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The MIDAS telescope for microwave detection of ultra-high energy cosmic rays

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ABSTRACT

We present the design, implementation and data taking performance of the MIcrowave Detection of Air Showers (MIDAS) experiment, a large field of view imaging telescope designed to detect microwave radiation from extensive air showers induced by ultra-high energy cosmic rays. This novel technique may bring a tenfold increase in detector duty cycle when compared to the standard fluorescence technique based on detection of ultraviolet photons. The MIDAS telescope consists of a 4.5 m diameter dish with a 53-pixel receiver camera, instrumented with feed horns operating in the commercial extended C-Band (3.4–4.2 GHz). A self-trigger capability is implemented in the digital electronics. The main objectives of this first prototype of the MIDAS telescope – to validate the telescope design, and to demonstrate a large detector duty cycle – were successfully accomplished in a dedicated data taking run at the University of Chicago campus prior to installation at the Pierre Auger Observatory.

1. Introduction

The origin and composition of Ultra-High Energy Cosmic Rays (UHECRs) remains uncertain [1], even after the progress made by the latest generation of experiments [2,3]. Due to the strong flux suppression above 10^{19} eV [4,5], very large detection areas are necessary to study cosmic rays at these energies. A future UHECR Observatory based on standard techniques – Surface Detector arrays (SD) and Fluorescence Detectors (FD) – may be limited by cost and difficulty of deployment. In this context, radio detection techniques are attractive thanks to the low cost of individual elements, the little maintenance required and a nearly 100% detection duty cycle.

Radio emission in the MHz range from extensive air showers (EASs) has been actively studied in the last decade by the LOPES [6] and CODALEMA [7] experiments. MHz radio-detection is now well established, and AERA [8], in commissioning phase at the Pierre Auger Observatory, will have a sufficiently large instrumented area to explore the potential of this technique for detection of the highest energy cosmic rays.

The use of the microwave (GHz) band for EAS detection was originally pursued by Jelley, Charman and collaborators [9,10] in the late 1960s, but abandoned due to the lack of satisfactory understanding of the emission mechanisms and to limitations in detector technology. Thereafter it remained mostly unexplored, until recent laboratory measurements [11] with particle beams have renewed the interest in this part of the radio spectrum. These measurements suggest that microwave radiation is emitted from the weakly ionized air plasma of free electrons produced by the EAS induced ionization of the atmosphere. The radiation is expected to be continuous and relatively flat in frequency, unpolarized and emitted isotropically, and its intensity to scale with the number of particles of the shower.

Detection of an isotropic emission in the GHz range – akin to the detection of ultraviolet fluorescence photons by FD pioneered by the Fly's Eye experiment [12] and currently used by the Pierre Auger Observatory [13] and the Telescope Array [14] – allows for the measurement of the EAS development in the atmosphere,

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which provides a calorimetric measurement of the energy and crucial information on the mass composition of primary cosmic rays. A GHz radio telescope would overcome the limitations of the FD technique, i.e. data taking only during moonless nights (≈15% duty cycle) and significant systematic uncertainties introduced by light attenuation in the atmosphere. In fact, microwave detectors can operate 100% of the time, and attenuation in the GHz range is minimal, even with rain or clouds. Moreover, commercial off-the-shelf GHz equipment, mostly developed for satellite TV reception, is readily available and inexpensive. Microwave telescopes could provide existing UHECR experiments of unprecedented sensitivity to primary comic ray composition, and be employed in a future large scale observatory.

Several complementary approaches to microwave detection of EAS are currently being pursued, including the AMBER and EASIER detectors [15] at the Pierre Auger Observatory, and the CROME experiment at KASCADE [16]. Also, new laboratory measurements with particle beams are being performed [17,18] to better characterize the microwave emission.

In this paper, we present the MIcrowave Detection of Air Showers (MIDAS) experiment, an imaging telescope whose primary objective is to confirm the microwave emission from EAS, and to demonstrate the feasibility of a low cost design for this novel technique. The MIDAS telescope is described in Section 2. The electromagnetic simulations of the telescope response are illustrated in Section 3. The calibration procedures and the measured sensitivity of the instrument are presented in Section 4. A simulation of the MIDAS detection of EAS is described in Section 5. Operation and data taking performance of the MIDAS telescope are presented in Section 6, and conclusions are drawn in Section 7.

Fig. 1. The MIDAS telescope at the University of Chicago, with the 53-pixel camera at the prime focus of the 4.5 m diameter parabolic dish reflector.

2. The MIDAS telescope

The telescope consists of a large parabolic dish reflector with a receiver camera at its prime focus, installed on the roof of the Kersten Physics Teaching Center at the University of Chicago (Fig. 1). In the following, the design and technical implementation of the different components of the MIDAS telescope are described.

2.1. Reflector and receiver camera

The parabolic dish reflector (Andrew) has 4.5 m diameter and $f/D = 0.34$. A motorized alt-azimuth mount allows for telescope movements in a range of 90° in elevation and 120° in azimuth. While not foreseen for the final design, the capability of pointing the telescope has been very useful for calibration purposes. During data taking for EAS detection, the telescope in a fixed position. The remote control of the telescope pointing (0.1° precision) is integrated in the data acquisition (DAQ) system (Section 2.5).

A 53-pixel receiver camera is mounted on the prime focus of the dish, covering a field of view of about $20^\circ \times 10^\circ$. The microwave receivers are arranged in seven rows, and staggered to maximize the sensitivity across the focal plane (Fig. 2).

A commercial low noise block feed-horn (LNBF) operating in the extended C-band (3.4–4.2 GHz) is used for the receiver. These feeds (WS International) are mass-produced for consumer satellite television. The LNBF integrates a feed horn, low noise amplifiers, and a frequency downconverter. The feed can receive two orthogonal linear polarizations which are remotely selectable through the LNBF power voltage level setting. A 5150 MHz local oscillator in the frequency downconverter mixes the input RF signal down to a frequency interval of 950–1750 MHz, which is transmitted with minimal loss through standard coaxial cable. The receiver bandwidth, its gain Γ and noise temperature were measured to be about 1 GHz, 65 dB and 20 K, respectively.

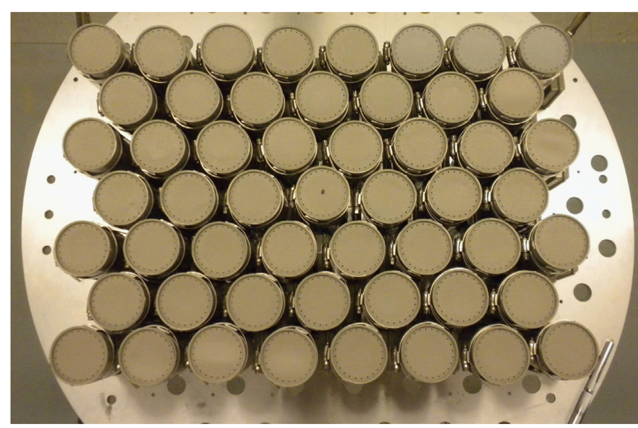

Fig. 2. A front view of the receiver camera, with LNBFs closely packed to maximize the sensitivity over the focal plane.

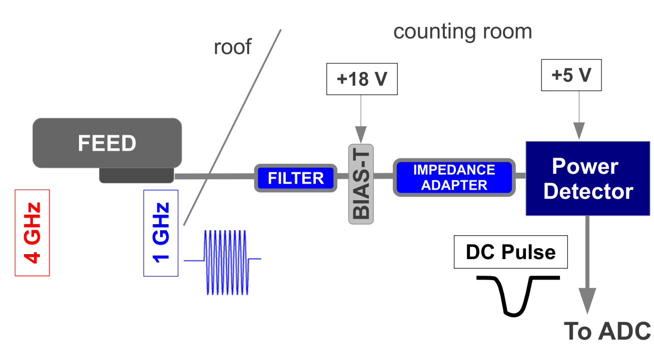

Fig. 3. The analog electronics chain. See text for details on the different components.