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.

http://www.springer.com/978-3-642-33659-1

Instruments and Methods for the Radio Detection of
High Energy Cosmic Rays
Schröder, F.
2012, XVIII, 190 p., Hardcover
ISBN: 978-3-642-33659-1