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Instruments and Methods for the Radio Detection of High Energy Cosmic Rays

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Frank G. Schröder

Instruments and Methods for the Radio Detection of High Energy Cosmic Rays

Doctoral Thesis accepted by
Department of Physics of the Karlsruhe
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Springer

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Supervisor's Foreword

Cosmic rays have been detected almost precisely 100 years before this dissertation was conducted. The Austrian physicist Victor Hess discovered on high-altitude balloon flights that ionizing radiation from space was impinging on his instrument, a special form of electrometer. In 1936, he received the Nobel Prize for his work. Since then, a lot of progress has been made to understand the origin, propagation, and nature of cosmic particles, but up to now we have not arrived at a complete and consistent picture. The energies of cosmic particles can be much higher than the energies of particles accelerated in our terrestrial accelerators; they exceed even the energy of the Large Hadron Collider LHC at CERN by a hundred million times. However, the most energetic particles are also extremely rare, and hence require huge observatories to be collected in sufficient quantities. The Pierre Auger Observatory in Argentina is the largest installation of its kind; it covers 3,000 square kilometers with a wireless network of 1,600 particle detectors. When a cosmic particle of very high energy hits the atmosphere, its energy gets transformed into billions of secondary particles, which cascade down as a so-called extensive air shower and finally some of them hit the particle detectors.

At this point, the research of Frank Schröder enters as an instrumental innovation that could improve our detection abilities significantly. He has investigated the emission of radio signals from air showers in the frequency range below 100 MHz. This kind of signal is conveniently recorded by an array of inexpensive wire antennas; however, the challenge is in the data transmission and later analysis. Frank Schröder has shown that the radio signal contains a lot of information about the properties of the primary particle, whereas the signals that are conventionally provided by particle detectors are washed out by the many interaction generations between high altitude and ground level. Ideas about the radio technique date back to the 1960s, but only with modern digital technologies it became possible to exploit them at large. In his thesis, Frank Schröder describes his innovative research that he conducted in Germany, Russia, and Argentina; he points the way toward high-qualitiy measurements of cosmic rays air showers using their radio emission, possibly in combination with other means. The scientific community has appraised this work a lot, e.g., by the Dissertation Award of the German Physical Society and by the Young Investigator Prize of the European Cosmic Ray Symposium.

Karlsruhe, July 2012

Johannes Blümer
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Preface

One of the grand open questions in astroparticle physics is the origin of ultra-high energy cosmic rays. Cosmic rays are high-energetic particles, mainly atomic nuclei, which regularly hit the Earth's atmosphere. Although cosmic rays have been discovered already 100 years ago during balloon flights by Victor Hess, it is still a mystery how nature accelerates particles upto energies orders of magnitude higher than the current technical possibilities of humans. While the world's largest particle accelerator, the LHC at CERN in Geneva, is designed for a maximum energy of 7×10^{12} eV, cosmic-ray particles with energies above 10^{20} eV have been observed. There are hints that cosmic rays with energies $< 10^{17}$ eV are accelerated by supernovae shock fronts in our own galaxy, the Milky Way, but there are only hypotheses for the sources of the highest energies, which may be found in other galaxies.

Resolving the origin is hampered by two main difficulties: First, cosmic rays do not propagate in straight lines, but are deviated by magnetic fields. Thus, it is insufficient to observe the incoming direction of the cosmic rays to determine their origin. Instead, the composition of the cosmic rays, i.e., the fraction of certain atomic nuclei, has to be measured in each energy interval, and thus can be compared to astrophysical predictions of different models for the cosmic-ray sources. Second, ultra-high energy cosmic rays are too rare to be measured directly with sufficient statistics by balloon or satellite experiments. Therefore, they are measured indirectly using the atmosphere as detector volume. When a primary cosmic-ray particle hits the atmosphere it initiates a cascade of secondary particles, an extensive air shower. Consequently, the properties of the primary cosmic rays, i.e., their arrival direction, energy, and mass, have to be reconstructed from measurements of the air shower. Measuring air showers with the highest statistics possible is thus as important as are methods to maximize the measurement accuracy for the properties of the primary particles.

Traditionally, air showers are either measured by ground arrays of particle detectors, or by light detectors which observe the faint fluorescence light or the Cherenkov light emitted by the air-shower particles. The latter methods have the higher precision for the mass of the primary particles, and thus for the cosmic-ray composition. Unfortunately, they can operate only during dark, clear, and moonless nights, and thus are effectively limited to about one-tenth of the observation time of particle ground arrays, which operate nearly 24 h around the clock. For this reason, alternative methods are researched which can combine the advantages of both methods, i.e., the high duty cycle of the particle detector arrays and the relatively high precision for the cosmic-ray composition provided by the air-Cherenkov and fluorescence-light techniques.

Detecting the radio emission of air showers is one of the most promising alternatives providing a high duty cycle and potentially also a high precision. Although the radio emission is known for about 50 years, historic experiments were limited by the analog electronics available at that time and the missing knowledge on the physics processes behind the radio emission. But recently, the radio methods experienced a revival using digital antenna arrays. Furthermore, the understanding of the underlying physics makes progress by comparing new Monte Carlo simulations of the air-shower radio emission with measured data.

The results of this thesis have been obtained mainly with the LOPES experiment at the Karlsruhe Institute of Technology, which is such a digital radio-antenna array. LOPES was designed as a prototype experiment: Due to the relatively high, human-made radio background in urban areas like Karlsruhe LOPES is not suited for precision measurements, but instead for the development of basic methods and techniques related to the radio detection of air showers. Several successful proof-of-principle demonstrations could be made with LOPES, some of them within this thesis. Also the latest success is based on developments presented in this thesis: LOPES could demonstrate experimentally, that radio measurements are indeed sensitive to the development of the air shower, which is the basic prerequisite for the reconstruction of the cosmic-ray composition with radio measurements.

This thesis starts with a general, but short overview on the physics of extensive air showers and their radio emission as well as on experiments used for measurements. The later chapters focus on techniques and methods developed for digital radio-antenna arrays, including a new method for time calibration, the proper treatment of radio noise during data analysis, and measurements of the lateral distribution and the wavefront of the radio signal—i.e., how the amplitude, respectively the time of the radio pulse depend on the distance to the axis of the air shower. One of the major results of this thesis is that the wavefront is approximately conical instead of spherical as previously assumed, and that the cone angle is sensitive to the mass of the primary cosmic-ray particle. Finally, a comparison of LOPES measurements with simulations of the radio signal confirms the expectation that both the lateral distribution and the wavefront can be used to reconstruct the cosmic-ray composition.

Consequently, the methods developed within this thesis now impact next-generation radio arrays constructed in rural regions with lower radio background, in particular AERA and Tunka-Rex. AERA, the Auger Engineering Radio Array, is the radio extension of the Pierre Auger Observatory in the Argentinian Pampa

Amarilla. It makes already use of the time calibration method developed in this thesis. Moreover, it can test the precision of radio measurements for the cosmic-ray composition by a direct comparison to fluorescence-light measurements of the same air showers, which are regularly performed at the Pierre Auger Observatory. Complementary to AERA is Tunka-Rex, the radio extension of the Tunka observatory in Siberia close to lake Baikal, which allows a cross-calibration of radio and air-Cherenkov-light measurements of the same air showers.

Thus, the developments and research made in this thesis open a promising perspective for next-generation radio arrays. If the potential of the radio methods can be confirmed there, this gives us a chance to measure air showers initiated by cosmic rays of the highest energies with high statistics and relatively high precision at the same time. This way, the radio detection of extensive air showers can be the secret of success to solve the mystery where the ultra-high energy cosmic rays originate.

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Last but not least, I thank my family and my friends.

Contents

Abbreviations

a.s.l.	Above sea level
ADC	Analog to Digital Converter
AERA	Auger Engineering Radio Array
AIRES	AIRshower Extended Simulations
AMIGA	Auger Muons and Infill for the Ground Array
BLS	Balloon Launching Station
CC	Cross-Correlation
cf.	Confer (compare)
CLF	Central Laser Facility
CODALEMA	COsmic ray Detection Array with Logarithmic ElectroMagnetic Antennas
CORSIKA	COsmic Ray SImulations for KAscade
CRS	Central Radio Station
DAQ	Data AcQuisition
DC	Direct Current
e.g.	Exempli gratia (for example)
FD	Fluorescence Detector
FFT	Fast Fourier Transform
FM	Frequency Modulation
FWHM	Full Width at Half Maximum
GPS	Global Positioning System
HEAT	High Elevation Auger Telescopes
i.e.	Id est (this is)
KASCADE	KArlsruhe Shower Core and Array DEtector
LNA	Low Noise Amplifier
LOFAR	LOw Frequency ARray
LOPES	LOFAR PrototypE Station
$\mathrm{LOPES}^{\mathrm{STAR}}$	LOPES Self Triggered Array of Radio detectors
LPDA	Logarithmic Periodic Dipole Antenna
MAXIMA	Multi Antenna eXperiment In Malargüe Argentina
MGMR	Macroscopic model of GeoMagnetic Radiation

PMT	Photo Multiplier Tube
REAS	Radio Emission from Air Showers
RFI	Radio Frequency Interference
RMS	Root Mean Square (Following the language use in physics, 'RMS' is used as synonym for 'standard deviation', although the exact mathematical definition is different)
SALLA	Short Aperiodic Loaded Loop Antenna
SD	Surface Detector
SNR	Signal-to-Noise Ratio
TEC	Total Electron Content
TIM	Trigger Interface Module

Chapter 1
Introduction

Almost a hundred years after their discovery, cosmic rays still have preserved some mysteries and fascinate an international community of scientists. By now, the acceleration of atomic nuclei by super nova shock fronts is a well established paradigm which can, at least partly, explain the origin of the galactic cosmic rays with energies $\lesssim 10^{15}$ eV. Yet, the nature and origin of particles at highest energies up to a few 10^{20} eV is not solved. Neither the end of the energy spectrum is known, nor the energy of the transition from galactic to extragalactic cosmic rays. One reason for this is that the flux of cosmic rays at the highest energies is extremely low. Thus, they can only be detected indirectly by measuring air showers of secondary particles. Consequently, answering those questions requires large air shower observatories, and methods to reconstruct the properties of the primary cosmic ray particles from the air shower observables, namely its energy, arrival direction, and type, respectively mass. The established methods rely on detection of secondary particles at ground, fluorescence and Cherenkov light emitted by the air shower. The first one allows the reconstruction of the primary particle properties only within large uncertainties due to statistical fluctuations and uncertainties of the models for shower generation and hadronic interactions at the highest energies. The latter ones suffer from limited operation time restricted to dark nights (see Chap. 2).

Radio measurements of air showers have the potential to combine the advantages of these established techniques (good reconstruction capabilities and high duty cycle). Historic experiments already showed that air shower induced radio pulses can in principle be used to reconstruct the primary energy and arrival direction, but neither the measurement precision nor the understanding of the radio emission mechanism was sufficient to compete with the other detection techniques.

This situation started to change when LOPES, a digital antenna array co-located with the KASCADE-Grande experiment at KIT, proved that air showers can be measured with radio interferometry (see Chap. 3). Nevertheless, to make the radio detection technique a feasible tool for cosmic ray physics, the reconstruction accuracies of arrival direction, energy and mass must be ameliorated, and the technical applicability to large scale experiments must be demonstrated. Both of these are goals

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of the Auger Engineering Radio Array (AERA) at the Pierre Auger Observatory in Argentina.

To achieve these goals, research on the following topics is required. First, the precision of the measurement of the amplitude and arrival time of the radio emission has to be enhanced. The arrival direction is essentially reconstructed by measuring arrival times, and the energy by measuring amplitudes. The primary mass can be probed either by the shape of the wavefront, i.e., by pulse arrival times, or by the slope of the lateral distribution of pulse amplitudes. Second, the theoretical understanding of the radio emission has to be improved, which can be done by comparing model predictions with measurements. Third, all techniques, be it data processing, or calibration methods must be scalable to large antenna array, for probing cosmic rays at highest energies.

This thesis made progress in all the three research topics. Like LOPES has already shown, the reconstruction of arrival direction, energy and mass can be done with interferometric beamforming. This technique improves the signal-to-noise ratio compared to analyses based on pulse arrival times and amplitudes at individual antennas. The precision of interferometric beamforming depends strongly on the relative timing accuracy and precision between different antennas. Thus, a new method for the time calibration of LOPES is introduced in Chap. 4. It allows to achieve the necessary timing resolution of $\lesssim 1$ ns per event by continuously measuring the phase of a reference signal emitted by a radio beacon.

This beacon technique has been made applicable to large scale experiments of autonomous stations with independent clocks (e.g., GPS). Such a beacon was deployed and tested at AERA (see Chap. 5). Without the beacon the relative timing of AERA would be insufficient for digital interferometry, and AERA could only rely on the analysis of lateral distributions and pulse arrival time distributions of the radio signal.

As shown in Chap. 6, especially for antennas with signals close to the noise level (e.g., at large lateral distances), noise can be the dominant source of error for time and amplitude measurements. Moreover, noise systematically flattens the lateral distribution. Hence, accounting for noise is an important issue for the reconstruction of shower parameters based on amplitude and time measurements in individual antennas.

One motivation to look not only at the interferometric combination of all antennas, but also at individual antennas, is that the lateral distribution is an excellent tool to compare theoretical models for radio emission with measured data. Because of the better comprehension of noise and other systematic effects, the precision of LOPES measurements has become sufficient to test recently improved models for radio emission, like REAS3 (see Chap. 7). LOPES measurements and REAS3 simulations generally match each other, which demonstrates that our understanding of the radio emission has greatly improved. Furthermore, the comparison of measurement and simulation confirms that the lateral distribution provides a method to reconstruct the primary mass.

Beside that, the mass sensitive shower maximum $X_{\max}$ can also be estimated by reconstructing the radio wavefront with pulse arrival time measurements (see

Chap. 8). The radio wavefront of LOPES measurements as well as REAS3 simulations can better be described with a cone than with a sphere. This is a new result, since up to now a spherical wavefront has been assumed in all LOPES beamforming analyses. X_{max} can be estimated from the opening angle of the conical wavefront. Although this method in principle works and yields X_{max} values in the expected order of magnitude, it became clear that uncertainties at LOPES are too large for a per-event reconstruction of X_{max}. Limiting factors at LOPES are the high level of ambient noise, and the small extension of the antenna array ($\sim$200 m). Hence, the approach is expected to be more successful at AERA, which by the end of 2010 has started to measure the radio emission of air showers in a less noisy environment and on larger scale. This thesis provides several techniques which will soon be applied on the analyses of first AERA data.