occurs mainly due to two mechanisms: the Geomagnetic effect and the Askaryan effect. The Geomagnetic effect occurs due to the deflection of the electrons and positrons of the air shower in the Earth's magnetic field [11]. This causes the production of a time-varying current that produces radio pulses. The Askaryan effect contributes to the radio emission by the development of excess charge at the shower front as the shower propagates through the atmosphere [12]. At higher frequencies, a Cherenkov ring is visible in the radio footprint. This is the compression of radio pulses due to the refractive index of air, causing the emission from various parts of the shower evolution to arrive at the same time at certain lateral observer distances. These distances together form a ring structure [13]. The Cherenkov ring is most pronounced at high frequencies. It is not usually visible at 30-80 MHz, which is the standard frequency band for air shower experiments.

The energy range of air showers thought to be accessible with the technique of radio detection is greater than 10^{16} eV [14][15]. At energies lower than this, the radio signals become weaker and this makes it harder to separate them from the background radio noise, which is dominated by the diffuse Galactic radio noise. This is especially the case for the band 30-80 MHz, which is the most thoroughly studied frequency band for air showers. Hence, in order to measure PeV events, the signal-to-noise ratio has to be increased. Thus, it is crucial to look for the frequency band where we can lower the energy threshold for the detection of PeV gamma-rays.

2.1. *Noise estimation*
A good understanding of the noise is required to optimize the signal-to-noise ratio so that there is a better chance of observing gamma-rays from the Galactic Center. At the South Pole, the major external contribution to radio noise comes from the Galactic diffuse radio background. Apart from this, thermal noise related to the detection equipment and the surrounding ice will also have contributions. The total noise has been studied by taking these two contributions into account.

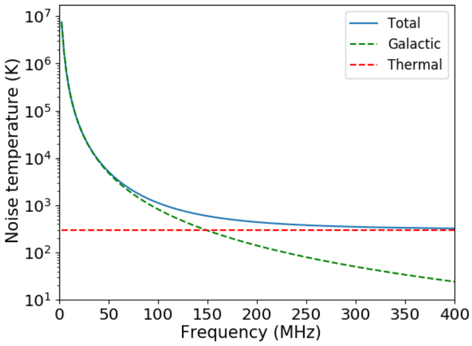


Figure 1: Noise temperature extracted from Galactic noise parametrization by Cane [16], added to a thermal noise of 300 K.

The Galactic noise contribution is taken from a model that has been developed by Cane [16], using measurements of the radio background from the South and North Galactic Poles. In addition, a thermal noise of 300 K is added. The total noise temperature from these two contributions and their behavior with respect to frequency is shown in Figure 1.

It is clear that the Galactic noise diminishes as we move to higher detection frequencies. At higher frequencies, we are mainly limited by the thermal component of noise. This indicates that the signal-to-noise ratio (SNR) could increase as we move to detection frequencies higher than the usual band of 30-80 MHz. The noise temperature from such a distribution can be converted to the power received by the antenna ($\mathrm{P} = \mathrm{k_B T} \Delta\nu$), which after convolving with the antenna response can be seen as time traces. Such time traces are then compared with the signal obtained from gamma-ray showers with energies within 1-10 PeV and a zenith angle of 61°.

2.2. *Understanding the optimum frequency band*
The signal-to-noise ratio, defined as SNR = S^2/N^2 where S is the maximum amplitude of the Hilbert envelope over the signal and N is the rms noise, can be looked at to obtain the optimum frequency bands where we have a chance of observing gamma-rays from the Galactic Center.

A scan of the SNR at different possible frequencies of operation is shown in Figure 2. The x axis shows the lower cut-off frequency of the frequency band and the upper cut-off frequency of the band is shown on the y axis.

The frequency scan in Figure 2 shows that the region in red characterizes the frequencies where a high level of signal-to-noise ratio is obtained. For example, the frequency band 100-190 MHz provides a much higher SNR for PeV gamma-ray showers from the Galactic Center. This frequency band is used for further studies.

2.3. *Zenith angle dependence*
The variation in SNR in the case of 10 PeV gamma-ray showers for various zenith angles is studied. This is done for two frequency bands: 30-80 MHz and 100-190 MHz in Figure 3 for

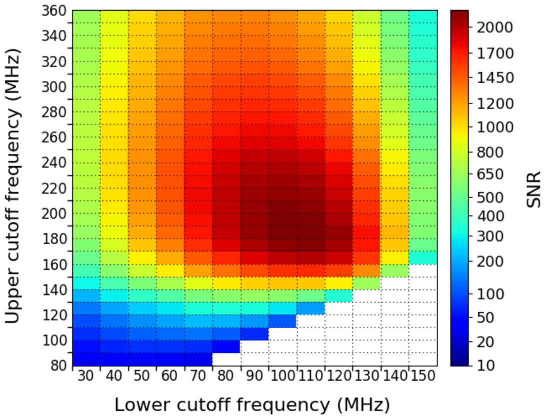
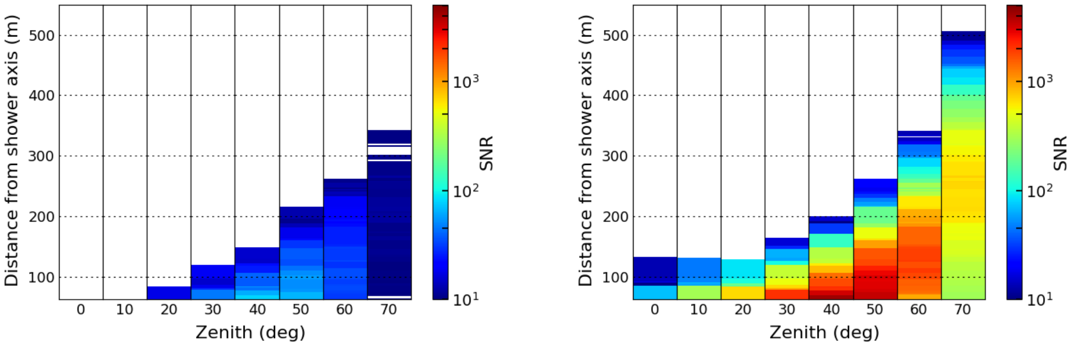


Figure 2: SNR seen in a typical antenna at a distance of 107 m from the shower axis, where the Cherenkov ring is visible, at various frequency bands. The scan is done for an air shower induced by a 10 PeV gamma-ray with a zenith angle of 61°.

antenna stations at various perpendicular distances to the shower axis. All antennas with a value of SNR less than 10 have been set to the color white, since this is the typical detection threshold in an individual antenna station. For the standard band of 30-80 MHz, the signal-to-noise ratio is significantly lower than that for 100-190 MHz. A much higher level of signal-to-noise ratio is obtained for the band 100-190 MHz for all zenith angles.



30-80 MHz.

100-190 MHz.

Figure 3: SNR for gamma-ray air showers with an energy of 10 PeV for different zenith angles for two frequency bands. Each zenith angle bin contains one typical shower.

2.4. Dependence on the primary energy

A much higher level of SNR for the frequency band 100-190 MHz when compared to the other bands indicates that this optimum band can be used for observing air showers of much lower energies than what has been achieved so far. The radio signal obtained at the antenna scales with the energy of the primary gamma-ray. This will directly influence the obtained SNR. Figure 4 shows the SNR in antennas that are hit by gamma-ray showers with a zenith angle of 61°. Each bin, with energies ranging from 1-9 PeV, contains one sample shower.

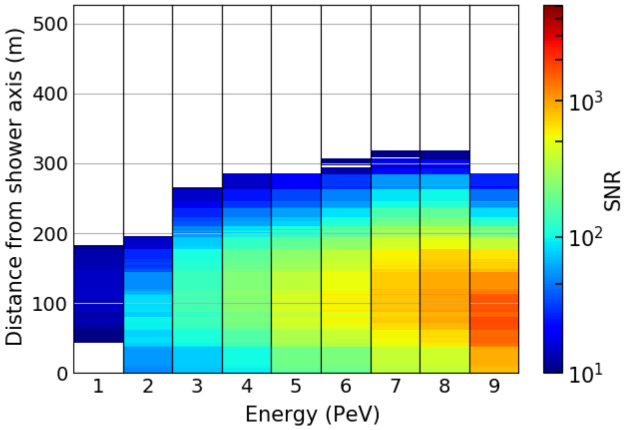


Figure 4: SNR for gamma-ray air showers of zenith angle 61° at the frequency band of 100-190 MHz. Each energy bin contains a sample shower at that energy.

3. Results and Discussion

A maximum level of SNR at the frequency band of 100-190 MHz makes it possible to lower the energy threshold for radio detection in this band. It is clear that for gamma-ray showers of inclination 61°, the threshold energy for the detection of radio signals can be lowered down to the level of 1 PeV. In order to detect these showers, a minimum of three antennas with a SNR greater than 10 should exist within a distance of around 50-180 m from the shower axis. This is for an antenna array with an average spacing of 125 m at the South Pole. The existence of cosmic-ray particle detectors at the IceCube Neutrino Observatory brings the possibility of triggering the antennas using the IceTop tanks and scintillators. Such an array at the South Pole can open new frontiers in the field of cosmic-ray and gamma-ray science.

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