A Radio Air-Shower Test Array (RASTA) for IceCube

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Abstract

In this paper we explore the possibility to complement the cosmic ray physics program of the IceCube observatory with an extended surface array of radio antennas. The combination of air-shower sampling on the surface and muon calorimetry underground offers significant scientific potential: the neutrino sensitivity above the horizon can be enhanced by vetoing air-showers on the ground, photon-induced air-showers can be identified by their small muon component and the coincident measurement of the particle density on the surface and the muon component gives useful information on the composition of the primary flux.

All of these analyses are pursued with the existing IceTop array. However, the IceTop footprint is small compared to the acceptance of the InIce sensor array, which severely limits the solid angle for coincident measurements, calling for an extended surface air-shower detector. As demonstrated by the LOPES experiment, measuring air-showers through their geosynchrotron emission has become a viable and cost-efficient method. The science case for the RASTA project - a dedicated radio array seeking to exploit this method at the South Pole - is presented.

Keywords: Radio detection, Air-showers, Cosmic rays, Neutrinos, UHE gamma-rays, South Pole, RASTA

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1. Motivation

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. A first proof of this technology has been provided by the LOPES experiment [2, 3]. Its main advantage are low costs 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). This technology is now not only being developed as an extension at many existing air shower experiments (KASCADE, AUGER, TUNKA,...), but also forms the key building block of LOFAR – a multi-site, multi-purpose radio detector spanning half of Europe [4].

In this paper, we will first outline the science case for an extension of the IceCube observatory with an extended O(10 km²) radio array, then describe the current status and finally outline a roadmap towards a full detector.

2. Science Case

The IceCube observatory [5] at the South Pole was originally designed and intended for detection of TeV–PeV neutrinos penetrating Earth, while at the same time using it as a shield against the abundant atmospheric muon flux. Beyond the original anticipation, IceCube has by now become a 4π observatory. In particular, the IceTop air-shower array [6] on the surface, expands the physics reach of IceCube in a threefold manner, as detailed in the sections below.

2.1. Composition

Two different observables are currently employed to determine primary composition of cosmic rays:

- the depth of the shower maximum \(X_{\text{max}}\), where on average protons of the same energy will penetrate deeper in the atmosphere
and show larger variations than heavier nuclei. This is used to measure composition e.g. with the fluorescence detectors in \textit{Auger}.

- the **electron over muon ratio**, where heavier primaries will cause higher muon multiplicities (c.f. fig.1), as exploited e.g. by \textit{KASCADE}.

Significant statistics of coincident \textit{InIce} and \textit{IceTop} events have been collected and are being analyzed. Due to the strong correlation of the muon and electron flux with the total primary energy and inclination of the shower, very good control of systematic effects in the reconstruction of the events is required [8].

For air showers that are coincidentally detected by an additional future large radio array, both – the muon and the electron component of the shower – will be measured by more than one type of detector, allowing an overconstrained determination of both components. Furthermore, simulations show that the steepness of the lateral distribution of the geosynchrotron signal will depend on the depth of the shower maximum [9] [10] – an effect that will be enhanced for higher observation levels [11]. Radio detection may thus provide a view of the shower development at high altitudes. It should be noted, though, that the simulation of the geosynchrotron emission is still a developing field. The reconstruction of the radio signals will thus have to be validated against the \textit{IceTop} measurements first.

The benefit will go beyond the independent systematic errors of the three detector types on the shower energy and directional reconstruction. With the increased statistics provided by a large array, the energy range that is covered with good statistics will be extended to the EeV regime, overlapping and complementing not only the measurements provided by the \textit{KASCADE} but also of the \textit{Auger} experiments. Using the additional information on the shower maximum, a combined measurement will eventually maximally exploit all handles on primary particle composition that are currently available to earth-bound detectors.

2.2. Neutrinos

At energies up to $\mathcal{O}(\text{PeV})$, the neutrino field of view of \textit{IceCube} is limited to the $2\pi\text{sr}$ of the northern hemisphere due to the abundant flux of atmospheric muons from air showers from above. This flux shows a much steeper spectrum than the expected signal flux. At energies above several $\mathcal{O}(100)\text{ TeV}$ the neutrinos themselves get absorbed in Earth, so that the search must be extended to the southern hemisphere. Still, even at these higher energies, the dominant background is from unresolved muon bundles induced by air showers, which can not be easily distinguished from single muons in \textit{IceCube}. While \textit{IceTop} in principle offers the possibility to detect the air showers from which these muons stem, its vetoing power is limited by its small size compared to the aperture available to \textit{IceCube} to around $0.25\pi\text{sr}$. A radio array with sufficient lateral extent can significantly increase the field of view in which air shower induced muons can be vetoed. An estimate shows that the sensitivity to the GZK neutrino flux may be increased by a factor of more than three for an array extending to $3\text{ km}$ around the center of \textit{IceTop} [12].

2.3. Ultra-high energy gamma rays

Photon induced air showers will show a muon flux that is a factor of $\approx 100$ lower than for hadron induced showers [13] (c.f. fig.1). At the same time, the flux of muons induced by hadron showers is energetic enough that \textit{IceCube} will have a nearly 100% detection efficiency for showers of energies above $10^{15}\text{ eV}$ if the shower axis intersects the geometric volume. This can be exploited to discriminate hadronic air showers against electromagnetic showers, turning the observatory in a km$^2$-scale PeV photon detector.

While at PeV energies, the UHE gamma horizon is limited to our own galaxy due to absorption on the cosmic microwave background, both the H.E.S.S. and \textit{MAGIC} experiment report un-
broken $E^{-2}$ spectra for some sources within our galaxy \cite{14,15}. Photons have been detected from the same sources with energies up to energies of 90 TeV \cite{14}. If point sources of gamma rays with unbroken spectra up to PeV exist, they should generate $\mathcal{O}(10) \text{evt yr}^{-1}$ in an array as described above. Non-excluding limits on the diffuse photon fraction in cosmic rays have been set previously at $< 10^{-4}$ for the energy range up $5 \cdot 10^{16} \text{eV}$ by the CASA-MIA collaboration \cite{16} and at $< 10^{-1.6}$ for energies above $2 \cdot 10^{18} \text{eV}$ by AUGER \cite{17}. Ongoing analyses \cite{18} with ICETOP show that a comparably high sensitivity can be reached, but only for the limited section of the galactic plane covered by the ICETOP-INICE field-of-view.

Again a future radio array will enhance the physics reach for UHE gamma detection. As the extent of a future radio array will be much larger than the extent of ICETOP, sources at higher declination – including the entire galactic plane – can be probed. At the same time, the larger collection area will increase event statistics, and will thus bridge the gap in energy between CASA-MIA and AUGER. Finally, as is discussed in section 2.1, the radio signal can additionally provide a handle on the depth of the shower maximum, hence further improve the photon identification in this search.

3. Current status and experimental setup

A set of dedicated measurements has been performed to explore the possibility of such a radio array in Antarctic conditions \cite{12}. A fat wire-dipole antenna depicted in Figure 2 has been developed with the aim of a high and uniform broadband response in the MHz-regime while limiting antenna dimensions and cost.

Two of these antennas were deployed at South Pole in the polar season 2008/2009 around the SPASE building and were read out using two channels of the pre-existing RICE DAQ \cite{19}. The sensitivity of the deployed instrumentation was severely limited by cable losses as only two 600 m and 500 m pieces of legacy 75 Ω coaxial cable were available for use. In the frequency range between 50 and 100 MHz signal transmission losses vary from 20-30 dB. In absence of a dedicated trigger for the surface antennas the $> 2 \mu s$ cable delays also resulted in signals that were often truncated by the limited buffer length of the RICE waveform capture. Nevertheless, the essential pre-conditions for establishing an enlarged footprint at South Pole have been achieved via two fundamental performance milestones.

1) Analysis of the spectrum shows the noise floor being limited by galactic and thermal contributions. Figure 3 shows the background spectrum from a single 8 \mu s sweep corrected for the attenuation effects of cable, filter, and amplifier. The strong increase below 25 MHz is an artefact of the high-pass filter being used. As in a previous short-term measurement during the 2007/2008 season, the spectrum lacks the typical monochromatic features from TV stations and other anthropogenic sources observed in other more inhabited areas.

2) To test the ability of surface antennas to identify sources at South Pole, a set of calibration pulser runs were taken in January 2009 using a RICE transmitter located at the 500 m distant MAPO building. Taking advantage of the nanosecond time resolution of the RICE DAQ, the source position has been reconstructed using only information from the two fat wire-dipoles plus two auxiliary dipole antennas at the roof of MAPO building. The vast majority of the events reconstruct to within $\sim 2 \text{ m}$ of the actual pulse location.
4. Roadmap

Here we outline a roadmap to assess the viability of an extended air-shower array for geosynchrotron radiation as described above. Considering the restricted hardware deployment cycle due to the remote location, a staged proposal spanning three years has been made. The setup in the first year will be aimed towards unambiguously establishing the detection of air-showers above the background radio noise and thus provide a proof-of-viability for this detection technique in the Antarctic environment. Using a conservative estimate based on REAS2 simulations [12], air-showers with a primary energy of $E_{\text{prim}} > 10^{17}$ eV should be detectable at $> 5\sigma$ above the ambient noise level at a distance of 125 m. Antennas will be deployed in pairs in orthogonal polarization. Four such pairs at a baseline of 55 m and requiring a four-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 [20], each of these clusters will detect $\sim 8$ events/day. Even allowing for considerable inefficiencies (e.g. due to anthropogenic backgrounds), some $10^5$ events will be accumulated per year.

While this primary setup will heavily rely on commercially available components and existing infrastructure, the setup in the second season should employ all of the key technologies that are required for a several-km$^2$ array, hence will also allow to demonstrate the scalability of the approach. In particular these include each antenna pair to be read out by an independent, customDAQ board deployed in close proximity. Connecting the stations in a peer-to-peer grid, in which each of the boards generates threshold triggers and communicates them to neighboring antennas will allow to establish local coincidences. Local storage of the waveform information with a buffer depth of several 100 ns will be required to read out the array following a global trigger either generated internally from the radio array or externally from IceCube or IceTop. 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.

The third year will be dedicated to investigation of long-term systematics. With data accumulated over two years, potential environmental changes (such as compactification of the snow around the antennas) or degradation of the antenna system will be studied in detail. Any needed in-situ recalibration of the antennas and comparison to previous calibrations would be conducted in this campaign. For this purpose a radio-frequency transmitter can be deployed at different locations in the array.

5. Summary

IceCube’s core mission includes several cosmic ray initiatives. While combined analysis of IceTop and INIce data is being used to target cosmic-ray composition, there will continue to be uncertainties driven by the ability to completely characterize individual events. An extended air-shower radio array using geosynchrotron radiation will significantly enhance the acceptance of IceCube for the veto and gamma-ray missions. It will also provide complementary information for shower reconstruction. The combined analysis of INIce/IceTop/RASTA events will permit cross-calibration of all detection techniques and improved composition measurements. The proposed three year development plan will allow to establish and test all the key ingredients required towards reaching these goals.

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