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The Radio Air Shower Test Array (RASTA) – enhancing the IceCube observatory

THE ICECUBE COLLABORATION[1], THE ARA COLLABORATION[2]
[1]*See special section in these proceedings*
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Abstract: Radio detection offers the opportunity to measure cosmic ray induced air showers at greater than PeV energies via their electromagnetic emission in the MHz region. We intend to use this technique to extend the capability of the IceCube and IceTop detectors at the South Pole to measure cosmic ray observables. The radio emission is dominated by the electron contribution in the shower maximum, hence providing an integral measure of the shower development. It supplements the measurement of high energetic muons deep in the ice by IceCube and the sampling of the air shower on the surface by IceTop. Using these new, complementary observables, a radio extension can improve the measurement of the composition of cosmic rays. Further, the surface radio detector will increase the neutrino sensitivity of IceCube by providing a veto for air showers. It also may allow the study of photon induced air showers, which contain a smaller muon component than air showers induced by charged particles. We present simulation and experimental studies demonstrating the feasibility and providing a first impression of the physics potential of this approach.

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1 Introduction

After first being discovered in the late 1960s [1], radio emission of air showers has again received increasing interest in the past years. This is mainly due to the achievements in information technology, which open the possibility to use phased arrays of radio antennas in combination with digital beam forming. Its main advantages are low cost and simple design of the radio antennas as compared to classical air shower detector elements (such as scintillators or photomultipliers) and the very large field of view provided by the phased array (usually close to 2π sr). A first proof of this technology has been provided by the LOPES experiment [2, 3], a prototype setup for LOFAR – a multi-site, multi-purpose radio telescope spanning half of Europe. Radio technology is today also being developed as an extension at many existing air shower experiments (KASCADE-Grande, Pierre Auger Observatory, Tunka, ...).

In this paper, we will first outline the physics motivation for an extension of the IceCube observatory with an extended $\mathcal{O}(10)$ km^2 radio array, then describe the current preparatory measurements, and finally outline a roadmap towards a prototype experiment at the South Pole: RASTA (Radio Air Shower Test Array), that will allow us to fully quantify the physics potential of a large scale radio extension for the IceCube observatory.

2 Physics Motivation

The all particle energy spectrum of cosmic rays follows a simple power law with two prominent changes in spectral index: a steepening at ~ 4 PeV, called the "knee" followed by a flattening at a few times 10^{18} eV, termed the "ankle". The knee is believed to result from the cut-off in protons from galactic sources, while the region between knee and ankle would represent the dying out of heavier elements from galactic accelerators and the transition to an extra-galactic component at the ankle. However, the chemical composition of cosmic rays in this energy range is not well constrained, yet. The composition is derived from the properties of cosmic ray induced extensive air showers. The two quantities sensitive to composition usually used are the depth of the shower maximum in the atmosphere $X_{\max}$ (and the width of the $X_{\max}$-distribution) and the electron-to-muon ratio at ground level.

The IceTop 1 km^2 air shower detector [4], part of the IceCube observatory [5] located at the geographic South Pole, has an energy threshold of 300 TeV primary energy and can measure up to ~ 1 EeV where it becomes limited by statistics. We propose to enhance the IceCube observatory with a large area ($\mathcal{O}(10)$ km^2) antenna field on the surface, centered at IceTop, to detect radio emission from air showers in the MHz frequency band. The envisioned radio detector is expected to have an energy threshold of $\mathcal{O}(10)$ PeV and its larger area will allow us to collect statistics up to higher primary energies, resulting in a significant overlap with the energy range accesible to the Pierre Auger Observatory. The range of cosmic ray primary energies covered by the enhanced IceCube observatory will in particular allow for measurements in the transition region between knee and ankle of the cosmic ray spectrum and will enable systematic studies and cross calibration between IceTop, the radio detector, and the Pierre Auger Observatory.

The IceCube observatory is a very well suited facility to study cosmic ray composition via the electron-to-muon ratio of air showers [6]. IceTop at the surface measures the charged particles at ground level while only high energy muons can penetrate through the Antarctic ice sheet and be measured in the deep in-ice detector. The radio signal gives an integral measurement of the electron component over the whole development of the air shower and the largest contributions are emitted in the shower maximum. The enhanced observatory would allow for three independent, coincident measurements of air showers—charged particles at ground level, high energy muons in-ice, and the radio signal emitted over the whole shower development—thus improving the knowledge about the primary particle. Studies on cosmic ray composition can be performed in two ways. First, for air showers where the muon bundle in the shower core penetrates the geometric volume of the IceCube in-ice detector, the amplitude of the radio signal on the surface can be used to estimate the electron number of the shower and thus its energy, while the muon number can be estimated from the in-ice signal. With this method a zenith range up to 60° can be covered with a radio array reaching out 3 km from the centre of IceTop. Second, the lateral distribution function of the radio signal is expected to be a composition sensitive variable [7, 8] which would allow for radio-only composition studies, largely increasing the aperture of the detector since no geometric overlap of the events geometry with IceCube is required. The first method described above would also allow us to explicitly search for UHE photons which manifest themselves as electromagnetic showers with no, or a very small, muon component in the deep in-ice detector.

Further, the increased area of the surface detector can be used as a veto against air shower muon bundles in the deep in-ice detector which are the main background channel in EHE neutrino searches in IceCube [9], increasing IceCube's sensitivity to horizontal and down-going high energy neutrinos. An estimate shows that the sensitivity to cosmogenic neutrinos can be increased by a factor of more than three using a radio array extending 3 km around the centre of IceTop [10].

To proof the technical feasibility of such a large area radio detector and to quantify the physics potential more precisely the installation of the RASTA test setup is proposed (cf. Sec. 4). In parallel, to study the physics potential of the envisaged radio detector, a detector simulation chain based on CORSIKA [11] simulations, the air shower ra-

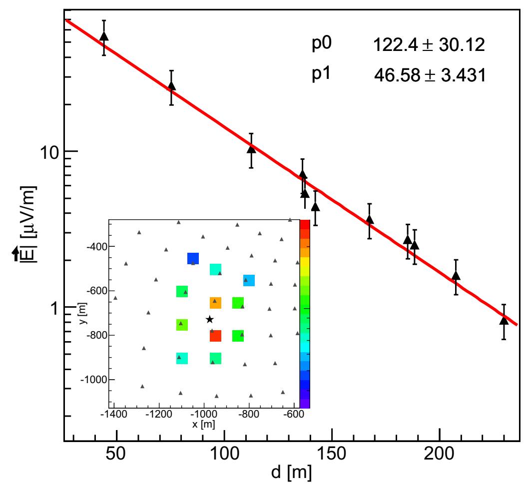

Figure 1: Radio signal strength as function of distance from the shower axis. The inset shows the distribution of recording antennas on the ground; the asterisk marks the position of the shower core. The origin of the coordinate system is located at the centre of IceTop.

dio emission code REAS3 [12], and the IceCube detector simulation software has been developed. This simulation chain allows for the uniform treatment of all three detector components and is currently used to study the energy threshold and composition sensitivity of different detector configurations. For simulations, a radial geometry reaching out to 4.5 km radius has been chosen for the antenna array, comprising a total of 1110 antennas. Since showers with their axis intersecting the geometric volume of the in-ice detector are most promising, the spacing between antennas increases from 80 m in the centre to 800 m at the outer circumference, taking into account the increasing zenith angle of these "golden events". A typical simulated event, induced by a 10 PeV primary proton, is shown in Fig. 1 together with part of the simulated antenna array and the lateral distribution of the radio signal amplitude. The muon bundle from this air shower generated a signal in 571 optical modules of the deep IceCube detector.

3 Preparatory Measurements

One important ingredient for the simulation of a radio detector and the estimation of its sensitivity is the knowledge of the electromagnetic background conditions at South Pole station. This includes both, the continuous background noise and its variations on different time scales, and possible transient backgrounds. In the past several measurement campaigns have been performed [10, 13], which for technical reasons always took place close to South Pole station buildings and thus yielded only upper limits on the

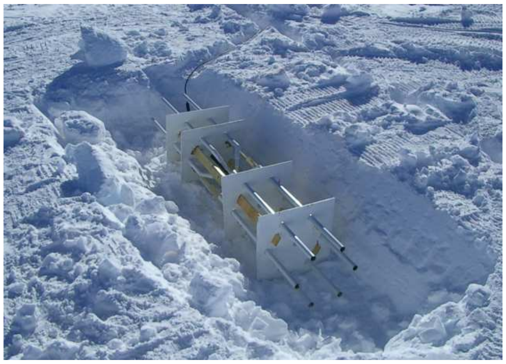

Figure 2: 'Fat Wire Dipole' surface antenna deployed in the ARA test setup. The 3.7 m long antenna is made from copper pipes stabilized in a wooden frame.

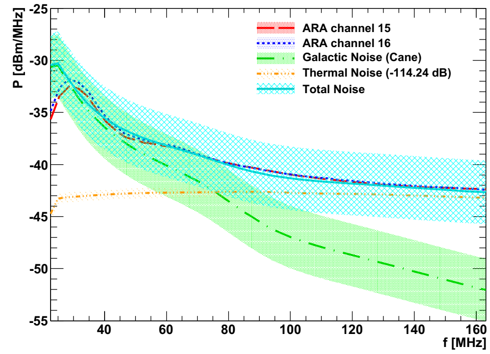

Figure 3: Time averaged background noise measured with the two ARA surface antennas. For comparison, the galactic [15] and thermal noise expectations, convoluted with the ARA amplification and system response, are shown.

noise conditions $\mathcal{O}(1)$ km away from all buildings, where a radio detector would be built.

In the austral summer 2010/2011 the ARA (Askaryan Radio Array) collaboration deployed a test setup [14] about 2.5 km away from South Pole station, outside the IceCube footprint. ARA is searching for Askaryan GHz radio emission in the ice from EHE neutrino interactions. Two DAQ channels of the test setup have been instrumented with 3.7 m dipole antennas on the surface (cf. Fig. 2) that are sensitive in the frequency range 25 – 160 MHz. The signal from the antennas is amplified with two low noise amplifiers (37 + 41 dB) and read out with 12-bit ADCs at a sampling rate of 1 GHz.

Minimum bias data recorded with the surface antennas of this setup allowed us to measure the power spectral density (PSD) of the electromagnetic background away from South Pole station in the frequency band from 25 – 160 MHz. Figure 3 shows the measured PSD (ARA channel 15 and 16) at the input of the ADC averaged over all data available from 18 January to 6 April 2011. For comparison a parameterization of the expected galactic noise (from [15]) and thermal noise folded with the ARA system response are shown. The antenna response has been simulated using NEC4 [16]. The data are well described by a superposition of galactic and thermal noise. The cut-off at $\sim$ 30 MHz is suspected to be due to unaccounted features in the ARA system response.

The surface antennas have been deployed in air in a trench which will we be snowed in during the year. This will allow us to study the difference in the antennas response on and under the snow surface in both data and antennas simulation and the long time performance of the antennas in the Antarctic environment.

Sensitivity of the setup to galactic noise can further be shown by analyzing the variation of the background noise during the sidereal day. At South Pole the galactic centre always has the same elevation but the antenna response is not uniform in azimuth. Figure 4 shows the RMS of the

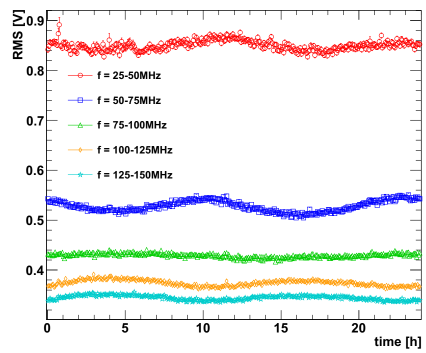

Figure 4: Modulation of the noise RMS in the surface antennas for different frequency bands during the sidereal day. See text for details.

background noise in ten minute bins modulo one sidereal day for different frequency bands. Following the symmetry of the antenna, two full oscillations are observed per day. The amplitude of the modulation decreases for higher frequencies as is expected from the galactic emission spectrum (cf. Fig. 3). At $\sim$ 90 MHz the phase of the modulation is inverted. This effect is understood from simulations of the antenna response function.

During the austral winter 2011 a dedicated surface trigger in the ARA test setup will allow us to study transient backgrounds at South Pole far from the station buildings and the IceCube array.

4 Roadmap

Considering the restricted deployment cycle due to the remote location, a staged proposal spanning three years has been made. In the first year we will aim towards unambiguously establishing the detection of air showers above the

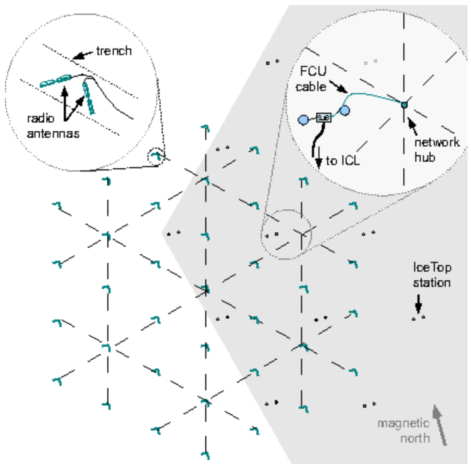

Figure 5: Possible configuration for RASTA having partial overlap with the IceCube footprint (gray shaded area). The configuration of the antenna pairs is shown in the upper left inset. The dashed lines indicate the data and power transmission network. The upper right inset illustrates the connection to the IceCube network using existing spare cables running to the IceTop stations.

background noise and provide a proof-of-viability for this detection technique in the Antarctic environment. Using a conservative estimate based on REAS2 [17] simulations, air showers with a primary energy of $E_{\mathrm{prim}} > 10^{17}$ eV should be detectable at $> 5\sigma$ above the ambient noise level at a distance of 125 m [10]. Antennas will be deployed in orthogonally polarized pairs. Four such pairs forming an equilateral triangle with 95 m side length and one pair in its centre and requiring a three-fold coincidence will provide an effective area of $3 \cdot 10^4$ m^2. Using the charged cosmic ray flux as measured by the KASCADE experiment [18], each of these clusters will detect ~ 8 events per day. Even allowing for considerable inefficiencies (e.g. due to anthropogenic backgrounds), some 10^3 events will be accumulated per year.

In the second and third seasons all of the key technologies that are required for a several-km^2 array should be employed. This will also allow us to demonstrate the scalability of the approach. With a significantly larger number of antennas on an enlarged footprint, this second stage will collect a data sample large enough to allow detailed verification of the array performance and shower reconstruction. Figure 5 shows a possible setup for the third year stage of RASTA. Partial overlap with the IceCube footprint allows for coincident air shower measurements with IceTop and allows us to study both, influences of possible noise from IceTop and data measured at some distance to existing infrastructures.

5 Conclusions and Outlook

A large area surface radio detector is a promising enhancement for the IceCube observatory to study the composition of cosmic rays in the transition region from the knee to the ankle and improve IceCube's sensitivity to UHE neutrinos. A full detector simulation chain based on REAS3 has been developed and different detector configuration and their physics potential are presently studied. In-situ measurements of electromagnetic interference show promisingly low noise levels. A path towards RASTA, a full test setup to demonstrate the viability of a full detector, has been presented.

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