First results of the CROME experiment

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Abstract: It is expected that a radio signal in the microwave range is produced in the atmosphere due to molecular bremsstrahlung initiated by extensive air showers. The CROME (Cosmic-Ray Observation via Microwave Emission) experiment was built to search for this microwave signal. Radiation from the atmosphere is monitored in the extended C band (3.4–4.2 GHz) in coincidence with showers detected by the KASCADE-Grande experiment. The detector setup consists of several parabolic antennas and fast read-out electronics. The sensitivity of the detector has been measured with different methods. First results after half a year of data taking are presented.

Keywords: Cosmic rays, detector, radio emission, microwave

1 Introduction

Low-energy electrons in extensive air showers (EAS) are expected to produce radio radiation at microwave frequencies. Beam measurements of this process provided a first estimate of the intensity of the microwave signal [1]. The unpolarized and isotropic microwave signal has been attributed to molecular bremsstrahlung radiation due to the interaction of electrons with neutral air molecules. If this radiation can be measured by standard GHz-radio instruments, it will provide a new and promising way of the observation of ultra-high energy cosmic rays (UHECRs) [1].

Microwave radiation (1–10 GHz) from EAS could provide information about the longitudinal development of EAS and, hence, the energy and chemical composition of the primary cosmic-ray particles. The advantages of a microwave measurement with respect to an observation of fluorescence light (see e.g. [3]) are the 100% on-time and the very small atmospheric attenuation of the signal even in the presence of clouds. The two frequency bands C (3.7–4.2 GHz) and Ku (10.7–12.7 GHz) for satellite communication are particularly attractive as they are characterized by very low natural background radiation and negligible human made radio frequency interference [2]. Moreover, commercial equipment for low-noise receivers for the C and Ku bands is commonly available.

Several projects aiming at measuring microwave emission from EAS have been started [4] but a signal detection has not yet been reported. In this work we discuss the status and calibration of the CROME (Cosmic Ray Observation via Microwave Emission) detector that has been set up within the KASCADE-Grande (KG) air shower array near Karlsruhe, Germany [5].

2 Detector setup

The CROME experiment aims at the detection of microwave signals from air showers as expected from molecular bremsstrahlung and Cherenkov emission. Commercially available GHz antennas are used to continuously monitor the air above the KASCADE-Grande array. Using a shower trigger provided by KASCADE-Grande 1, the measured GHz signal is stored for all high-energy showers detected with the scintillator array.

The antenna setup consists of several microwave receivers for the frequency ranges 1–1.8, 3.4–4.2 (C band), and 10.7–11.7 GHz (low Ku band). While the 1–1.8 GHz antenna is a scientific instrument originally built for observing the 21 cm hydrogen line, the other antennas are commercially available parabolic reflectors equipped with low noise block-downconverters (LNBs). All antennas are oriented vertically upwards.

The current setup of CROME consists of a 2.3 m dish with one receiver for 1–1.8 GHz, two 3.4 m dishes each with a camera with 9 C band receivers (see Figure 2) and a small
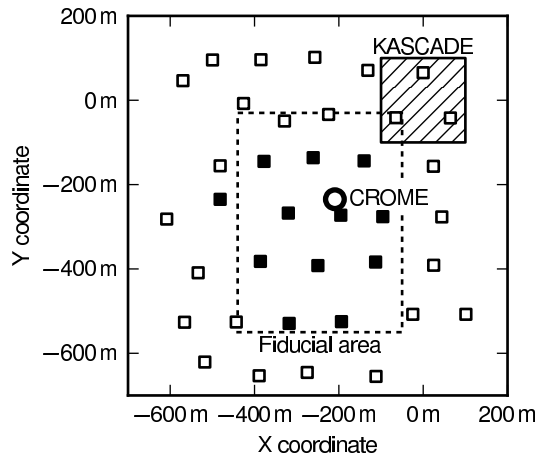
Figure 1: Location of CROME antennas in the KASCADE-Grande array. Full squares indicate the scintillator stations that provide the trigger for CROME. The information from the smaller but much denser KASCADE array [6] (upper right corner) with separate electron and muon counters is used for estimating the number of muons.

Figure 2: Photo of segmented parabolic dish (Prodelin 1344) of 335 cm diameter and 119 cm focal length. The camera of 9 linearly polarized C band receivers, each consisting of a feed matched to the antenna size and a Norsat 8215F LNB, is supported by four struts.

0.9 m dish with one receiver for the Ku band. The field of view of a single C band receiver in the 3.4 m antenna corresponds to an opening angle of $\sim 1.6°$ for a drop in the signal by 3 dB (for more details see Section 4).

The layout of the setup is shown in Figure 1. Twelve scintillator stations in the center of the KASCADE-Grande array, indicated by full squares in the figure, provides the trigger with a rate of a few hundred events per day. Only showers with the core position reconstructed inside the area marked by the dashed lines in Fig. 1, corresponding to $2.0 \times 10^5 \, \text{m}^2$, are used in the data analysis.

A fast logarithmic power detector (Analog Devices AD8318) is used to measure the envelope of the antenna signals. Measurements show that the exponential time constant of the whole chain of electronics together with the LNB is ~ 4 ns (i.e. ~ 9 ns for 10-to-90% risetime). The measured signal is readout by five 4-channel digitizers (PicoScope 6402 and 6403) with a sampling time of 0.8 ns and 8-bit dynamic range. All channels are readout in a time window of 10 μbefore and after the trigger delivered by KASCADE-Grande.

Particular attention has been paid to the time synchronization between the CROME and KASCADE-Grande DAQs since the radio signal is expected to be as short as 20 ns for nearly vertical showers. A GPS clock identical to the one of KASCADE-Grande is used (Meinberg 167 lcd) and, in addition, the trigger time from one scintillator station of KASCADE-Grande is stored for each event. The reconstructed arrival direction, core position, and energy of the showers recorded by the KASCADE-Grande array are used in the further analysis.

3 Expected event rate

The calculation of the number of showers measurable by the CROME antennas is based on a detailed simulation of air showers detected by KASCADE-Grande together with the estimated microwave signal according to [1].

KASCADE-Grande is optimized to detect air showers in the range from $10^{15.5}$ to 10^{18} eV. On average, one shower above 10^{17} eV per day is measured by KASCADE-Grande and successfully reconstructed. Details can be found in [5]. The energy range of KASCADE-Grande includes also the energy of 3.4×10^{17} eV for which Gorham et al. [1] made the accelerator measurement.

Lacking a detailed microscopic model for microwave emission in air showers, we assume that a fixed fraction of the energy E_{dep} deposited by a shower in the atmosphere is radiated off in the microwave frequency band $\Delta \nu$. This fraction, in the following called microwave yield Y_{MW}, is determined by comparing the simulation results for air showers with the expected signal given in [1]

$$Y_{\text{MW}} = \frac{1}{\Delta \nu} \frac{E_{\text{MW}}}{E_{\text{dep}}} \approx 1.2 \times 10^{-18} \, \text{Hz}^{-1}. \qquad (1)$$

Using a 3-d simulation of the showers [7] with iron nuclei as primary particle and neglecting attenuation in the atmosphere, which is lower than 0.01 dB/km below 10 GHz, we get ~ 2 showers per 9 C band receivers in a 335 cm dish per month with a microwave signal above the minimum detectable flux. The minimum detectable flux is given by $k_B T_{\text{sys}}/A_{\text{eff}}/\sqrt{\tau \Delta \nu}$, where k_B is the Boltzmann constant, T_{sys}=80 K the system temperature, A_{eff}=6.4 m^2 the effective area of a dish, $\Delta \nu$=600 MHz the bandwidth, and τ=10 ns the integration time. It should be noted that the pa-

rameters of the calculation were chosen to obtain a robust lower limit to the expected rate for the given microwave yield.

4 Calibration and radiation pattern

A end-to-end system temperature of 60 K is estimated for the C band system by comparing the measurement for clear sky with the measurement with a microwave absorber (radiating as black body at ambient temperature) placed in front of the camera.

The calibration of the individual receivers (LNBs with feeds) has been measured with a microwave absorber at room and liquid nitrogen temperature of 77 K. The setup is shown in Figure 3. The flat 5 cm thick microwave absorber is placed along a steel wall, in the bottom and also upper part of a cryostat which is covered by a copper lid. The feed can be mounted in stable position and its entrance is below the copper plate. The liquid nitrogen has been filled inside the cryostat and also in the upper part above the copper lid. The temperature has been kept uniform and stable in the whole inner part of the cryostat. The difference in the measured voltage corresponds to the system temperature ranging from 40 up to 50 K for the tested LNBs.

The antennas do not have an astronomical mount and are kept in stable positions. Therefore a flying radio source has been developed to study the sensitivity pattern of the antennas. The radio transmitter is mounted to a remote-controlled copter together with differential GPS for the precise measurement of the position. A two-element Yagi antenna with a one-sided main lobe (about 4.1 dBi) and high backward attenuation (-10 dB) to avoid reflections of the copter is used as the radio transmitter. The Yagi antenna consists of a half-wavelength dipole with a radiation coupled reflector in quarter-wavelength distance. The maximum power generated by the stabilized transmitter is 8 dBm (6 mW) and covers the frequency range between 2970 and 3950 MHz. Six operating modes with different modulation patterns are implemented, which may be triggered by an external source or internal 3 Hz clock. The antenna provides a wide main lobe with -3 dB beamwidth of 110° on average. Moreover, a logarithmic-periodic dipole antenna is being prepared for wideband sweep operating modes.

Preliminary results in the transition zone between the near and far field of the CROME antennas allow us to determine the radiation pattern of the whole system. Relative radiation patterns for the central and two off-center receivers are shown in Figure 4. The obtained results are consistent with simulations for the far field zone obtained with the software package GRASP [8]. The main lobes are clearly visible and the -3 dB beam-widths are less than 2° for all channels. An effect of aberration has been measured for off-center receivers. The first side lobe is down by more than 10 dB relative to the peak of the main beam and is pointed towards the main lobe of the central receiver.
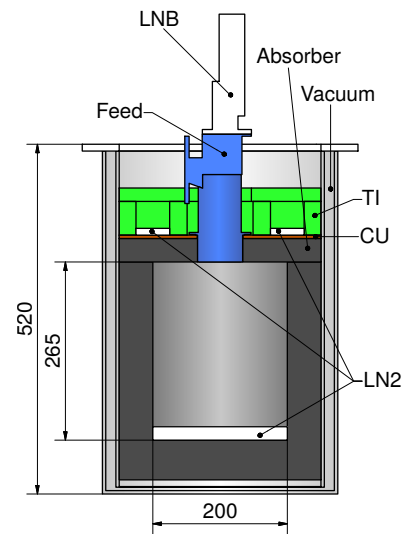

Figure 3: Cryostat built for the calibration of feeds with LNBs. The copper plate (CU) supports the feed, closes the inner part of the cryostat and holds temperature insulation material (TI). Liquid nitrogen (LN2) is filled in the upper part above the copper lid and also inside the cryostat which is fully covered by microwave absorber material.
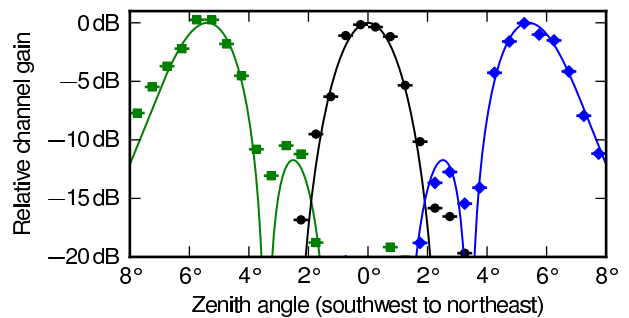

Figure 4: Two-dimensional radiation pattern of the central and two off-center receivers measured by the airborne radio source. Points indicate measured values and curves show simulated far field radiation patterns. The gain pattern has been normalized separately for each feed.

5 Performance and data analysis

CROME is taking data since September 2010. The initial C band configuration has been enlarged from a single antenna with 4 receivers to two antennas with 18 receivers. The second antenna has been installed in April 2011. A few important changes have been made during the measurement apart from the installation of new receivers and read-out electronics. The first was an implementation of in-line filters for the measurement of the average power (fluctuations of frequencies less than 100 kHz) together with fast fluctuations. Later on high pass filters (MiniCircuits

Table 1: Performance of the CROME C band setup till May 10th, 2011. The columns show the start dates of measurement with a given setup, the number of receivers used for the measurement, the uptime in days (percent) and the number of well reconstructed events above 5×10^{16} eV passing through field of view.

Date	Receivers	Uptime		Events
14/09/2010	4	33.5 d	(48%)	10
19/11/2010	8	106.7 d	(82%)	49
01/04/2011	15	26.8 d	(83%)	17
04/05/2011	18	4.9 d	(100%)	3
all	–	171.8 d	(73%)	79

VHF-1200) have been installed in the electronic chain to suppress signals from airplane altimeter radars.

The uptime and number of reconstructed events crossing the field of view of at least one C band receiver is shown in Table 1 for the given a detector configuration. The uptime of the detector has been affected in particular by the downtime of KASCADE-Grande and then by detector upgrades, calibration or test measurements. Total uptime (i.e. period for which CROME and KASCADE-Grande provided data and full reconstruction of KG events was possible) equals to more than 170 days with 8.6 receivers taking data on average.

In total 79 events with energy higher than 5×10^{16} eV were detected by KASCADE-Grande that pass the quality criteria for reconstruction and have crossed a field of view of at least one receiver in the C band setup. The most energetic event was measured on September 24th, 2010. Its energy is 7.9×10^{17} eV with a zenith angle of $10.5°$ and a distance between the shower core to the antenna of 159 m. The simulated signal for this event is shown in Figure 5. The highest expected signal is about 4 dB above noise fluctuations and the time width of the signal is about 20 ns.

It is worth to mention that we might detect also a Cherenkov signal from almost vertical events with reconstructed shower-core distances less than 100 m from the antenna (see e.g. [9]).

6 Conclusion

The first results obtained with the CROME antenna array have been presented. The detector has shown stable performance over more than half a year complemented by several improvements in the setup or test measurements. We have built an airborne GHz transmitter which has been successfully used for mapping the sensitivity pattern of the antennas and will be used also for absolute calibration. Also the properties of the receivers have been measured with a dedicated test setup. Many extensive air showers initiated by primary particles with an energy above 5×10^{16} eV have
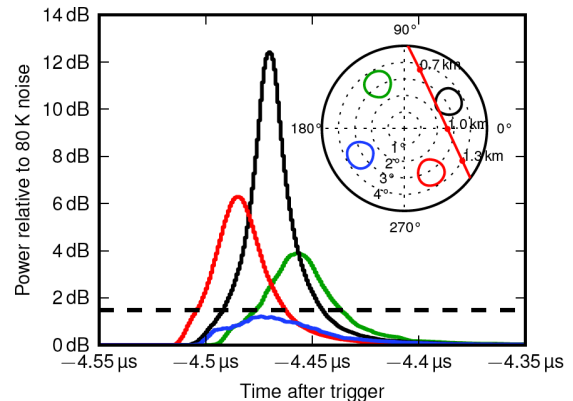

Figure 5: Simulated power flux of the most energetic event crossing the field of view of the 4-receiver camera. The dashed line corresponds to the minimum detectable flux (see Section 3). The fields of view of the receivers are shown in an inset along with the shower track and its altitude above the antenna.

crossed the field of view of at least one installed receiver. The analysis of the measured data is in progress, with the candidate events being studied in detail.

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