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LOPES - Detecting Radio Emission from Cosmic Ray Air Showers

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Abstract. High energy cosmic rays, hitting the Earth's atmosphere, produce large amounts of secondary particles in an extensive air shower (EAS). Radio pulses from these air showers were measured during the late 1960 ies and early 1970 ies. Mainly due to difficulties with radio interference these measurements ceased in the late 1970 ies. LOFAR (**Lo**w **F**requency **Ar**ray), the new digital radio interferometer under development, will work in the frequency range of interest for air showers. It will be able to store the collected radio data for a short time and form beams after an air shower has been detected. To test this new technology we are building a "**LO**FAR **P**rototyp**e** **S**tation" (LOPES). This will operate in conjunction with an existing air shower array (KASCADE in Karlsruhe) to clarify the nature and properties of radio emission from air showers and develop the software to use LOFAR as a cosmic ray detector.

1. Introduction

A standard method to observe cosmic rays is to measure the secondary particles of an air shower with an array of particle detectors on the ground. As the state of an air shower at the ground level depends on many factors, the determination of primary particle energy and type from the measured particles is not straight forward. Very useful information can be obtained by observing the air shower as it evolves. So far this is only done by observing optical emission like Cherenkov or fluorescence light. This requires dark, clear and moonless nights and thus limits the available efficiency to about 10%.

Measuring radio emission from air showers might be an alternative method for such observations, providing a much better efficiency. This becomes particularly relevant since a new generation of digital radio telescopes promises a new way of measuring air showers.

2. Radio Properties of EAS

Radio emission from cosmic ray air showers were discovered for the first time by Jelly et al. (1965) at 44 MHz. The results were soon verified and in the late 1960's emission from 2 MHz up to 520 MHz were found. In the following years these activities ceased almost completely due to several reasons: difficulty with radio interference, uncertainty about the interpretation of the results and the success of other methods.

The radio properties of extensive air showers are summarized in an excellent review by Allan (1971). The main results of this review can be summarized by an approximate formula for the received voltage:

$$\epsilon_\nu = 20\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\left(\frac{\mathrm{E_p}}{10^{17}\mathrm{eV}}\right)\sin\alpha\cos\theta \times \exp\left(\frac{-\mathrm{R}}{\mathrm{R_0}(\nu,\theta)}\right)\left(\frac{\nu}{55\,\mathrm{MHz}}\right)^{-1} \qquad (1)$$

Here $\mathrm{E_p}$ is the primary particle energy, R is the distance to the shower center, $\mathrm{R_0}$ is around 110 m at 55 MHz, θ is the zenith angle, α is the angle to the geomagnetic field and ν is the observing frequency. This formula was determined experimentally from data in the energy range $10^{16} < \mathrm{E_p} < 10^{18}$eV at a frequency of 55 MHz.

The spectral form of the radio emission seems to be valid in the range $2 < \nu < 520$ MHz but in general is fairly uncertain. Figure 1 shows a tentative spectrum with the ν^{-1} dependence. The $\nu = 2$ MHz data point was later questioned and there is a good chance that the spectrum is actually flat between 10-100 MHz (see Sun 1975).

3. LOFAR

LOFAR is a new attempt to revitalize astrophysical research at 10-200 MHz with the means of modern information technology. The basic idea of LOFAR is to build a large array of 10^2 stations of 10^2 dipoles in which the received waves are digitized and sent to a central supercluster of computers. Each station will act as a "phased array" where the phasing is done digitally, the computer will then correlate the data streams and digitally form beams in any desired direction.

A new feature is the possibility to store the entire data stream for a certain period of time. If one detects a transient phenomena one can then retrospectively form a beam in the desired direction. LOFAR therefore combines the advantages of a low-gain antenna (large field of view) and a high-gain antenna (high sensitivity and background suppression). This makes it an ideal tool to study radio emission from cosmic ray air showers. With its range of baselines between 10 m and 400 km LOFAR will be capable to detect air showers from $> 2\cdot 10^{14}$ eV to $\sim 10^{20}$ eV.

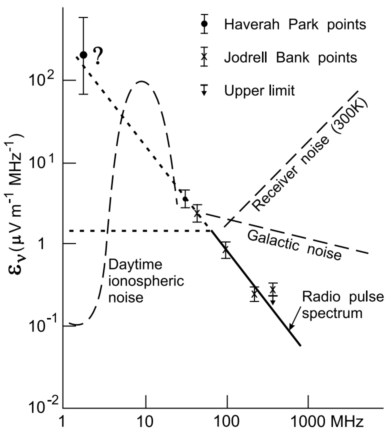

Fig. 1. A tentative radio pulse spectrum for particles normalized to $E_p = 10^{17}$MHz. From Allan (1971) and Spencer (1969).

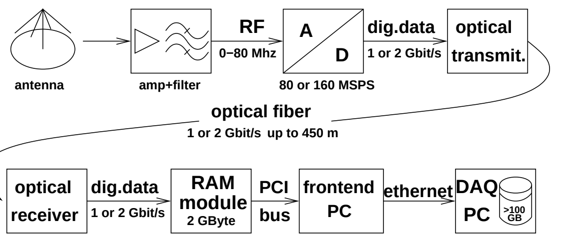

Fig. 2. Outline of the hardware, that will be used for LOPES. In the first phase the 80 MSPS / 1 GBit/s configuration will be implemented. In the second phase the 160 MSPS / 2 GBit/s configuration will be implemented, allowing full Nyquist sampling of the 80 MHz.

4. LOPES

To test the technology of LOFAR and demonstrate its capability to measure air showers we are building LOPES. This will be located at the site of an existing air shower array (KASCADE in Karlsruhe/Germany) and operate in conjunction with it. The data from a well tested air shower experiment provides us with starting points for our air shower reconstruction and allows us to calibrate the radio data with other air shower parameters. Also LOPES will provide KASCADE with valuable additional information about the air shower, as the radio data and the particle data come from different stages in the evolution of an air shower.

In its first stage LOPES will consist of 10 antennas and will be extended to 100 antennas after successful completion of the first stage. With this LOPES will be sensitive to cosmic rays from 10^{15} to 10^{17}eV

It will operate in the frequency range of 40–80 MHz, because in this range there are only few strong radio transmitters and the radio emission from air showers are strong compared to the sky noise. The hardware for LOPES (active antenna, A/D-electronics etc.) is currently being developed at ASTRON in Dwingeloo/NL. It will sample the RF-signal without the use of a LO directly at the antenna (see figure 2). This prevents the need for long analog signal cables and keeps overall costs low.

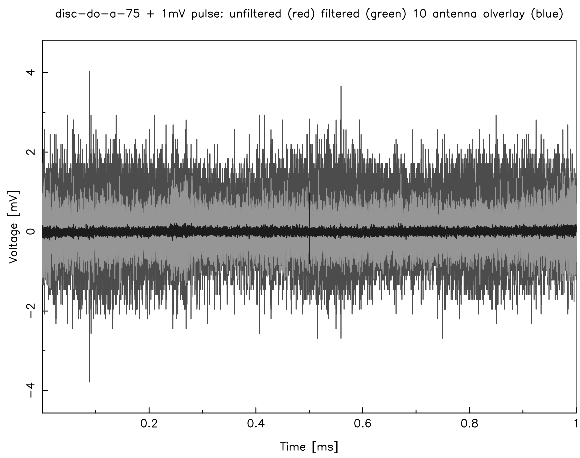

Fig. 3. Time series with added pulse at 0.5 ms (dark grey), after suppression of narrow band RFI (light grey) and after combining 10 antennas as a phased array (black).

5. Digital RFI Suppression

In February and March 2002 we did first RFI measurements in Dwingeloo and at KASCADE in Karlsruhe. At both sites significant RFI was present, both as narrow band transmissions and short-time pulses. An important result is, that no radio pulses coming from the particle detectors of KASCADE have been detected, as they would be hard to distinguish from air shower emission.

In Figure 3 one can see the effects of digital RFI suppression. The time series data is Fourier transformed, narrow band RFI is filtered, transformed back to the time domain and data from different antennas is combined. Pulses that get weaker by a large amount can then be identified as RFI and filtered out.

6. Outlook

We will finish the first stage of LOPES in the end of 2002/beginning 2003, in early 2004 we plan to have LOPES with all 100 antennas working.

The same technology can be applied to other forthcoming digital radio telescopes like the SKA, providing additional detection area for high energy cosmic rays.

Equipping the Pierre Auger Observatory, a giant air shower array that is currently being built in Argentina, with radio capability could also greatly enhance it's sensitivity. In the long run a digital radio telescope could even form the northern part of the Pierre Auger Project.

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