Radio detection of cosmic ray air showers in the digital era

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Abstract

In 1965 it was discovered that cosmic ray air showers emit impulsive radio signals at frequencies below 100 MHz. After a period of intense research in the 1960s and 1970s, however, interest in the detection technique faded almost completely. With the availability of powerful digital signal processing techniques, new attempts at measuring cosmic ray air showers via their radio emission were started at the beginning of the new millennium. Starting with modest, small-scale digital prototype setups, the field has evolved, matured and grown very significantly in the past decade. Today's second-generation digital radio detection experiments consist of up to hundreds of radio antennas or cover areas of up to 17 km². We understand the physics of the radio emission in extensive air showers in detail and have developed analysis strategies to accurately derive from radio signals parameters which are related to the astrophysics of the primary cosmic ray particles, in particular their energy, arrival direction and estimators for their mass. In parallel to these successes, limitations inherent in the physics of the radio signals have also become increasingly clear. In this article, we review the progress of the past decade and the current state of the field, discuss the current paradigm of the radio emission physics and present the experimental evidence supporting it. Finally, we discuss the potential for future applications of the radio detection technique to advance the field of cosmic ray physics.

Keywords:

high-energy cosmic rays, radio emission, extensive air showers

1. Introduction

Even though more than 100 years have passed since the discovery of cosmic rays, many questions about their origin, the physics of their acceleration and their hadronic interactions in the atmosphere are still unanswered [1]. To tackle the complexity of the problem, two ingredients are very important: First, cosmic rays have to be measured with sufficient statistics, a difficult task at the highest energies where the particle flux becomes as small as one particle per km² per century, see Fig. 1. Second, the measurement quality has to be as good as possible to provide enough information, in particular, to identify the mass of the primary particles, an essential piece of information in testing hypotheses for particle acceleration and propagation. Techniques such as large-scale particle detection with ground-based arrays and fluorescence detection of air showers with optical telescopes have been employed with great success over many decades [2]. These approaches detect "extensive air showers", cascades of secondary particles initiated by the primary cosmic ray in the atmosphere [3]. However, the established detection methods all have their drawbacks, and the community is constantly looking for ways to improve on the established techniques. A prime example of such an endeavor is the proposed AugerPrime [4] upgrade of the Pierre Auger Observatory, which strives to achieve sensitivity to the mass composition of cosmic rays at the highest energies via separate measurements of the electromagnetic and muonic air shower components using an additional layer of scintillators deployed on top of the existing water-Cherenkov detectors.

In the past decade, the field of radio detection of cosmic ray air showers has undergone an impressive renaissance. Building on the knowledge gathered from historical radio detection experiments in the 1960s and 1970s, innovative projects were started in the early 2000s, driven by high expectations [5]. The goal of these projects was to first provide a proof of principle for the detection of air showers using digital radio techniques, and then to evolve these approaches into a new technology for large-scale air shower measurements. Having met with great success, these activities

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Figure 1: The energy spectrum of the highest energy cosmic rays measured by various experiments. The energy range accessible to radio measurements is indicated. At low particle energies, radio signals become weak and are overwhelmed by background. At high energies, concepts to cover very large effective detection areas have yet to be developed. Diagram updated and adapted from [3].

steadily gained in momentum, as is illustrated in Fig. 2. Today's experiments have matured well beyond the prototyping phase. They are aimed either at covering large areas with a minimum number of antennas or at measuring individual air showers with hundreds of radio antennas at a time. Radio signals are expected to be measurable above background at energies $\leq 10^{17}$ eV, and probably down to energies as low as $\geq 10^{16}$ eV when applying interferometric analysis techniques, see Fig. 1.

In parallel to the experimental activities, models for the physics of the radio emission emanating from extensive air showers have matured to a degree that the emission mechanisms are now generally assumed to be well-understood. As it turns out, there is a large overlap between the physics of radio emission from air showers and the physics of radio emission from particle showers in dense media. We will mention these parallels where appropriate. However, we deliberately focus this review on the case of air showers and the methods to detect them with radio techniques.

After a short introduction of the starting point for the modern-day experiments, including an overview of the merits warranting the investigation of radio detection of cosmic rays, we will set the scene with a review of the current paradigm of air shower radio emission physics and the most important characteristics of the emission. Next, we will discuss the evolution of modelling efforts which, in conjunction with results from various experiments, led to this paradigm. Afterwards, we will describe the experimental projects which were developed over the past decade and highlight their goals and technological choices, before discussing some analysisrelated aspects and then moving on to a detailed description of the important experimental results achieved to date and how they compare to theoretical predictions. Finally, we close with an outlook to possible future directions of the field of air shower radio detection.

2. The starting point for digital radio detection of air showers

Modern radio experiments built on knowledge gained 50 years ago, which provided a valuable starting point. Here, we quickly discuss the most relevant information available from the historical works and then outline the promises of the radio detection technique which led to renewed interest and sparked the new projects.

2.1. The knowledge from historical experiments

Radio detection of cosmic rays *per se* is not a new technique. In fact, the experimental proof that air show-



Figure 2: Number of contributions related to radio detection of cosmic rays or neutrinos at the bi-yearly International Cosmic Ray Conferences. Data up to 2007 were taken from [6].

ers emit impulsive radio signals was made as early as 1965 [7]. As a consequence, several groups engaged in experimental and theoretical work to study the details of the radio emission. It is not the goal of this article to review these historical works, and we kindly refer the reader to the excellent article of Allan [8] for such a review.

However, let us briefly discuss the most relevant pieces of information which were available from the historical works at the time that the community rediscovered its interest in radio detection of cosmic rays. These were:

- Air showers initiated by cosmic rays emit impulsive radio emission. The emission was originally discovered at a frequency of 44 MHz, but successful detections from as low as 2 MHz up to 500 MHz followed.
- The radio signal, at least at frequencies below 100 MHz, is coherent. In other words, the received power generally scales quadratically with the number of emitting particles, and thus with the energy of the primary cosmic ray (with the exception of showers being truncated when hitting the ground).
- The emission is dominated by a geomagnetic effect, since a clear correlation of the radio signal strength is seen with the angle between the air shower axis (the axis determined by the arrival direction of the primary cosmic ray particle) and

the geomagnetic field axis. Due to the geomagnetic nature of the emission, the signal is generally expected to be strongest in antennas measuring the polarisation component aligned with the Lorentz force. For detection sites at geographic mid-latitudes, this corresponds to the east-west polarisation component.

• The signal strength measured by an antenna depends on the lateral distance from the air shower axis and can be fitted with an exponential lateral distribution function (LDF).¹

The gist of this knowledge can be summarized in one formula, often referred to as the "Allan-formula" (eq. (84) in Ref. [8]), as follows:

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

in which ϵ_{ν} denotes the peak total amplitude (modulus) of the electric field vector divided by the effective bandwidth of the measurement, E_p is the energy of the primary cosmic ray, α is the so-called "geomagnetic angle", i.e. the angle between the air shower axis and the

¹Keep in mind, however, that the historical experiments only measured the radio LDF averaged over many different air showers, not the radio LDF of an individual air shower itself.

geomagnetic field axis, θ is the "zenith angle", i.e. the angle wrt. vertical incidence of the cosmic ray primary, and *R* denotes the lateral distance perpendicular from the air shower axis, often denoted "axis distance". The scale factor R_0 depends on frequency and zenith angle, but there were no particularly quantitative results available at the time.

In spite of this significant knowledge, a number of important questions were open:

- Several secondary emission mechanisms had been investigated on a theoretical basis, and there were some experimental results suggesting that the geomagnetic emission was not the only mechanism. However, these were indications at best, and they were far from being accepted in the community. The relevance of the atmospheric refractive index gradient had also been studied to some extent [9, 10].
- There were theoretical investigations on the sensitivity of the radio signal, in particular its LDF, on the longitudinal evolution of the air shower [9, 10], and thus the mass of the primary particle, but no experimental tests or quantitative studies were available.
- The absolute strength of the radio emission was reported very differently, up to factors of 100 in amplitude, by different groups [11]. The assumption was that this was due to difficulties in providing an absolute calibration for the measurements.
- It was unclear how important the influence of electric fields in the atmosphere (say in thunderclouds [12]) could be and whether an effect on the radio signal was to be expected even for fair weather. If the latter were true, it would make the technique unreliable for any quantitative measurements, as the atmospheric electric field at altitudes of several kilometers is hard to monitor.

In the mid-1970s, the activities on radio detection of cosmic rays ceased almost completely, as is evident also from Fig. 2. This was due to a number of reasons, for example there were problems in associating the radio measurements reliably with the relevant air shower characteristics, which was sometimes attributed to the effects of unknown atmospheric electric fields. Also, the fluorescence imaging technique pioneered in the Fly's Eye experiment [13] seemed more promising and made good progress, which shifted the interest of the cosmic ray community. It took 30 years for the interest in radio detection to renew. We will discuss the reasons for this renewal in the next subsection.

2.2. The promises of radio detection

As mentioned in the introduction, existing techniques using particle detector arrays and optical fluorescence detectors (or optical Cherenkov light detectors) have been very successful in studying cosmic rays over a very wide range of energies. However, they do have their shortcomings.

All detection techniques at energies beyond $\gtrsim 10^{14}$ eV rely on the measurement of the extensive air shower cascade initiated by a primary cosmic ray in the atmosphere. This air shower is dominated by the electromagnetic component (electrons, positrons and photons) and has a characteristic evolution with atmospheric depth, shown in Fig. 3. The shower first grows, then reaches a maximum, and afterwards dies out.



Figure 3: Longitudinal evolution profiles of the electromagnetic components of extensive air showers initiated by proton and iron primaries with an energy of 10^{19} eV, as simulated with CORSIKA [14]. The depth of the maximum of the air shower evolution, X_{max} , provides valuable information about the mass of the primary particle. More massive particles on average have a lower depth of shower maximum, and their distribution of X_{max} values scatters less than for lighter particles.

Particle detectors only measure a momentary snapshot of the secondary particles in an air shower reaching the ground, and typically only sample a small fraction of these particles due to their limited area coverage. This yields very indirect information about the original primary cosmic ray particle. In particular, uncertainties in the hadronic interactions at energies well beyond those accessible in collider experiments introduce significant systematic uncertainties in the reconstruction of the characteristics of the primary particle from the ground-based particle detector measurements [3]. An important problem unsolved to date is the discrepancy in the number of muons predicted by simulations, which at 10^{19} eV is at least 30% lower than the one derived from hybrid measurements with fluorescence telescopes and particle detectors at the Pierre Auger Observatory [15]. The most likely explanation for this discrepancy is in the extrapolation of hadronic interaction physics well beyond the scale probed with measurements at particle accelerators, which also measure in a very different regime than the extreme forward interactions in air showers. While particle detectors can be seen as the "work-horse" of cosmic ray detection, since in particular they can measure with 100% duty cycle, information from other detectors is thus needed to exploit them to their full potential, especially with regard to a reliable reconstruction of the absolute energy scale of cosmic-rays. The Pierre Auger Observatory in particular has committed to such a "hybrid approach" by combining particle detectors with optical fluorescence telescopes which are used to calibrate the energy scale of the particle detectors. It remains very difficult, however, to determine the mass of the primary particle from ground-based particle detectors. This requires at least the separate measurement of the electromagnetic and muonic components of the air shower, as is the goal of the AugerPrime upgrade [4], and still might suffer from systematic uncertainties in hadronic interaction models.

The most-used optical detection technique is the detection of ultraviolet light emitted by excited air molecules in the air shower. Using pixelated UV cameras, the longitudinal evolution of an air shower as shown in Fig. 3 can be imaged. The integral of the longitudinal evolution profile yields a calorimetric energy measurement of the air shower. As the emission of fluorescence light is vastly dominated by the electromagnetic component of the air shower, it is much less affected by hadronic interaction uncertainties. Also, the atmospheric depth at which the air shower reaches its maximum particle number, the "shower maximum" or $X_{\rm max}$ (in g cm⁻²) can be read off from the profile and yields precious information about the mass of the primary particles, again visible in Fig. 3. Fluorescence detectors thus yield very high quality data - however, they do it effectively in less than 10-15% of the time. Their "duty cycle" is limited to such small numbers because the technique relies on clear, moon-less nights. Fiducial volume cuts further limit the fraction of data usable for analyses. At the very high energies, the loss in statistics of more than a factor of 10 is an important drawback. Also, the air quality at the site has to be good and has to be monitored very closely [16].

In light of these limitations, interest in the radio de-

tection technique re-emerged in the early 2000s; for a review of the field at that time see [5]. Radio detection was expected to have the following advantages:

- The radio emission is caused by the electromagnetic component of the air shower. As such it does not suffer strongly from uncertainties in the hadronic interaction models.
- The radio signal is integrated over the full shower evolution. (There is no relevant damping in the atmosphere at VHF frequencies.) It thus represents a calorimetric energy measurement.
- Radio measurements can be performed with essentially 100% duty cycle.²
- The radio signal should be sensitive to the longitudinal shower evolution and thus X_{max} .
- Radio antennas can be built comparably cheaply. Possibly, very large areas could be instrumented economically with radio detectors to detect cosmic rays at the highest energies.
- In contrast to the 1960s and 1970s, powerful digital signal processing is available today. (No more photographing of oscilloscope traces!) While digital electronics do come with a price tag, radio detections directly profits from Moore's law. Digital electronics get exponentially cheaper in time.

In the early 2000s, the idea arose to apply digital radio detection to the problem of cosmic ray physics [17]. One vision driving these activities was the hope that a combination of particle detectors and radio antennas could yield similar information as the combination of particle and fluorescence detectors — but with 100% duty cycle instead of 10% duty cycle.

We will discuss in the course of this review which of these promises can be kept and which cannot. Before we go into any more detail of the evolution of the radio emission experiments, let us set the scene with a summary of what we know about the nature of the radio emission from air showers today.

3. The physics of radio emission from extensive air showers

Before reviewing the progress of the last decade on both the theoretical and the experimental side in detail,

 $^{^{2}}$ As we will see, only thunderstorms lower this value, but it typically remains at a level of more than 95% at most sites.

let us first go through a concise summary of the radio emission physics as we understand it today. We will keep the discussion mostly non-technical, readers interested in the details are encouraged to study the original publications referenced in the text.

3.1. Geomagnetic emission

The main emission mechanism for radio pulses from cosmic ray showers is associated with the geomagnetic field: Secondary electrons and positrons in the air shower are accelerated in the magnetic field. One idea that was followed was that this acceleration directly leads to the radio emission as in synchrotron emission, hence the term "geosynchrotron emission" was coined [17]. However, this view does not correctly describe the emission physics in air showers. The reason is that electrons and positrons do not propagate unimpeded on long, let alone periodic orbits. Instead, they interact continuously with air molecules. The situation is comparable to the one of electrons in a conductor to which a voltage is applied. In the equilibrium of acceleration by the magnetic field and deceleration in interactions with air molecules a net drift of the electrons and positrons arises in opposite directions as governed by the Lorentz force

$$\vec{F} = q \, \vec{v} \times \vec{B}.\tag{2}$$

where q denotes the particle charge, \vec{v} is its velocity vector and \vec{B} is the magnetic field vector. For particles originally moving along the shower axis, the resulting current will be perpendicular to the shower axis, i.e. we can refer to them as "transverse currents".

There is one more important ingredient: These transverse currents vary as the air shower evolves and the number of secondary particles first grows, then reaches a maximum, and then declines as the shower dies out (cf. Fig. 3). It is this time-variation of the transverse currents which leads to electromagnetic radiation. Due to the relativistic speed of the emitting particles, the emission is compressed in short pulses in the forward direction, along the shower axis (Fig. 4, top). Correspondingly, the emission has broad-band frequency spectra (Fig. 4, bottom). For geometrical reasons, the pulses get broader and the frequency spectra cut off at lower frequencies as the observer moves away from the shower axis. Interpreted in a microscopic way, the timevariation of the transverse currents can be associated with acceleration of individual particles, i.e., it is in fact acceleration of charged particles that produces the radiation.



Figure 4: Radio pulses (top) arising from the time-variation of the geomagnetically induced transverse currents in a 10^{17} eV air shower as observed at various observer distances from the shower axis and their corresponding frequency spectra (bottom). Refractive index effects are not included. Adapted from [18].

The polarisation of the radiation by the time-varying transverse currents is linear with the electric field vector aligned with the Lorentz force, i.e. along the $\vec{v} \times \vec{B}$ direction, where the propagation direction of the particles \vec{v} can be approximated with the shower axis. This is illustrated in the left panel of Fig. 5.

In principle, any charged particle undergoes the processes described here. However, only electrons and positrons contribute significantly to the radio signal as they have by far the highest charge/mass ratio. Already muons are much too heavy to make a significant contribution.

This emission physics has already been described by Kahn & Lerche [19]. A modern formulation was developed by Scholten, Werner and Rusydi [18].

3.2. Charge excess emission (Askaryan effect)

In addition to the dominating geomagnetic contribution³ a secondary effect exists. It is well known that there is a negative charge excess of $\approx 10 - 20\%$ in air showers, which is caused mostly by the fact that the ambient medium is ionized by the air shower particles and the ionization electrons are swept with the cascade, while the much heavier positive ions stay behind. As the shower evolves, the absolute negative charge present in the moving cascade grows, reaches a maximum and finally decreases when the shower dies out. Hence, again there is a *time-varying* charge excess, and this leads to pulses of electromagnetic radiation.

This radiation also has linear polarisation. However, the electric field vector is oriented radially with respect to the shower axis. In other words, the orientation of the electric field vector depends on the location of an observer (radio antenna) with respect to the shower axis, as is illustrated in the right panel of Fig. 5.

The mechanism described here, together with Cherenkov-like effects that will be described in the next section, is essentially the Askaryan-effect [22, 23]. It usually plays a sub-dominant role in air shower physics, however it is the sole relevant emission mechanism in particle showers in dense media and has been investigated in considerable depth in the context of neutrino detection via radio emission in ice and the lunar regolith (see, e.g., [24]). Since the length scales of particle showers in dense media are much smaller, the resulting radiation is strongest at GHz frequencies. The underlying physics, however, is the same as in air.

3.3. Superposition of the contributions and signal asymmetries

When the electric field vectors associated with the two emission mechanisms are superposed, complex

asymmetries in the radio signal arise, as depending on the observer location, the two contributions can add constructively or destructively. The arising asymmetry, specifically along the direction denoted by $\vec{v} \times \vec{B}$ (eastwest for vertical air showers) is illustrated by the visualization of the "radio footprint" (two-dimensional radio LDF) depicted in Fig. 6. The degree of asymmetry depends on the relative strength of the geomagnetic and charge excess contributions, and thus in particular on the geomagnetic angle of a given air shower as well as the strength of the local geomagnetic field.



Figure 6: Simulation of the total electric field amplitude in the 40-80 MHz band for a vertical cosmic ray air shower at the site of the LOPES experiment. The asymmetry arises from the superposition of the geomagnetic and charge-excess emission contributions. Refractive index effects are included. Adapted from [25].

While the footprint shown in Fig. 6 illustrates the peak amplitude measured at various observer locations, a closer look at the time-evolution of the impulsive radio emission is shown in Fig. 7. The pulses associated with the two emission mechanisms are not perfectly synchronized, a sign that the time-variation of the transverse currents induced by geomagnetic effects and the timevariation of the net charge excess are slightly offset over the course of the longitudinal evolution of the extensive air shower. Therefore, the electric field vector does not generally trace a line in the plane perpendicular to the shower axis; instead, it generally traces an ellipse. In other words, the radio emission from cosmic ray air showers is generally of elliptical polarisation, i.e. an admixture of linear and circular polarisation. This effect remains to be proven experimentally.

³Obviously, the geomagnetic contribution vanishes for air showers arriving parallel to the magnetic field. For air showers with a small geomagnetic angle thus the charge excess emission can actually become dominant.



Figure 5: Left: Illustration of the geomagnetic radiation mechanism. The arrows denote the direction of linear polarisation in the plane perpendicular to the air shower axis. Irrespective of the observer position, the emission is linearly polarised along the direction given by the Lorentz force, $\vec{v} \times \vec{B}$ (east-west for vertical air showers). Right: Illustration of the charge excess (Askaryan) emission. The arrows illustrate the linear polarisation with electric field vectors oriented radially with respect to the shower axis. Diagrams have been adapted from [20] and [21].



Figure 7: Illustration of the time-evolution of the electric field vector in the 40-80 MHz frequency band for antennas at 100 m lateral distance to the north, north-east, east, south-east, south, south-west, west, and north-west (counting clockwise from the top panel) of the impact point of a vertical 10^{17} eV air shower at the LOPES site. The field is decomposed in components along the direction of the Lorentz force and perpendicular to that. The map in the center illustrates the total amplitude footprint. Refractive index effects are included. Adapted from [25].

3.4. Forward beaming, coherence and Cherenkov-like effects

An important factor in the emission physics is coherence. As long as radiation at a given frequency from different particles acquires negligible relative phase shifts during its propagation to the observer, the vectorial electric fields add up coherently. This means that the electric field amplitude scales linearly with particle number and thus (approximately) with the energy of the primary particle. The linearity of this dependence is a very useful feature for energy measurements with radio techniques. Equivalently, the received power scales quadratically with the energy of the primary particle.

Obviously, coherence is frequency-dependent and more pronounced at low frequencies. Coherence is influenced by the spatial particle distribution (mainly the thickness of the air shower disk, but for observers at large lateral distances also its lateral extent) as well as geometrical effects and propagation physics.

Due to the relativistic motion of the radiating particles along the air shower axis, the radiation is strongly forward-beamed, requiring antennas placed within a constrained "illuminated area". Furthermore, the refractive index of the atmosphere is not unity. At sea level a typical value is n = 1.000292, and it scales proportionally with the air density to higher altitudes.



Figure 8: For different models of the atmospheric refractive index n, emission emanating from certain heights h can be strongly compressed in time, as indicated by the compression factor on the left vertical axis. If the strongly compressed emission region coincides with those parts of the longitudinal shower evolution profile (black line and right vertical axis) at which the shower changes rapidly, strong compressed radio pulses occur. Adapted from [26].

This refractive index gradient has important consequences for the resulting radiation pattern. If for a given emission region along the shower axis an observer is located at the corresponding Cherenkov angle⁴, radiation emitted from all along this region arrives simultaneously at the observer. In other words, pulses are



Figure 9: Simulated radio pulses for an air shower with a primary energy of 5×10^{17} eV. The observer is located at an axis distance of 100 m. The refractive index *n* has been adopted as unity (vacuum), 1.0003 (sea level) and a realistic gradient in the atmosphere *n*(*z*), illustrating the ensuing time compression of the radio pulses. The particle distribution is approximated to have no lateral extent. Adapted from [27].

compressed in time and can thus become very short, as is shown in Figs. 8 and 9. This can lead to coherent emission up to GHz frequencies for observers located on a "Cherenkov ring" with typical ring radii for vertical 10^{17} eV air showers of order 100 m, as is shown in Fig. 10.

At lateral distances which fall inside the Cherenkov ring, the pulses are stretched by the refractive index effects and the transition frequency from coherent to incoherent emission is decreased. Also, the time-ordering of signals is reversed: signals emitted in the early stages of the air shower arrive later than those emitted in late stages.

At large lateral distances, outside the Cherenkov ring, the refractive index effects are negligible, as the pulsewidths are dominated by geometrical effects. The larger the lateral distance, the broader the received pulses and the lower is the transition frequency from coherent to incoherent emission.

We stress here that the refractive index gradient influences the radiation emitted by the time-varying transverse currents and time-varying charge excess by compressing (or stretching) it in time. It is valid to term this "Cherenkov-like" effects. However, the reader should not confuse this with "Cherenkov radiation" in the sense

⁴Due to the refractive index gradient in the atmosphere, there is of course strictly speaking no well-defined, unique Cherenkov angle.



Figure 10: Radio-emission footprint of the total field strength of a vertical 10^{17} eV air shower induced by an iron primary at the LOPES site as seen in the frequency range from 300 to 1,200 MHz. Adapted from [25].

of a (constant) net charge moving through a medium with a velocity which is higher than the medium-speedof-light [28]. Such a contribution by "Cherenkov radiation" must certainly be present, but to our knowledge it is completely negligible for the case of air showers at radio frequencies.

3.5. Source distance effects

As the radio emission is strongly forward-beamed, into a cone of a few degrees opening angle, the distance of the radio source from the observer has a strong influence on the size of the illuminated area. It should be noted that for the radio emission, geometrical distance scales, in particular the distance from source to observer, matters. This is in contrast to the air shower evolution which is governed by the amount of matter traversed (atmospheric depth).

A particularly important effect is the dependence of the radio emission on the air shower zenith angle. As the zenith angle increases, the traversed atmospheric depth grows as⁵ $\cos^{-1}(\theta)$. The air shower reaches its maximum at a given atmospheric depth, thus for more inclined showers this maximum will be at significantly larger geometrical distances from the observer than for vertical air showers. As a consequence, the forwardbeamed radio emission illuminates a much larger area, as is illustrated impressively in Fig. 11. The average electric field amplitude is lower (the radiated power is distributed over a larger area), but also the LDF is less steep. This makes inclined air showers more favourable for detection with a sparse antenna grid [29].

For a fixed zenith angle, another important factor influencing the geometrical source distance is the depth of the maximum of an individual air shower, X_{max} . This quantity undergoes statistical fluctuations, but is one of the most important observables to determine the mass of the primary particle. Changes in Xmax are also reflected in the geometrical distance between radio source and observer, and thus can be exploited to determine X_{max} from radio measurements. The most obvious way to access this information is the LDF, as discussed above and illustrated in the comparison between Fig. 6 for an iron-induced air shower (small X_{max}) and Fig. 12 for a proton-induced air shower (large X_{max}) (note the different scales). For the same geometrical reasons, the geometrical source distance also influences the shape of the radio wavefront, which can be determined by precise timing measurements, and the pulse shape (or spectral index of the frequency spectrum) measured at a given lateral distance. We will discuss the sensitivity of the radio signal to the mass of the primary particle in more depth in the chapter on experimental results.



Figure 12: Radio-emission footprint of the 40-80 MHz total field strength of a vertical 10^{17} eV air shower induced by a proton primary at the LOPES site. Adapted from [25].

4. Modern models and simulations of air shower radio emission

In parallel with the modern experimental efforts, modelling efforts for the radio emission from extensive air showers were started. We give an overview here of approaches that have been tried out, but will focus on

 $^{^5} This$ is an approximation for a planar atmosphere which is valid up to zenith angles of $\approx 70^\circ.$



Figure 11: Simulated footprints of the radio emission of extensive air showers with various zenith angles in the 30-80 MHz frequency band for an air shower with an energy of 5×10^{18} eV. The detection threshold governed by Galactic noise typically corresponds to $\approx 1-2 \,\mu\text{V/m/MHz}$. The footprint is small for air showers with zenith angles up to $\approx 60^{\circ}$, but becomes very large for inclined showers with zenith angles of 70° or higher. The white rectangle denotes the size of the 50° inset. The strong increase of the area illuminated by inclined air showers is due to the large geometrical distance of their emission region from the ground. Adapted from [30].

those that are still being maintained at the time of writing this review.

4.1. Flawed modern approaches

A number of efforts that were started in the early 2000s later turned out to be flawed. The "geosynchrotron" scheme was followed initially with a semianalytic calculation in the frequency domain [31]. The explicit assumption of synchrotron radiation of particles on long orbits dominating the emission, however, later turned out to be untrue.

Time-domain calculations inspired by the "geosynchrotron" idea were started as well. Approaches by Du-Vernois et al. [32] and Suprun et al. [33] were developed at the same time as the REAS Monte Carlo code, which was first based on parameterized air showers (REAS1) [34, 35] and later on histogrammed particle distributions [36] extracted from CORSIKA [14] simulations (REAS2). Independently, the ReAIRES code [37], based on the AIRES air shower Monte Carlo code [38], was implemented. A simplified point-like model was also formulated [39]. The SELFAS1 code was developed on the basis of parameterizations of particle distributions determined from REAS2 histograms [36]. proaches the discretized implementation of the classical electrodynamics calculation was flawed. For details, we refer the reader to [40]. The problem was that these models start from the Liénard-Wiechert description of the electric field of a single moving charged particle [41], $\vec{E}(\vec{x},t) = e\left[\frac{\vec{n}-\vec{\beta}}{\vec{n}-\vec{\beta}}\right]$

It turned out later that in all these time-domain ap-

$$\vec{E}(\vec{x},t) = e \left[\frac{n-\beta}{\gamma^2 (1-\vec{\beta}\cdot\vec{n})^3 R^2} \right]_{\text{ret}} + \frac{e}{c} \left[\frac{\vec{n} \times \{(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}\}}{(1-\vec{\beta}\cdot\vec{n})^3 R} \right]_{\text{ret}}, \quad (3)$$

with *e* for the electron charge, *c* the speed of light, γ the Lorentz factor of the particle, \vec{n} the unit vector along the line-of-sight between particle and observer, $\vec{\beta}$ the particle velocity in units of *c*, and *R* the distance between particle and observer. The index "ret" specifies that the equations have to be evaluated at the appropriate retarded time. Using this expression as their building block, the models took into account the emission from acceleration of particles in the magnetic field. However, in an air shower, the radio emission emanates from an ensemble of *N* relativistic charged particles. Because *N* varies over the air shower evolution, it has a time-

dependence N(t). The flawed models calculated the radio emission from the ensemble of particles in an air shower as

$$\vec{E}_{\text{tot}}(\vec{x},t) = N(t)\vec{E}(\vec{x},t)$$
(4)

Although this equation seems to take into account the variation of the number of relativistic charged particles, radiation associated with this variation of the number of charges is neglected. This becomes apparent when recalling that the electric field equation (3) itself is derived from the Liénard-Wiechert potentials

$$\Phi(\vec{x},t) = \left[\frac{e}{(1-\vec{\beta}\cdot\vec{n})R}\right]_{\text{ret}}$$
$$\vec{A}(\vec{x},t) = \left[\frac{e\vec{\beta}}{(1-\vec{\beta}\cdot\vec{n})}\right]_{\text{ret}}$$
(5)

via

$$\vec{E}(\vec{x},t) = -\nabla \Phi(\vec{x},t) - \frac{\partial}{\partial t} \vec{A}(\vec{x},t).$$
(6)

The fact that the number of charged particles N(t) is changing as a function of time thus must be taken into account in the calculation of $\vec{A}_{tot}(\vec{x}, t) = N(t)\vec{A}(\vec{x}, t)$ already. The time-derivative applied to calculate $\vec{E}_{tot}(\vec{x}, t)$ then leads to additional radiation terms appearing because of the time-dependence of N(t).

This problem in the early approaches was only realized around 2009, when comparisons were made with the modern macroscopic approaches described in the next subsection.

4.2. Modern macroscopic approaches

Models for the radio emission from extensive air showers describing the radiation physics with macroscopic concepts such as electric currents and electric charge rather than individual particles are called "macroscopic approaches". The advantage of these approaches is that they provide direct insight into relevant effects contributing to the radio emission from extensive air showers. Also, they are mostly analytic and can thus predict a signal with very small computational effort.

The MGMR [18] approach, a modern representation of the original Kahn & Lerche approach [19], contributed significantly to our understanding of the radio emission from extensive air showers. It describes the transverse drift currents that arise in the interplay between the acceleration of particles in the geomagnetic field and their deceleration due to interactions with atmospheric molecules. These drift currents vary with time as the air shower evolves. The time-derivative of the transverse currents then leads to the dominating radio emission component. Secondary mechanisms such as a radiation from a moving dipole, the contributions from the time-varying charge-excess [42] and the role of the positive ions left behind in the atmosphere are also investigated and accounted for. A similar approach was presented in ref. [43].

Macroscopic approaches have the advantages of speed and transparency, and were essential in arriving at today's understanding of the radio emission from cosmic ray showers. However, they also have important drawbacks.

One problem is that they "sum up mechanisms" such as radiation from transverse currents, a time-varying charge excess, and other effects. Unfortunately, these "mechanisms" cannot be always clearly separated under realistic conditions [28], and thus there is a risk of double-counting contributions. Likewise, relevant effects could be forgotten in the description.

Another difficulty is that there are parameters that can be tuned, such as the drift velocities in the MGMR approach, which directly scale the predicted electric field strengths. A related disadvantage is that macroscopic approaches have to make simplifying approximations. It is very difficult to reflect the full complexity of the particle distributions in a macroscopic description, in particular regarding correlations between particle energy, particle position and particle momentum direction. Deviations arising from non-optimal choices for these free parameters and related parameterizations can be sizable [44].

Approaches such as EVA [45, 46], which includes the treatment of the atmospheric refractive index gradient and couples the macroscopic description of the radio emission with a Monte Carlo simulation of the air shower cascade, try to mitigate these problems. However, the clarity and speed of the analytic calculation is lost to some extent in this approach without actually reaching the accurateness of a purely microscopic approach.

4.3. Modern microscopic approaches

In microscopic approaches, each single electron and positron in an extensive air shower is considered separately. Its radio emission is calculated and superposed to arrive at the total radio emission from an extensive air shower. Coherence effects are automatically taken into account by proper incorporation of the time-delays (phase shifts) acquired by the emission from individual particles. This means that a combination of a Monte Carlo simulation of the electromagnetic cascade in an air shower coupled with a formalism for the classical electrodynamics calculation of the radio emission from single particles fully determines the result.⁶ There is no ambiguity in "mechanisms" that need to be summed up, and there are no free parameters which influence the result. The radio signal is basically predicted from first principles, uncertainties only arise from the treatment of the air shower cascade itself (e.g., due to hadronic interactions). Four independent simulation codes have been developed for the microscopic calculation of radio emission from extensive air showers.

The code of Konstantinov et al. [47, 48] was based on EGSnrc [49] and can be considered the earliest that provided a self-consistent microscopic simulation of the radio emission from extensive air showers. It did, however, not take into account refractive index effects and mostly applied to air showers with energies below 10^{15} eV, i.e., below the typical detection threshold for air shower radio signals. The code is no longer actively maintained today.

To provide a self-consistent calculation of the radio emission in the REAS line of codes, the "endpoint formalism" was developed and implemented in REAS3 [50]. This formalism calculates the radio emission from moving particles arising from instantaneous acceleration of charges at the beginnings and ends of straight track segments [28]. The follow-up version REAS3.1 included the effects of the refractive index gradient in the air. Finally, the endpoint formalism was implemented directly in CORSIKA, leading to the CoREAS code [25].

The long-standing ZHS formalism [51] for the frequency-domain calculation of radio emission from moving charges was adapted for application in the time domain [52] and built into the AIRES code to arrive at ZHAireS [26]. In contrast to the endpoint formalism, ZHS describes the radiation as arising from the straight track segments themselves (not the acceleration at the ends of the tracks). It has been shown that the two approaches are mathematically equivalent [48, 53]. However, there are various advantages and disadvantages between the two approaches in the practical implementation. For example, the ZHS algorithm builds on the Fraunhofer approximation, i.e., tracks have to be subdivided such that they are small with respect to both the wavelength of interest and the distance from radiating particle to observer. Such a sub-division is not necessary for the endpoint formalism, which leads to a potential performance advantage. On the other hand,

⁶In that sense, it is fair to refer to these codes as "simulation codes" rather than "models", as the underlying model is well-proven classical electrodynamics.

the endpoint formalism becomes numerically unstable when calculating the emission of a particle for an observer near the Cherenkov angle, and a fall-back to a ZHS-style calculation becomes necessary. A detailed comparison of the computing performance of the two approaches has not yet been conducted. The agreement on the predicted signals is commented on in the next subsection.

Finally, the SELFAS2 code [54] was developed using an independent formalism for the calculation of electromagnetic radiation from track segments. Unlike the other three codes, SELFAS2 is not based on a Monte Carlo simulation of the underlying air shower. Instead, the particle distributions are regenerated from parameterizations that were originally derived from histograms made for REAS2 [36], which does neglect some potentially important correlations.

4.4. Agreement between different approaches

From the point of view of accurateness of the radio emission calculation, CoREAS and ZHAireS can be considered the current state of the art, and the most directly comparable. Both couple a formalism for the calculation of the radio emission directly with a full Monte Carlo simulation of the air shower, without any simplifying approximations made in the process. Comparisons of the predictions between the two models show that they agree within $\approx 20\%$ with each other, both quantitatively and qualitatively (pulse shape, frequency spectra, shape of the LDF, ...), as is illustrated in Fig. 13.

Cross-checks between the ZHS and endpoints formalisms have been made in the context of the SLAC T-510 experiment [55], indicating that the formalisms produce results agreeing within $\approx 5\%$ of each other [56]. It is thus likely that deviations between CoREAS and ZHAireS are related mostly to the underlying air shower simulation between AIRES and CORSIKA, possibly related to hadronic interaction models and/or the choice of energy cuts for the simulation of the particle cascade. Possibly, a different model for the atmospheric refractive index could also explain some of the deviation [57]. These differences need to be studied in further detail.

Semi-analytic models such as EVA as well as microscopic simulations based on histogrammed/parameterized particle distributions such as REAS3.11 and SELFA2S show qualitative agreement with CoREAS and ZHAireS, but there are significant deviations, as is again visible in Fig. 13. This indicates that simplifications with respect to the full Monte Carlo simulation of the particle cascade deteriorate the quality of the prediction.



Figure 13: Comparison of the west-component of the electric field predicted for a vertical 10^{17} eV proton-induced air shower at the site of the Pierre Auger Observatory by the indicated models. The refractive index of the atmosphere was modelled according to atmospheric density. In the Monte Carlo models, particle noise is visible. It results from the finite number of particles in the air shower and is amplified by thinning of the particle cascade to keep computing times reasonable. Adapted from [58].

4.5. Additional aspects and comments

At the time of writing, modern microscopic simulation approaches, in particular CoREAS and ZHAireS, can explain all experimentally observed features of the radio emission (for details see section 7). There thus does not seem to be any pressing need to improve the codes at this time. A few ideas have been voiced for effects that could be relevant and could be investigated in the future. These include the effect of scattering of the radio emission by the plasma of the air shower disk, which propagates in front of the radio emission. Another factor that could be investigated is the influence of water vapor on the propagation of the radio signals. For detectors at high altitudes, the reflection of radio signals off a reflective surface have been treated within ZHAireS [59]. In the same analysis it was ruled out that ray bending plays a significant role.

A practical limitation arising in full microscopic Monte Carlo simulations is that of particle thinning. To keep computation time for high-energy air showers reasonable, several low-energy particles are approximated by single particles with a higher weight. This introduces artificial coherence and thus leads to artifacts in the resulting predicted radio signals. As long as these artifacts are at a level below the typical level of Galactic noise, they do not pose a problem. When high-energy particles are simulated, however, these artifacts can reach amplitudes above the noise floor. The only currently available way to deal with this is to thin the simulation less, at the cost of computation time. Similarly, it is necessary to thin less if high-frequency emission is to be predicted. Parallelized simulations, especially on GPUs, could help mitigate problems of computing resources for high-quality simulations in the future. Unthinned simulations have so far only been presented for individual air showers [60], showing some interesting features such as small-scale ripples on the radio emission footprints.

Although the codes discussed here have been developed for the application at MHz frequencies, they also predict the radio signal at GHz frequencies. In fact, the predictions show that the characteristics of the radio emission at frequencies beyond ~ 2 GHz change: For a vertical air shower, CoREAS simulations predict the absence of radio signals along the north-south axis from the shower core (the Cherenkov ring is "broken"), and the north-south polarisation component of the signal shows a "clover-leaf" pattern as is indeed expected for synchrotron radiation, see Fig. 14. One possible explanation is that the originally proposed "geosynchrotron radiation" could indeed be relevant at high frequencies [25].

Predictions of the current codes at low frequencies (well below a MHz) should be treated with some caution. At these frequencies the positive ions left behind in the air shower can play an important role, and they are neglected in most of the codes.

5. Experiments for radio detection of cosmic rays

In this section, we give a concise overview of the experiments that have been performed in the past decade, compared to scale in Fig. 15. It is our goal to shortly discuss the various approaches and highlight the differences, but not go into any technical details. Results gathered by the various experiments will be discussed in section 7 to allow a better discussion of the physics, detached from the specific experiments.

5.1. First generation digital experiments

The first generation of experiments for digital detection of radio emission from cosmic ray air showers comprised the CODALEMA [61] and LOPES [62] experiments. Both of them began in 2003, approximately at the same time. In a sense, the approaches were complementary to each other. In the case of CO-DALEMA, an existing astronomical radio array (the decametric array in Nançay, France) was equipped with a special readout system and a small array of particle detectors for triggering purposes. Later, dedicated antennas of various types were set up. The advantage of the CODALEMA approach was that the site was very well-suited for radio observations, as it was located in a sparsely populated area underlying special regulations for radio frequency interference. On the downside, the particle detector array was fairly simple and not very optimized or well-studied. In contrast, the LOPES experiment followed the strategy of complementing an existing precision particle detector experiment, KASCADE-

Grande [63], with radio antennas and readout electronics that were prototypes developed for the Low Frequency Array (LOFAR). The disadvantage of this approach was that the site was almost the worst imaginable for radio detection activities, as the environment at former Forschungszentrum Karlsruhe can best be qualified as an industrial one including the regular operation of heavy machinery, welding, an on-site particle accelerator and a lot of high-frequency-emitting equipment such as computers, etc. In the end, this meant that LOPES data analysis had to exploit sophisticated interferometric analysis techniques (see Fig. 16), without which the radio signals from cosmic ray showers would never have been identified among the strong noise. This required supreme timing resolution of ≈ 1 ns, which was achieved in particular with the development of a "beacon timing calibration" approach [64]. In this scheme, a transmitter emits sine-waves with defined frequencies within the measurement band of the experiment. The relative phasing of these sine waves can then be used to correct for clock-drifts from event to event. A more advanced version of this approach is also used today within the Auger Engineering Radio Array (AERA) [65]. A cross-check of the AERA beacon timing correction using pulses emitted by commercial air planes at known positions has recently confirmed that the beacon technique, applied in a distributed detector on the scale several km², indeed yields a timing precision of 2 ns or better [66].



Figure 17: Minimum world-wide background noise temperatures according to CCIR report 670 [68].

Both CODALEMA and LOPES focused on the frequency range between low-frequency atmospheric noise dominating over Galactic noise at frequencies below \approx 30 MHz, cf. Fig. 17, and the FM band above \approx 85 MHz. Due to the second-Nyquist sampling scheme



Figure 14: Radio-emission footprints of the total field strength (left) and north-south component of the electric field (right) for a vertical 10¹⁷ eV air shower at the LOPES site in the frequency range from 3.4 to 4.2 GHz. Adapted from [25].

of LOPES⁷, its frequency band was strictly limited to 40-80 MHz, whereas CODALEMA recorded also lower and higher frequencies. Another important technical difference was that LOPES used deep ring buffers in which the raw waveform data was continuously sampled digitally, while CODALEMA used an "analogue-memory" type of approach ever only buffering short snapshots of data.

CODALEMA underwent several development stages, from 11 circularly polarised antennas of the decametric array in Nançay (CODALEMA-1, [69]) to 24 cabled linearly polarised fat dipole antennas (CODALEMA-2, [70]) with single polarisation only (either north-south or east-west) to 57 autonomous stations using dual-polarised bow-tie antennas ("butterfly", later also deployed in AERA) which are self-triggered on radio signals (CODALEMA-3) [71]. The CODALEMA-3 setup covers an area of roughly 1 km² and measures over a broad frequency band from 20 to 200 MHz. In its context, new concepts continue to be explored [72]. This includes the search for low frequency emission in the EXTASIS setup (see section 8.6) as well as a compact array performing real-time interferometric analysis to improve the efficiency and purity of self-triggering on radio signals from extensive air showers.

The LOPES experiment also evolved strongly over the course of the decade that it was taking data. First, there were 10 linearly polarised inverted V dipole antennas measuring in the 40-80 MHz band with eastwest polarisation only (LOPES-10, [62]), followed by an enlarged array with 30 antennas (LOPES-30, [73]). Afterwards, a setup mixing antennas with either northsouth, either east-west and some dual-polarised antennas (LOPES-30pol, [74]) followed. Finally, LOPES tested the concept of 3D measurements using tripole antennas (LOPES-3D, [75]). However, this was severely limited by the ambient noise, especially in its latest stage when a refinery was going online only dozens of meters away from the array. Another activity was the LOPES-STAR [76] setup for the tests of self-triggered radio detection.

Although both CODALEMA and LOPES had prototype character and were not intended at precision measurements, they yielded very important results, which we will highlight in section 7.

5.2. Second generation digital experiments

Based on the experience gathered with CODALEMA and LOPES, a second generation of experiments was designed and deployed. These consisted in particular of the Auger Engineering Radio Array (AERA) [65], the cosmic ray detection capabilities of the Low Frequency Array (LOFAR) [77] and the Tunka Radio Extension Tunka-Rex [78].

Activities to set up the Auger Engineering Radio Array started in 2007, first with small-scale prototype experiments [79], and then later with various deployment

⁷Conventionally, an analog signal has to be sampled at least with double the frequency of the highest-frequency component in the signal to avoid aliasing effects in digitization. A measurement in the second Nyquist zone can be performed with the same frequency as that of the highest-frequency signal component when ensuring that no signal components below the sampling frequency are present.



Figure 15: Overview of digital radio detection experiments plotted on the same scale. Each symbol represents one radio detector (typically with dual-polarised antenna), except for the SKA where individual detectors are not discernible due to their very high density. The number in brackets denotes the total number of antennas.



Figure 16: Left: Radio signals measured in various LOPES antennas during the arrival of an extensive air shower. The most prominent pulses originate from the high-voltage feeds of the KASCADE particle detectors. The radio pulse from the extensive air shower is smaller in comparison. It is only discernible from the noise because the signal is coherent in all antennas. Right: Cross-correlation beam of the signal in the LOPES radio antennas. The radio pulse from the extensive air shower correlates strongly between antennas and can thus be clearly identified in the presence of much stronger incoherent pulses from the particle detectors. Adapted from [67].

phases of the actual array. The science goals of AERA are to do the necessary engineering for a larger-scale application of the radio detection technique, then determine the capabilities and limitations of the detection method at energies beyond 10¹⁸ eV and finally exploit radio detection to contribute to actual cosmic ray research in the region of transition from Galactic to extragalactic sources. The technological challenges that had to be overcome were in particular the design of a rugged, autonomous, wirelessly communicating radio station that can be deployed on areas as large as 20 km² in the harsh environment of the Argentinian pampa. At the same time, one of the goals was to investigate the possibility of self-triggering on the radio detectors. In a first phase in 2011, 24 radio detection stations using dual-polarisation logarithmic periodic dipole antennas based on a design initially developed for LOPES-star were deployed on a triangular grid of 144 m. The measurement frequency band was 30 to 80 MHz. Two types of readout electronics were used, one of which providing the possibility to buffer data for up to 7 seconds. This provides enough time to wait for a trigger from the Auger particle detector array in addition to triggering on the radio signals themselves. In a second stage in 2013, an additional 100 radio detection stations were deployed on grids of 250 and 375 m distance. The antennas used here were of the "butterfly" type, originally developed in the context of CODALEMA. Again, two different kinds of electronics were used, one with a deep buffer and one incorporating small scintillators to provide a local trigger used in conjunction with the radio self-trigger. In a third phase in spring 2015, AERA was extended by an additional 25 radio detection stations with deep buffering. Those antennas are spaced on a grid of up to 750 m, so that in total an area of roughly 17 km² is covered. One of the main advantages of AERA is its co-location with the very sophisticated particle detection and fluorescence detection instruments of the Pierre Auger Observatory. The latter in particular will allow a direct cross-check of the sensitivity of radio detection to mass-sensitive parameters such as the depth of shower maximum, which is directly accessible with fluorescence detectors.

While AERA comprises a "sparse array" covering a large area with a homogeneous array of radio antennas, LOFAR can be characterised as a "dense array". LO-FAR is a general-purpose radio astronomy instrument for which cosmic ray detection is only one mode of observation. To facilitate cosmic ray detection, transient buffer boards have been installed which act as a ring buffer for the continuously sampled radio signals of individual LOFAR antenna elements. Upon a trigger from a dedicated particle detector array, LORA [80], the buffers are frozen and the buffered data are read out for analysis. The scheme is similar to the one originally used at LOPES, yet on a much larger scale. In the dense core, roughly 300 antennas sensitive to the frequency band from 10 to 90 MHz are distributed over an area of $\sim 0.1 \text{ km}^2$. Further antennas are located outside the core. Independent sets of high-band antennas sensitive to the frequency range of 110 to 240 MHz are co-located with the low-band antennas, but these are only usable when dedicated high-frequency observations have been scheduled for astronomical targets, thus statistics are lower than in the low-band mode. The antenna spacing in LOFAR has been optimized for the needs of interferometric radio-astronomical observations with long integration times. As a consequence, the antennas are distributed in stations that consist of very dense rings of antennas with large distances between the stations (cf. Fig. 15). If a cosmic ray shower does fall within a favorable location near the core, however, several hundreds of antennas are illuminated by the radio signal, giving an extremely detailed measurement of individual air shower radio footprints. LOFAR is thus the most powerful tool to date to test the details of the radio emission physics and compare them with model predictions. Also, the wealth of information measured for individual air showers can be used to determine characteristics of the underlying cosmic ray shower with very high precision, as is described in section 7.

The Tunka-Rex experiment focuses on the aspect of determining the capabilities of a radio detection array built with a dedicatedly economic approach. It comprises an extension of the Tunka-133 optical Cherenkov light detector array with currently 44 radio antennas measuring in the 30-80 MHz band. The grid size is ~ 200 m. The antennas are short aperiodic loaded loop antennas (SALLA antennas) [81, 82], which were originally developed within LOPES for one of the prototype systems at the Pierre Auger Observatory. These antennas can be built very cheaply (less than 500 USD including analog electronics). Also, antennas are cabled and integrated with the pre-existing infrastructure of the Tunka array. As the Tunka Cherenkov detectors provide information on the depth of shower maximum of the measured air showers, Tunka-Rex can also directly evaluate the mass sensitivity of radio measurements. In an upgrade campaign in September 2014, 19 antennas were deployed which are triggered by scintillators rather than optical Cherenkov detectors. This allows duty cycles of nearly 100% rather than the $\lesssim 10\%$ achieved with triggers from optical Cherenkov detectors.

5.3. Air shower measurements at higher frequencies

Although the main focus of radio detection of cosmic rays has been at frequencies below 100 MHz where the coherence of the emission is maximized, several experiments have also been performed to search for radio emission at higher frequencies, up to several GHz. The main motivation for GHz measurements was given by particle accelerator experiments in which microwave emission at GHz frequencies had been found after shooting a particle beam into air in an anechoic chamber [83]. The presumed source of the measured radio signal was so-called "molecular bremsstrahlung" from low-energy electrons in the particle cascade. As the low-energy particles are non-relativistic, the emission should be isotropic. Thus, the air shower development should be observable "from the side" in an approach analogous to imaging fluorescence telescopes however, with the tremendous advantage that receivers can be bought cheaply off-the-shelf and the possibility to observe with 100% duty cycle.

Several projects have been started to search for this "molecular bremsstrahlung". The CROME [84] experiment within the framework of the KASCADE-Grande array consisted of various antennas covering frequencies up to 12 GHz. Its main focus was on the C-band from 3.4 to 4.2 GHz which was measured with 3 x 3 receivers measuring radio emission from near the zenith after receiving a trigger from the KASCADE-Grande particle detector array. Other experiments searching for microwave emission from cosmic ray air showers have been developed and later deployed within the framework of the Pierre Auger Observatory, namely MIDAS [85] as well as EASIER and AMBER [86]. As will be discussed in more detail in section 7.9, none of these efforts were able to confirm the original measurement reported in ref. [83].

Another experiment measuring radio emission at higher frequencies is the ANITA balloon-borne radio detector which was flown in so far three flights over the antarctic ice. Its original purpose was to search for Askaryan radio emission arising from neutrinoinduced particle showers in the antarctic ice in the 200 to 1200 MHz band. Somewhat unexpectedly, however, radio pulses from cosmic ray air showers, understood today as arising from time-compression of geomagnetic and charge-excess emission, have been detected instead [87].

5.4. Laboratory measurements

To verify the approaches developed for simulations of radio emission from extensive air showers, the SLAC T-510 experiment [55] was conceived and carried out. Its goal was to reproduce a particle shower in the lab, including a tunable magnetic field that mimics the geomagnetic field, and measure the arising radio emission with well-known antennas of the ANITA experiment.

The SLAC T-510 experiment builds on the experience gathered with previous accelerator experiments that successfully measured Askaryan radiation from particle showers in dense media [88, 89], which is directly relevant for radio detection of showers in ice or the lunar regolith. As the exact configuration of the particle shower can be controlled, such a laboratory experiment allows a precise cross-check with the simulation codes.

The activities for radio detection of air showers in the GHz range were complemented by the AMY [90] and MAYBE [91] projects, the goal of which was to verify the "molecular bremsstrahlung" measurement with independent experiments using particle accelerators. With the Telescope Array Electron Light Source [92] microwave radiation was also searched for in artificially generated air showers.

5.5. Related activities and projects

A number of related activities have been performed, which we will not discuss in detail, but want to mention here shortly. The RASTA [93] project intended to complement the IceCube neutrino detector with a cosmic ray radio detector, in particular for veto purposes. While the project could not be realized, it yielded the result that the rate of transient noise is very low in Antarctica. This is a result to be kept in mind as it is an important prerequisite for successful self-triggered radio detector setups. The Yakutsk array has set up a handful of modern radio antennas and measured radio signals from air showers [94], but the results are only very sparsely documented in the literature. The TREND project [95] was initiated with the long-term aim to detect radio signals from air showers induced by tau particles arising from neutrino interactions in the Earth or mountain ridges [96]. TREND itself reported the successful self-triggering on radio emission from air showers. Based on the experience gathered with TREND, plans have recently emerged to build a very large detector for air showers initiated by taus from neutrino interactions, called GRAND [97]. Finally, a number of projects have continued to investigate the oldest proposed technique for the detection of air showers with radio waves: radar detection of the ionization trails left behind by the passage of air showers, originally proposed 1940 by Blackett and Lovell [98]. No successful detection has been reported to date. Recent results from the TARA experiment [99] put very stringent upper limits on the radar cross-section of extensive air shower ionization trails, far below levels exploitable for practical detection. This pessimistic view is also confirmed by recent theoretical calculations [100].

6. Analysis aspects

Here, we discuss some important aspects related to analysis of radio detector data. The goal is to explicitly state some pitfalls and subtleties that can make interpretation and comparison of results difficult and should hence be kept in mind.

6.1. Considerations on signal and signal-to-noise definitions

An important aspect to keep in mind is that there is a variety of signal definitions, noise definitions and consequently signal-to-noise definitions used throughout the field. In fact, often signal and noise are defined in different ways, leading to somewhat arbitrary "signal-tonoise" ratios. One thus has to be very careful when interpreting and comparing results. It is important to realize that radio signals, unlike other measurements such as the energy deposited in particle detectors, possess phase information and can thus not only sum up but also interfere destructively. While this might seem a trivial statement, it has important non-trivial consequences.

One important question is how to define "the radio signal" in the first place. Options include

- voltages measured at antenna foot-points or some other point in the electronics chain
- electric field vectors (or components thereof) at the location of the antenna
- power quantities derived from peak amplitudes of electric fields or voltages
- energy quantities derived from time-integrals of power quantities

Voltages measured at antenna foot-points or later in the signal chain have not been deconvolved for antenna responses and thus are not comparable between different experiments. However, experiments that only measure with one antenna polarisation per location (as was the case for a long time for LOPES and CODALEMA) have to rely on analysis of voltage traces, as a reconstruction of the electric field vector is not possible without the measurement of a second polarisation component. (Possibly, a detailed model for the signal polarisation could be used to replace the missing information of a second polarisation component, but this has not been demonstrated in practice.)

Going from voltages to the electric field vector (V/m)in air at the location of the antenna requires measurements in at least two polarisations. As electromagnetic waves in air are transverse waves, the third piece of information needed to reconstruct the three-dimensional electric field vector is then provided by the arrival direction of the electromagnetic wave, which is accessible from the arrival time distribution of the pulses in the array of antennas. Ideally, the electric field vector reconstructed from the measurements has been deconvolved from all experimental effects (antenna characteristics, electronic gain and dispersion) except for the limited frequency window measured by the experiment. Therefore, electric field vectors are much more suitable than voltages for comparison between different experiments. They can also be directly compared with emission simulations.

From the squared electric field vector, the Poynting flux in units of power per area can be calculated. Power quantities are easier to handle because they can only sum up and not interfere destructively. An immediate consequence is that one can subtract noise from a measurement that contains signal and noise to estimate the pure signal. However, phase information is lost when analysing only signal powers.

In comparison with power quantities, the influence of noise on voltages and electric field vectors is much more difficult to describe, as depending on the (random) phase of the noise, signal and noise can add constructively or destructively. The fact that signals are usually identified when they exceed some signal-to-noise threshold leads to a bias at low signal-to-noise levels: pulses amplified by constructive interference of signal and noise are selected, while pulses diminished by destructive interference of signal and noise are deselected. A careful treatment of the influence of noise at low signal-to-noise ratios is thus required to estimate the uncertainties on reconstructed signals correctly [101].

Often, analyses refer to the maximum amplitude (in voltage or electric field strength) of a radio pulse only. Maximum amplitude was in particular the quantity of choice for the CODALEMA and LOPES experiments. As the spatial extension of these experiments was rather small, the width of the pulses measured in different antennas was fairly constant, usually dominated by the impulse response (due to bandwidth limitation) of the filters used in the experiment. When data from larger experiments are analyzed, this assumption is no longer valid and in addition to the maximum amplitude, the width of the varying pulses should be taken into account. One way to do this is to integrate over the time of the pulses (determined by some criterion such as FWHM), which in case of the Poynting flux leads to quantities of energy deposited per area. Another integration over area, which needs an interpolation/extrapolation of the radiation pattern illuminating the ground between the sampled locations, can then yield the energy deposited in the radio signal on the ground [102]. This quantity has the benefit of an intuitive physical interpretation, and it should be largely insensitive on the distance between source and antennas, provided that the measurement allows the determination of the complete radiation pattern.

In summary, readers should pay particular attention when signal, noise and signal-to-noise quantities are referred to in the literature, as they can have very different underlying definitions.

6.2. Determination of pulse arrival times

Special care has to be taken when determining arrival times of radio pulses from extensive air showers. Different choices can be made for the time of arrival: The time of the maximum amplitude of a pulse. The middle of some fit to the radio pulse. The rise time of the signal to a certain fraction of its maximum amplitude. These choices can all be made, but they are influenced differently by instrumental effects (dispersion broadening pulses) and by the intrinsic pulse characteristics changing as a function of observer position.

It was in particular realized that wavefront analyses trying to determine cosmic ray characteristics from the arrival time distribution of radio signals at individual antennas are strongly influenced by these choices [103]. It is therefore imperative to clearly define the way in which arrival times are determined when publishing results.

6.3. Time domain versus frequency domain data

Particular confusion can arise in comparisons of data in the frequency domain. While time-domain quantities such as the instantaneous electric field as a function of time are well-determined, there are ambiguities in the definition of frequency-domain quantities. One particular example are spectral amplitudes with units of μ V/m/MHz. First, an ambiguity arises from the freedom in normalizing Fourier transformations where a factor of $1/(2\pi)$ can be introduced in the forward transformation only, the backward transformation only or symmetrically in each of the two directions with a factor of $1/\sqrt{2\pi}$. The last option seems to be the most natural definition as it ensures equality of the integral over the squared entries in both time-domain and frequencydomain data. However, it is far from safe to assume that everybody consistently uses this convention. Additionally, there is an ambiguity of a factor of two involved because one can describe the frequency spectrum with frequencies from $-\infty$ to ∞ or just from 0 to ∞ as the values for negative frequencies are just the complex conjugate of those at positive frequencies for real time series data. To make things even worse, in many occasions authors use quantities that also have units of spectral amplitudes such as μ V/m/MHz, but have not been determined from frequency-domain quantities but rather represent a maximum amplitude (μ V/m) normalized by the effective bandwidth of an experiment (MHz). The resulting quantity is of course related to spectral amplitudes, but it implies a flat spectrum and a particular distribution of phases for the spectral components (the pulse shape is mostly dominated by the phases). The exact relation of bandwidth-normalized amplitudes to spectral amplitudes thus depends on all of the aspects described above.

In summary, frequency-domain data should be treated with great care. If possible, comparison of timedomain quantities is strongly preferred.

6.4. Interferometry versus single pulse analysis

Typically, today's analysis approaches are based on the detection of radio pulses in individual radio detector stations. Once the pulse is identified, its characteristics can be determined. From the relative arrival times at different radio detectors, the arrival direction can be deduced. This approach is analogous to the analysis of particle detector data. It does, however, not exploit the full information content of the radio signal, as it does not take into account the phase information.

The full information content can be exploited when an interferometric analysis technique is employed. For ground-based arrays, this has so far only been applied by the LOPES experiment [104], and as mentioned before (cf. Fig. 16), interferometry has been a key element in making radio measurements in the noisy environment of the LOPES experiment feasible. The ANITA experiment has also been using interferometric techniques [105] in analysing their data, and for the fourth flight a real-time interferometric trigger is being developed. In the LOPES interferometric approach, the time traces s(t) of the radio signals measured with N different antennas are correlated with each other, multiplying the data from each pair of antennas time-bin by time-bin and then averaging while keeping the sign of the term under the square-root (positive means correlated, negative means anti-correlated):

$$cc(t) = \pm \sqrt{\left|\frac{1}{(N-1)N/2} \sum_{i=1}^{N-1} \sum_{j>i}^{N} s_i(t)s_j(t)\right|}$$
(7)

This approach allows the calculation of a sky map (cf. Fig. 18) that allows the identification of the radio source. There has been some discussion on whether the signal-to-noise ratio of bandwidth-limited pulses ideally achievable with this analysis approach scales as \sqrt{N}



Figure 18: Interferometric sky-map of the radio emission from an extensive air shower measured with LOPES. The main source is clearly identifiable and its direction is consistent with the direction reconstructed by the KASCADE particle detectors. Secondary emission regions are an artifact of the antenna array layout ("grating lobes"). Adapted from [62].

(see, e.g., [105]) or as $\sqrt{(N-1)N/2} \approx \sqrt{1/2}N$, i.e., linearly with the number of antennas for a large number of antennas [31]. Another caveat for application to groundbased arrays is that this analysis approach is based on a classical far-field assumption, pretending that the radio emission observed at all locations is identical (except arriving with a different time-delay). Only for the calculation of the delays, a wavefront model different than a plane wave (source at infinity) has been used [106]. We know, however, that the radio pulses at different axis distances vary not only in amplitude but also in width. For LOPES, this effect was fairly small due to the limited size of the array. For larger arrays, however, it will play a central role, and the far-field approach will have limited use (except probably for inclined air showers, see section 8.2).

Advanced analysis techniques for "near-field interferometry" have yet to be developed, but there is high potential. Ideally, one could not only make a twodimensional sky map of the signal distribution, but go to a three-dimensional tomography of the signal distribution and thus the radiating electromagnetic component of the air shower.

6.5. Polarisation characteristics

In radio astronomy, signal polarisation typically refers to signals received (and usually integrated) over significant time-scales, in particular over many oscillation periods of the frequency components contained in the signal. The electric field vector of polarised signals performs a defined motion within the plane perpendicular to the transverse electromagnetic wave, a line for pure linear polarisation, a circle for pure circular polarisation (cf. Fig. 7). In contrast, unpolarised radiation would follow a random path in this plane. But this raises interesting question: Can an impulsive radio signal (present only for one oscillation of the contained frequency components) be unpolarised? And what is the polarisation of the maximum amplitude of a detected radio pulse? In fact, it is not possible to define the polarisation of a radio signal at a certain point in time (e.g., the maximum), as polarisation is related to the time-evolution of the electric field, the path that the electric field vector follows in the plane perpendicular to the propagation direction. Statements about polarisation thus always have to be made for the evolution of impulsive signals over a certain time-scale. This can be an explicit-time scale defined in an analysis, or it can be an implicit time scale introduced for example by the bandwidth-limitation of an experimental measurement (which broadens the pulses to a minimum width) or an enveloping procedure such as a Hilbert-Envelope. If the time scale over which the signal evolution is observed is short enough, the signal will always have a high degree of polarisation. Therefore, it can be questioned whether a quantification of the degree of polarisation as presented in ref. [107] is actually meaningful for impulsive emission. Characterizing the fraction of circular versus linear polarisation, however, can extract useful information.

In astronomy, it is usual to express polarisation using Stokes parameters (for an excellent review of polarisation and various ways to represent it see the review by Radhakrishnan [108]). Adoption of this approach is also possible for impulsive radio emission, but has the disadvantage of being somewhat obscure.

7. Results of digital radio detection

In this chapter, we review important experimental results that have been achieved over the past decade. We will not report these along the lines of specific experiments, but rather structure this section with respect to the relevance for the understanding of the radio emission physics and how it can be used for cosmic ray research. Where appropriate, we directly compare the experimental results with the predictions from the emission modelling and simulations.

7.1. Self-triggering vs. external triggering, noise background and detection threshold

Encouraged by the successes of the externally triggered first-generation digital radio experiments for air shower detection, the community strove to develop the radio detection technique towards a full-fledged approach which could be used completely independently of other detectors, ideally in large-scale radio detection arrays that could potentially be built at much lower cost than comparable particle detector arrays. One necessary prerequisite for this is the ability to self-trigger on cosmic ray air showers from radio signals alone.

In particular in the context of AERA, the goal for self-triggered detection was followed with significant efforts. Original site-surveys had indicated that the continuous background noise in the Pampa Amarilla is very low, dominated by Galactic noise. When the first radio detector prototype stations had been deployed, it became evident, however, that transient noise (short bursts of radio emission) was prominent. This is not a contradiction, as transient RFI contributes little power to the continuous noise, i.e., a survey with a spectrum analyzer or any other approach integrating over time-scales larger than a few hundreds of nanoseconds will not reveal its presence. The sources at the site of AERA were investigated and seemed to include a mixture of faulty powerlines a few kilometres away, transformers in a nearby village and other, unidentifiable origins [109].

Transient noise, however, makes it very hard to develop a self-trigger on radio pulses which is both efficient and pure. Data rates that can be handled are limited by several factors. For detectors communicating wirelessly such as those in AERA, bandwidth poses significant limitations on the number of individualdetector-level triggers that can be communicated to a central data acquisition for coincidence search. In the presence of frequent noise pulses, this means that the trigger threshold has to be raised to lower the trigger rates. In turn, this means that the detection threshold rises to high cosmic-ray energies. Even if one can handle the high rates, another problem appears: the trigger becomes strongly contaminated by noise pulses, and cosmic ray pulses only constitute a vanishing fraction of the data set. This could in principle be accepted if one could reliably identify cosmic ray signals in the huge data set of noise pulses. The only reliable way to do so, however, so far has been to check for coincident detection with particle detectors. This approach has been demonstrated to work in principle at a prototype detector of AERA [79]. However, it is not entirely convincing for two reasons: First, this is not the independent radio detection that was the original goal. Second, the efficiency reached with this approach is much worse than can be reached with a direct external trigger by particle detectors.

Significant efforts were made to overcome the problems involved in self-triggering. Much effort has been made to reduce the trigger rate on the level of individual detectors. These included on-the-fly cleaning of the measurement spectrum of narrow-band transmitters as well as approaches to identify pulses and compare them to the expectation of cosmic ray signals [109]. However, the rate reduction achievable with these approaches is not sufficient. Many transient signals of anthropic origin constitute bandwidth-limited pulses, just like cosmic ray pulses, and cannot be suppressed without additional information. The rise-time of pulses has been investigated as an additional means to differentiate cosmic ray pulses from RFI, as is currently being investigated with CODALEMA-3 [110]. It has not yet been shown, however, that this will bring the rates of false triggers down far enough. The situation is better when information from several detectors is combined in the coincidence search. All signals that repeatedly arrive from similar directions over the course of a few minutes are clearly of anthropic and can be rejected. This can lower the false trigger rate significantly. An interferometric real-time trigger as currently investigated in the compact array of CODALEMA-3 [72] could lower the detection threshold and suppress anthropic sources from the horizon. Again, however, the practical use of this approach still needs to be demonstrated. Additional characteristics of air-shower radio signals such as the lateral amplitude distribution, the signal polarisation and the signal wavefront could be used in self-triggering to identify cosmic rays reliably. However, this would require a very sophisticated online (real-time) analysis of large amounts of radio data. If a (simple) particle detector, which has virtually no false positive coincidences, is available to generate the trigger, this seems to be the much easier and more promising approach, yielding both a much more efficient and purer trigger. Therefore, this author is convinced that the true power of the radio detection technique lies in combining it with other detection methods so that systematic uncertainties can be controlled better.

Using an external trigger, radio detection has been demonstrated to be able to reliably detect radio pulses as of cosmic ray energies $\gtrsim 10^{17}$ eV, where the radio pulses become clearly visible above the Galactic noise background in the signals recorded by individual radio detectors. This threshold, of course, depends on the strength of the local geomagnetic field, the air

shower arrival direction (geomagnetic angle) and also the altitude of the detector. There is potential to lower this threshold significantly using interferometric analysis techniques which do not rely on the identification of pulses within the data of individual detectors (cf. section 6.4).

Radio self-triggering might be feasible in environments where the rate of transient RFI is very low. One site that could be suitable is in Antarctica, as indicated by RASTA [93] measurements. The successful selftriggering of cosmic ray events at high frequencies with ANITA [87] over Antarctica lends further support to this. Also the TREND project in rural China reported successful identification of cosmic ray pulses on the basis of radio data [95]. Nevertheless, combining radio detectors with particle detectors should be considered where possible, as the combination ensures a robust, efficient and pure trigger.

7.2. Absolute amplitude calibration

One particularly important, and particularly challenging, experimental aspect is an accurate absolute calibration of the radio measurements. In the early days of radio detection, comparisons between cosmic ray radio measurements made with different experiments revealed apparent discrepancies by orders of magnitude in amplitude [11]. The authors speculated at the time that these problems were related to the amplitude calibrations of the different experiments.

In the modern experiments, tremendous efforts have been made to get the calibration under control. Two approaches, and combinations thereof, have been followed. First, the single components comprising a radio detector can be characterized individually to estimate the overall response. This includes antennas with their frequency-dependent directivity patterns, cables, filters and amplifiers. Dispersion plays a significant role in many of these elements and needs to be taken into account properly. Care also has to be taken in adequately modelling the impedance matching of individual components. While cables, filters and amplifiers can easily be characterized individually in the lab using vector network analyzers, antenna characteristics are usually modelled with simulation codes such as NEC-2 [111], which are then cross-checked with measurements in the field. These cross-checks are difficult for antennas in the frequency range of 30-80 MHz, as the antennas are large and far-field measurements require significant distances from the antennas (the wavelength at 30 MHz corresponds to 10 m). They are, however, very important, as previous experience has shown that simulations do not always accurately predict the antenna response in the field (probably due to environmental affects not properly accounted for in the simulations). The second approach in characterizing a radio detector consists of end-to-end measurements in the field using an external reference source placed appropriately in the fieldof-view of the antenna, or relying on the universal calibration source available to radio detectors, the Galactic noise.

The LOPES experiment has been calibrated earlyon using a commercial external reference source that emits a frequency-comb with a defined power at steps of 1 MHz [112]. In involved calibration campaigns this source was placed ~ 10 m above LOPES antennas for an end-to-end calibration of the analogue chain of the experiment. Recently, a re-calibration of the reference source revealed that amplitudes published by LOPES before 2015 were on average a factor of 2.6 too high [113] — calibration data for *free-field* conditions had been used while air shower measurements actually correspond to free-space conditions. The absolute scale of the amplitudes in LOPES has a systematic uncertainty of 16%, as specified by the manufacturer of the calibration source. The calibration source has since been provided also to the Tunka-Rex and LOFAR experiments, which means that these three experiments share the same amplitude scale and can thus be directly compared, unaffected by the 16% systematic scale uncertainty. In a recent publication, a cross-check of this calibration scale has also been performed with the Galactic noise, yielding agreement within the systematic uncertainties [114].

The most accurate absolute calibration quoted so far is the one of the Logarithmic Periodic Dipole Antennas (LPDA) of AERA, which has been quantified at 14% [82]. This value has been determined with a combination of measurements of the analog signal chain, simulations of the antenna and cross-checks of the antenna with a reference transmitter on a balloon. The LPDAs have the advantage that they are fairly insensitive to ground conditions (wet/dry/snowy/...). The butterfly antennas deployed in later phases of AERA use the ground as a reflector for improved sensitivity at high zenith angles. This comes at the cost of increased sensitivity to ground conditions, which yet need to be quantified. The SALLA antennas used within Tunka-Rex [78] are mostly insensitive to the ground and should thus yield a well-calibrated measurement without the need for monitoring environmental conditions closely [115].

7.3. Validation of emission models and simulations

To efficiently exploit the information encoded in the measured radio signals from cosmic ray air showers, a

detailed understanding of the underlying radio emission physics is imperative. In section 3 we have discussed the current paradigm of the emission physics. Here, we present experimental results that validate the radio emission models and simulations.

Radio emission from air showers can be interpreted as a superposition of geomagnetic and charge-excess radiation. The geomagnetic effect was already known to dominate the emission in the historical experiments, and was also immediately confirmed by both the LOPES [62] and CODALEMA [69, 70] results. The chargeexcess emission, however, took much longer to confirm explicitly.

Already in the 1970s, there were some results pointing to emission in addition to the geomagnetic effects. One of them [116] demonstrated that the radio emission does not vanish completely for air showers propagating parallel to the geomagnetic field, for which the geomagnetic emission should vanish. It was presumed that this could be related to charge excess (Askaryan) emission. However, no additional characteristics of the signal were known. Other results at the time seemed to be compatible with pure geomagnetic emission.

A first modern result showing the presence of a secondary mechanism in addition to the geomagnetic radiation was shown at the ICRC 2011 by the CODALEMA experiment [117, 118] (see Fig. 19). An analysis on CODALEMA data showed that the core position determined from a one-dimensional lateral distribution fit to the radio data was systematically offset to the east from the position determined with an analysis of the particle detector data. This is expected for a secondary contribution on top of the geomagnetic component in case that this secondary contribution is linearly polarised with electric field vectors oriented radially with respect to the shower axis, as is expected for charge excess emission. A comparison with SELFAS2 simulations confirmed that the charge excess emission can explain the observed core shift.

The first result demonstrating directly the presence of a contribution with the polarisation characteristics expected for charge excess radiation was given by the Auger Engineering Radio Array [119] (see Fig. 20). The analysis showed that the orientations of the electric field vectors measured in individual antennas depend on the relative locations of the given antennas to the shower axis, and that they behave as expected for the superposition of geomagnetic and charge excess radiation with their corresponding polarisation characteristics. Furthermore, the relative strength of this contribution could be quantified, yielding an average value of 14%. There were already indications that the scatter in



Figure 19: CODALEMA measurements revealed a systematic offset to the east in the core positions reconstructed from the lateral distributions of air shower radio signals (white crosses and contours derived from the distribution of these) with respect to the cores measured with particle detectors (origin of the diagram). This was an indication of the asymmetry in the radio emission footprint introduced by the charge-excess mechanism. The observed offset to the south is not explained by the asymmetry in the radio signal. Adapted from [117].

the relative strength for different measurements is larger than expected from statistical fluctuations for a constant strength.

In fact, LOFAR later demonstrated [107] that the relative strength of the charge excess contribution is not a constant but depends on the lateral distance from the shower axis and the shower zenith angle, as is shown in Fig. 21. A dependence on lateral distance had previously been predicted by simulations [120]. Of course, the relative strength also depends on the strength of the local magnetic field, the observing frequency window also plays a significant role, and the altitude of observation can have an effect, too.

Measurements thus have clearly confirmed the predictions of macroscopic models and microscopic simulation codes that the emission can be described with a superposition of a dominant geomagnetic and a subdominant charge-excess contribution, which leads to a characteristic asymmetry in the lateral distribution with peculiar polarisation features. The presence of a rising part of the lateral distribution function arising from the Cherenkov-like compression effects has also been observed early on in LOPES data, which found a small but significant fraction of events with a "rising lateral distribution function" [73], before being shown much more



Figure 20: AERA measured a radially polarised emission contribution a with an average strength of 14% relative to that of geomagnetic emission. Positive values denote the radial polarisation expected for charge-excess emission, negative values denote orientation of the radial electric field component opposite to that expected for chargeexcess emission. Adapted from [119].



Figure 21: Analyses of LOFAR data revealed that the relative chargeexcess contribution depends on the air shower zenith angle and observer lateral distance from the shower axis. Adapted from [107].

explicitly by higher-frequency experiments (see below).

Given that the *qualitative* description of the radio emission features observed in data agrees with our current paradigm for the emission physics, the question arises, however, how good the *quantitative* agreement with today's state-of-the-art simulations is. We focus on predictions of the microscopic simulation codes CoREAS and ZHAireS for such a comparison, as these provide the most precise description of the emission physics in an extensive air shower.

The LOPES experiment was the first to publish a quantitative, high-statistics comparison between its measurements and CoREAS simulations. The data were in good agreement in all characteristics except the absolute amplitudes, which were approximately a factor of two higher in the LOPES data than predicted by CoREAS simulations [67]. With the aforementioned recalibration of the absolute amplitude scale of LOPES, the comparison has recently been repeated [121, 113]. For a set of ~ 500 cosmic ray events, simulations for proton- and iron-induced showers were performed with CoREAS. The measured and simulated radio signals were fitted with a simple 1-dimensional exponential lateral distribution function

$$\epsilon(d) = \epsilon_{100} \exp[-\eta(d - 100 \,\mathrm{m})] \tag{8}$$

with two free parameters: the amplitude at a lateral distance of 100 m and a slope parameter characterising the steepness of the lateral distribution. The result obtained after the LOPES re-calibration is shown in Fig. 22. LOPES data and simulations are in very good agreement. The mean offset is only 2% for proton simulations and 9% for iron simulations, well within the systematic amplitude scale uncertainty of the LOPES experiment of 16% (at 68% confidence level). The observed scatter is in good agreement with the one expected from the measurement uncertainties [121]. Also the slope parameters of the measured and simulated events were confirmed to be in good agreement. The only hint at a discrepancy visible in LOPES data is a slight deviation in the scaling of the mean ϵ_{100} values between simulations and data with zenith angle, shown in Fig. 23. The deviations are at the level of the uncertainty in the LOPES antenna directivity pattern, and should thus not be over-interpreted. Nevertheless, it is important to check this effect with additional measurements of other experiments.

An example for a quantitative comparison between simulations and data with AERA is given in Fig. 24 which shows direct comparison of an individual cosmic ray radio event with dedicated CoREAS and ZHAireS simulations. As simulation input, the arrival direction, core location, and particle energy as reconstructed from Auger particle detector measurements have been varied 50 times within their uncertainties, taking into account the covariances between these parameters appropriately. Then, CoREAS and ZHAireS have been run



Figure 23: Offset factor for the comparison of the amplitude at 100 m lateral distance between LOPES data and CoREAS simulations as a function of air shower zenith angle θ . A complete simulation of the LOPES detector has been performed for the comparison. Adapted from [103].

for these 50 parameter sets for both proton and iron primaries. The resulting predicted electric field traces have been fed through a complete detector simulation of the Auger Engineering Radio Array [122] and then reconstructed in the same way as have the measured radio data, finally reading off the maximum of the total electric field. The comparison shows that there is a good agreement between the measured and simulated signals, within the uncertainties given by the variation of the input parameters. The absolute scale of the emission is well-reproduced within $\approx 20\%$. (The previously mentioned deviations between the absolute amplitudes predicted by CoREAS and ZHAireS are, however, apparent once more.) The error bars on the data points only denote the statistical uncertainty, and not the systematic uncertainty on the absolute calibration of the experiment. Nevertheless, also for AERA, there seems to be good agreement between data and state-of-the-art simulations.

A third quantitative comparison of simulated and measured signal amplitudes has been published recently by Tunka-Rex [78] and is shown in Fig. 25. Here, the signals measured in individual antenna stations are compared with the corresponding CoREAS simulation. Again, the quantitative agreement is very convincing.

Three different experiments have thus confirmed that the absolute amplitudes predicted with state-of-the-art simulation codes (in particular CoREAS) are in agreement with the measurements. This is a very important achievement, first because this implicitly indicates that the absolute calibrations of the experiments are in agreement, unlike the orders-of-magnitude discrepancies in the 1970s. (Please note that Tunka-Rex and LOPES



Figure 22: Event-by-event comparison of the amplitude at a lateral distance of 100 m (ϵ_{100}) derived from LOPES measurements and from CoREAS simulations for simulations of proton-induced showers (left) and iron-induced showers (right). The black lines indicate the 1:1 expectation (solid) and the 16% systematic scale uncertainty of the LOPES amplitude calibration (dashed). The colored lines mark the actual correlation between simulations and data (long-dashed) and the systematic uncertainty of the simulated amplitudes arising from the 20% systematic uncertainty of the energy reconstruction of KASCADE-Grande (dotted). The few outlier events in the lower-right parts of the diagrams are not understood (they were not recorded during thunderstorm conditions), but constitute less than 2% of the data. Adapted from [121].



Figure 24: Predictions of cosmic ray radio signals as a function of lateral distance from the shower axis with CoREAS and ZHAireS compared to data for a particular air shower event recorded with AERA. Different hadronic interaction models (as indicated) have been used in the two codes, which can explain at least part of the differences in the simulation predictions. Adapted from [123].

share the same absolute calibration scale, still the agreement illustrates that the two independent data analyses yield consistent amplitudes.) Second, and more importantly, this also means that simulations based on firstprinciple calculations, without any free parameters that can be tuned, are indeed able to correctly predict the radio emission amplitudes. This has important consequences for using radio detection as a technique to determine the energy scale of cosmic ray detectors, cf. section 8.1.

Another question is how well the simulations describe the complex asymmetric lateral distribution of the radio emission, shaped by the superposition of the different emission mechanisms as well as the Cherenkovlike compression in the refractive index gradient of the atmosphere. This has been probed in a very power-



Figure 25: Comparison of electric field amplitudes measured in individual Tunka-Rex antennas for several events with corresponding CoREAS simulations. Adapted from [78].

ful way with the detailed per-event measurements performed with LOFAR. Here, not the maximum amplitude of the electric field is used as the quantity of comparison, but rather the time-integral over the power in the pulses measured at individual antennas. A number of simulations with various input energies has been run and the core position has been varied to find the best possible agreement between simulated and measured radio signals, a procedure that profits from the high number of antennas available per shower in LOFAR. Examples are shown in Fig. 26, the left and middle panels of Fig. 40 (both 30 to 80 MHz) and Fig. 45 (110 to 190 MHz). The agreement is impressive, and it is on a very similar level of quality for almost all events measured with LOFAR. While one has to keep in mind that this comparison does not test the absolute scale of the emission (the LOFAR calibration scale has been established recently, quantitative comparisons have yet to be published), it becomes clear that the radio emission simulations can correctly reproduce the measured data with impressive detail.

The evidence for the agreement between simulations and measured data discussed so far has been provided by air shower experiments. Important complementary information, unaffected by systematic uncertainties in hadronic interactions and the mass-composition of the primary cosmic rays, can be gathered with laboratory



Figure 26: Comparison of the lateral distribution of the radio signal measured by LOFAR and simulated with CoREAS. The data do not lie on a line as there are significant asymmetries in the twodimensional lateral distribution function which is here projected to a one-dimensional representation. Adapted from [124].

experiments. In particular, the SLAC T-510 experiment has recently demonstrated on the basis of a well-defined electromagnetic particle shower in a well-known target encompassed by a strong magnetic field that microscopic simulations describe all aspects of the measured radio signals both qualitatively and quantitatively [55]. This includes the signal polarisation, confirming the superposition of magnetic and charge-excess emission, the linear scaling of the magnetic emission component with the strength of the magnetic field, the presence of a Cherenkov cone, and even the absolute strength of the emission, within the systematic uncertainties of the measurement of $\approx 40\%$ in absolute amplitude. An example result is is shown in Fig. 27. The systematic uncertainty of SLAC T-510 is currently dominated by uncertainties in the reflection of radio emission at the bottom of the target, and can likely be reduced with further measurements.

In summary, it can be stated that the radio emission physics has been understood well within the systematic uncertainties of the experimental data available today. This quantitative understanding of the radio emission is a major achievement of the modern studies, and can be considered a true breakthrough. Today's state-of-the-art radio emission simulations can thus be used with confidence for the development of analysis strategies and reconstruction algorithms, as well as an independent cross-check of the energy scale of cosmic ray detectors.

7.4. Detection of inclined air showers

Very inclined extensive air showers were detected early on with the LOPES experiment [125], up to zenith



Figure 27: Pulses arising from magnetically induced radio emission (Voltage at oscilloscope) measured in the SLAC T-510 experiment for various applied magnetic field configurations, in comparison with predictions from microscopic simulations of the radio emission emitted by the electromangetic particle shower. The simulations slightly underpredict the measured radiation strength, but the deviation is within systematic uncertainties of the measurement. Adapted from [55].

angles of 77° and later 82°. Already in this early analysis, it could be shown that the detection efficiency for inclined air showers is higher than for near-vertical showers. Unfortunately, LOPES was too small to determine the extent of the illuminated area and verify if indeed it becomes as large as expected from the source-distance effects described in section 3.5. Recent results from AERA [65], however, show very convincingly that the radio emission footprint becomes very large, with radio pulses at axis distances of 1000 m clearly observed. This confirms the predictions by event simulations and illustrates the potential for the measurement of highly inclined extensive air showers with the radio technique.

7.5. Direction reconstruction and radio wavefront

Reconstruction of the arrival direction of a cosmic ray air shower from radio measurements is usually performed on the basis of the arrival times of radio pulses in the individual detector stations (but note the caveat described in section 6.2). Alternatively, interferometric techniques can be used to find the sky position from which the measured radio signal exhibits the strongest correlation between antennas (cf. section 6.4). In both approaches, an assumption has to be made on the shape of the radio emission wavefront.

The simplest approach is to use a plane wave front, as is expected for a source at infinity. This gives a robust reconstruction on scales of ≈ 1 to 2°. As the radio source, however, is not at infinity, the wavefront is not planar. This was seen very early in the analyses of LOPES data, which showed that a spherical wavefront works much better in the interferometric reconstruction, in the sense that both the fraction of reconstructable events and the achievable direction resolution improves. A spherical wavefront corresponds to a (static) point source at a finite distance, which obviously is not an adequate description for the case of air showers, either. With LOPES data it could be shown that a conical wavefront, as can be expected for a source extended along a line, provides a better reconstruction [126]. Finally, it was realized that a hyperbolic wavefront, which constitutes a mixture between a spherical (near the shower axis) and conical (far from the shower axis) wavefront, can describe the data best, both in CoREAS simulations and in a statistical analysis of LOPES data [106]. The achieved direction resolution using the interferometric reconstruction on the basis of the various wavefront models is shown in Fig. 28.



Figure 28: Combined LOPES-KASCADE direction resolution achieved with interferometric reconstruction of the radio source on the basis of various models for the radio wavefront. Adapted from [106].

The hyperbolic wavefront is characterized by two parameters, the opening angle of the asymptotic cone ρ and an offset at the shower axis *b*. Using the geometrical quantities defined in Fig. 29 and *c* as the speed of light, the hyperbolic wavefront is described by [106]

$$c\,\tau_{\rm gco}(d,z_s) = \sqrt{(d\sin\rho)^2 + (c\cdot b)^2 + z_s\cos\rho + c\cdot b.(9)}$$

The result that the radio wavefront has hyperbolic shape was confirmed by LOFAR [106], which could



Figure 29: Geometrical delays $\tau_{geo}(d, z_s)$ as a function of the antenna position in shower coordinates (d, z_s) for a hyperbolic wavefront. θ denotes the zenith angle of the air shower, and $\tau_{proj}(d)$ is the geometric delay after projecting the antenna position to the shower plane. Adapted from [106].

measure the shape of the wavefront with very high precision in individual measured events with signals detected in hundreds of antennas (Fig. 30). Using the hyperbolic wavefront, the precision of the reconstructed direction of LOFAR events becomes as small as 0.1° (versus 1° when using a planar wavefront). However, a possible bias cannot be ruled out with the current data. Another feature that remains yet to be investigated experimentally is a slight azimuthal asymmetry in the wavefront predicted from CoREAS simulations [127].



Figure 30: hyperbolic wavefront measured in an individual air shower event measured by LOFAR. Adapted from [128].

The LOFAR authors have also provided a simple geometrical model explaining why the radio wavefront, depending on the length and distance of the air shower cascade, generally has hyperbolic shape but can also be nearly spherical or conical for individual air showers. The governing factor is the length of the emission region in relation to the closest distance between emission region and observer, as is illustrated in Fig. 31.

The sensitivity of the wavefront parameters on the distance between radio source and observer can be exploited to measure the depth of shower maximum of extensive air showers. We will review this approach in section 7.8.

7.6. Lateral distribution function and core reconstruction

In addition to the arrival direction, the location of the shower core on the ground needs to be known for quantitative analyses of the measurements. There are in principle three ways to determine this core position: from the amplitude distribution of the radio signal, from the wavefront timing information (cf. ref. [129]), or from the signal polarisation. Naturally, a combination of these approaches would be the most powerful, but has not been used in any analyses to date. In fact, the only approach that has been studied in some detail is the one based on the amplitude distribution, as it is closely linked with the important question of how to correctly describe the lateral distribution of the radio signal.

Due to the asymmetry of the radio emission footprint (cf. Fig. 6), any approach assuming a rotationally symmetric lateral distribution function will lead to a biased result, as was demonstrated in the CODALEMA analysis that revealed the charge-excess contribution [117]. This added complexity might seem like a disadvantage at first. If, however, the functional form of the complex lateral distribution function is understood well enough, the complexity of the lateral distribution function is in fact an advantage: there is a wealth of information encoded in the radio footprint, which can be exploited for an accurate reconstruction of the core position and even the depth of shower maximum, as we will discuss below.

Several approaches have been made at describing the radio emission LDF. The first and easiest approximation is that of rotationally symmetric one-dimensional exponential LDF. This has been used for many analyses, in the historical experiments and also in CODALEMA and LOPES, cf. section 7.3. The advantage of an exponential LDF is that it only needs two free parameters, namely an absolute scale (e.g. the amplitude at the axis or at a fixed distance such as 100 m) and a scale radius or, equivalently, slope parameter. The one-dimensional exponential LDF can neither describe the asymmetries nor the Cherenkov bump observed in the radio footprint. For some limited analyses of small-scale arrays, it can however be useful because it is robust and, if applied consistently to simulations and measured data, al-



Figure 31: Empirical model for the expected radio wavefront shape. Depending on the length of the emission region in relation to the closest distance between emission region and observer, the wavefront can have a dominantly conical shape (left), a dominantly spherical shape (middle) or the intermediate hyperbolic shape (right). Adapted from [128].

lows direct comparison of the two. Another approach has been to use rotationally symmetric Gaussian LDFs [130]. While adding one free parameter, these can accommodate the rising part of the LDF near the shower axis, introduced by the Cherenkov-like compression effects. The disadvantage of the implied rotational symmetry is that biases occur, the asymmetries in the radio LDF only average out if the radio emission footprint is sampled sufficiently homogeneously, which is not necessarily the case. For high-quality studies, it is therefore necessary to take the asymmetry in the radio LDF into account.

One approach is to correct for the charge-excess effects, thereby removing the asymmetry and allowing the use of a rotationally symmetric LDF. This approach was followed in some analyses of AERA [131]. A more evolved version of this approach has also recently been published by members of the Tunka-Rex collaboration [132], it is the approach that will be used for the analysis of the Tunka-Rex data. Both approaches rely on information on the relative strength of the charge excess to perform the correction. The former approach was based on an estimate from polarisation measurements, while the latter approach relies on the predictions from CoREAS simulations. As the agreement between data and measurements is excellent (see above), however, this seems well-justified.

Another possibility is to use a non-rotationally symmetric two-dimensional LDF. This approach has been developed in the frame of LOFAR. First, a simulation study based on CoREAS simulations was used to develop a two-dimensional parameterization which is based on the empirical result that the two-dimensional LDF (in this case of time-integrated power pulses) can be described well as the superposition of a large positive and a smaller negative Gaussian with some offset and scaling parameters [133].8 One important aspect of this approach is the choice of a well-suited coordinate system for the shower plane (the plane perpendicular to the shower axis) using one unit vector along the $\vec{v} \times \vec{B}$ direction (the direction of the Lorentz force and thus of the polarisation arising from the dominant geomagnetic emission) and one unit vector along the $\vec{v} \times \vec{v} \times \vec{B}$ direction which does not contain any emission contribution from the geomagnetic effect. Many of the parameters in the parameterization exhibit strong correlations and can thus be expressed as functions of each other, reducing the number of free parameters. The version used to fit LOFAR events [134] has been reduced to six free parameters, two for the core position, two for the arrival direction and two related to the energy and depth of shower maximum, which can be well-constrained in measurements of LOFAR events with hundreds of data points. Recently, the same empirical two-dimensional function with parameters adapted to the appropriate altitude and local geomagnetic field of the site of the Auger Engineering Radio Array has also been successfully employed in AERA analyses [102]. If the core position has been established with another approach (such as the Auger surface detector information), the twodimensional LDF can be applied to AERA events with only three signal detections. If at least five signal detections are available, the core position can be estimated

⁸This two-dimensional parameterization in fact contains the essence of hundreds of CoREAS simulations and can thus be used as a powerful tool whenever the received power as a function of observer position needs to be estimated quickly, e.g., in array simulation studies.

from radio data using the two-dimensional LDF.

A related work, motivated by the peculiar polarisation characteristics of the geomagnetic and charge excess contributions, was presented in [135]. It does not describe the lateral distribution function of the radio emission *per se*, but can interpolate the asymmetric radio-emission footprint from simulations performed only along two major axes of the radio footprint (such that information on both emission contributions is obtained). This approach could in principle be developed further to give a more physically motivated twodimensional lateral distribution function than the empirical two-dimensional LDF based on two summed Gaussians.

7.7. Energy reconstruction

One of the primary interests in cosmic ray measurements is to precisely and accurately determine the energy of cosmic ray particles. It has by now been successfully demonstrated that radio measurements can give a very direct and precise access to this energy.

The main reason for this is the coherent nature of the radio emission. The amplitude of the radiated radio pulses is proportional to the number of electrons and positrons in the cascade, which in turn is proportional to the energy of the primary particle. As essentially only electrons and positrons contribute to the radio signal (all other particles have a much lower charge/mass ratio, their radio emission is thus very strongly suppressed), radio detection directly probes the electromagnetic component of air showers. This is the bestunderstood air shower component, and it also harbors the vast majority of the energy of the cascade, more than 80% up to almost 100% depending on the primary energy, primary mass and the hadronic interaction model adopted to interpret the data [136]. Furthermore, the radio emission from all along the shower evolution is integrated when it arrives at the ground, as the radio emission undergoes no relevant absorption or scattering in the atmosphere. In other words, radio detection provides a calorimetric measurement of the energy in the electromagnetic cascade of an air shower.

The important question is how precisely the energy can be determined and how strongly the determination suffers from intrinsic shower-to-shower fluctuations, which — unlike instrumental uncertainties, are not addressable. According to a simulation study, the intrinsic energy resolution of air shower radio measurements was expected to be very good, with intrinsic resolutions below 10% [137], illustrated in Fig. 32. (This study was based on the flawed REAS2 approach, but as these effects are purely geometry, the main results are independent of the emission model. Consequently they have later been confirmed also by other simulation approaches [48, 138].) By now, several experiments have published analyses regarding the reconstruction of the primary particle energy from radio measurements. We shortly review the different approaches here and state the achieved resolutions.



Figure 32: There is a lateral distance at which the energy-normalized radio amplitude is influenced little by shower-to-shower fluctuations. Measurements at this distance can thus be used for a precise energy estimation. Adapted from [137].

The first quantitative analysis on the reconstruction of the cosmic ray energy from radio data was published by the LOPES experiment [130]. This analysis exploits the result of the above-mentioned simulation study [137]: A characteristic lateral distance from the shower axis exists at which the influence of showerto-shower-fluctuations on the radio amplitude is minimized. This is a geometrical effect directly related to the forward-beaming of the radio emission. In ref. [130], an updated simulation study with CoREAS, tailored to the specific situation of the LOPES experiment and based on a rotationally symmetric Gaussian LDF, confirmed the expectation for the presence of such a characteristic distance (pivot-point) in the LDF. The intrinsic resolution of an energy measurement with a radio array the size and density of LOPES was predicted to be better than 10% (Fig. 33, left). Part of the scatter in this distribution is due to the systematic difference of energy in the electromagnetic cascade for proton- and ironinduced air showers. If the energy in the electromagnetic cascade of the shower (rather than the total energy of the primary particle) needs to be determined, then intrinsic fluctuations are expected to be even as low as 5%. Hence, radio detection should be a very precise technique for energy determination with small intrinsic fluctuations. The predicted correlation between the radio amplitude at the pivot-point, normalized for the scaling of geomagnetic emission with geomagnetic angle, and the primary particle energy determined by KASCADE-Grande has then been verified in LOPES data (Fig. 33, right). There is a clear correlation, and the combined uncertainty on the energy determined with LOPES and KASCADE-Grande is $\approx 20-25\%$. As the energy resolution of KASCADE-Grande alone is $\approx 20\%$, the intrinsic resolution of the radio-based energy determination is probably indeed much smaller than 20%, even for a non-ideal prototype experiment such as LOPES and an analysis procedure which does not take the asymmetries of the radio footprint into account explicitly.

A conceptually similar approach as in LOPES, exploiting the minimum intrinsic fluctuations in the radio amplitude of the LDF, but this time using an approach that correctly compensates for the effects of the charge-excess contribution [132], has been applied to Tunka-Rex data. The main result is depicted in Fig. 34. Again, a very good correlation of the energy determined from the radio signal with the energy determined from another detector, in this case an optical Cherenkov detector, is observed. The combined resolution of the two energy estimators amounts to 20%, which as in the case of LOPES is only slightly larger than the energy resolution of the reference detector alone (amounting to 15%).



Figure 34: Correlation of the radio energy estimator of Tunka-Rex, determined from a Gaussian LDF after correction of charge-excess asymmetries, in comparison with the energy reconstructed with the Tunka-133 optical Cherenkov detectors. Adapted from [139].

LOFAR has applied the two-dimensional lateral dis-

tribution function [133] discussed in section 7.6 to measured events. One of the LDF fit parameters, A_+ , the amplitude of the dominant Gaussian in their fit to the measured signal powers, is expected to correlate with the energy of the primary cosmic ray. Indeed, a good correlation between this LDF fit parameter and the energy reconstructed with the LOFAR particle detector array LORA [140] is observed. However, this result so far lacks an absolute calibration of the radio amplitude scale.



Figure 35: Correlation of the normalized A₊ parameter in the twodimensional LDF [133] applied to LOFAR data in comparison with the cosmic ray energy reconstructed with LORA. Adapted from [134].

While the approaches discussed above used quantities such as the maximum amplitude at a characteristic distance or a fit parameter of a two-dimensional lateral distribution function as estimators for the energy of the primary cosmic ray, AERA has recently published a result that has the major benefit of using an intuitive, well-defined, and universal quantity as an energy estimator: the total energy contained in the radio signal in the frequency band from 30 to 80 MHz [102]. To determine this *radiation energy*, the time-dependent electric field (in units of V/m) reconstructed from the AERA measurements at individual detector locations is squared to calculate the local Poynting flux. A timeintegration over the detected pulse yields the energy fluence (in units of eV/m^2) measured at each individual radio detector. Using an adapted version of the twodimensional LDF [133], an LDF fit (see Fig. 36) and an integration over the shower plane is performed. This yields the total energy in the radio signal (in units of eV) in the 30 to 80 MHz range. All known detector effects have been deconvolved from this radiation energy. Since the contribution of the charge-excess effect to the radiation energy is minimal, the radiation energy can be normalized with sin² of the geomagnetic angle,



Figure 33: Correlation between the radio amplitude at the pivot-point of the radio LDF and the Monte Carlo true energy as predicted with CoREAS simulations of LOPES events (left). The predicted linear correlation is also observed in data measured with LOPES as compared with the energy reconstructed by KASCADE-Grande (right). Amplitudes have been normalized appropriately for the angle to the geomagnetic field. The amplitudes reported for LOPES data still have to be scaled down by a factor of 2.6 due to the revised calibration of the experiment. Adapted from [130].

yielding the radiation energy for air showers with perpendicular incidence to the geomagnetic field. This normalized radiation energy $E_{30-80\,\text{MHz}}^{\text{Auger}}/\sin^2(\alpha)$ shows the expected quadratic correlation with the cosmic ray energy determined with the surface detector of the Pierre Auger Observatory, as is shown in Fig. 37. (Due to the radio signal coherence, amplitudes scale linearly with the cosmic ray energy, and the radiated energy scales quadratically.) From the power-law fit, the radiation energy for a cosmic ray shower with perpendicular incidence to the geomagnetic field at the Auger site can be read off. After a normalization with the strength of the geomagnetic field, this yields the following result:

$$E_{30-80 \text{ MHz}} = (15.8 \pm 0.7 \text{ (stat)} \pm 6.7 \text{ (sys)}) \text{ MeV}$$
$$\times \left(\sin \alpha \, \frac{E_{\text{CR}}}{10^{18} \text{ eV}} \, \frac{B_{\text{Earth}}}{0.24 \text{ G}}\right)^2. \quad (10)$$

In other words, an extensive air shower with an energy of 10^{18} eV arriving perpendicular to a geomagnetic field with a strength of 0.24 G radiates a total of 15.8 MeV in the form of radio signals in the frequency range from 30 to 80 MHz. This result should be directly comparable between different radio detectors (provided the air shower can evolve and radiate the bulk of its radio emission before it reaches the ground) and can thus be used for cross-calibration of detectors. The systematic uncertainty of the result is currently dominated by the uncertainty of the absolute energy scale of the Pierre Auger Observatory, which has been propagated from the fluorescence detector to the surface detector.

From the scatter of the energy reconstructed with the Auger surface detector and the radiation energy deter-



Figure 36: Illustration of the energy fluence in the radio signals measured with individual AERA detectors and their fit with a twodimensional lateral distribution function. Radio detectors with a detected signal (*data*) as well as detectors with a signal below detection threshold (*sub-threshold*) participate in the fit. Measurements exhibiting deviating polarisation characteristics are excluded (*flagged*) to suppress transient radio-frequency interference. The fit is performed in the shower plane, the x-axis being oriented along the direction of the Lorentz force for charged particles propagating along the shower axis \vec{v} in the geomagnetic field \vec{B} . The best-fitting core position of the air shower is at the origin of the plot, slightly offset from the one reconstructed with the Auger surface detector (*core* (*SD*)). The background-color illustrates the two-dimensional lateral distribution fit. Adapted from [102].

mined with AERA (Fig. 37), the resolution of the energy reconstructed from radio data has been determined. (The degree of correlation between the two quantities was estimated with a Monte Carlo simulation study.)



Figure 37: Correlation between the radiation energy, normalized for incidence perpendicular to the geomagnetic field, and the cosmic ray energy determined by the Auger surface detector. Open circles represent air showers with radio signals detected in three or four AERA detectors. Filled circles correspond to showers with five or more detected radio signals. Adapted from [102].

For the high-quality subset of events measured in at least five AERA detectors, the radio energy resolution has been determined to 17% [102]. This again illustrates the high resolution of radio energy measurements that has already been achieved today.

7.8. Depth of shower maximum reconstruction

In addition to the energy of the primary particle, the depth of shower maximum (X_{max}) is a key quantity for the study of cosmic ray air showers. It is the parameter sensitive to the mass of the primary cosmic ray particle which is used in particular by fluorescence detector telescopes. Radio emission is sensitive to the depth of shower maximum, because the geometrical distance between the source and antenna directly shapes the radio emission arriving at the antenna, as discussed in some detail in section 3.5.

Sensitivity to X_{max} in the radio signal was already presumed in the 1970s [9, 10] and has also been predicted by modern simulation studies [137] (later confirmed on the basis of other calculations [48, 138]). In particular, the slope of the lateral distribution function provides information on the distance of the radio source: a far-away source (low X_{max} value) produces a flatter LDF than a close-by source (high X_{max} value). A first experimental proof that indeed the slope of the radio LDF probes the longitudinal air shower evolution was published by the LOPES experiment [141]. It could be shown that the mean muon pseudorapidity, a parameter related to the height of muon production and thus to the longitudinal air shower evolution, is correlated with the slope of the radio LDF (Fig. 38).



corrected LOPES lateral slope [1/km]

Figure 38: Correlation of the mean muon pseudorapidity as measured with KASCADE-Grande and the slope of the lateral distribution function as determined with LOPES. Higher muon pseudorapidities (corresponding to larger production heights and thus showers developing earlier in the atmosphere) are clearly associated with flatter radio LDFs. Addapted from [141].

The next step in exploiting the radio LDF for X_{max} determination has then been presented in [130]. In this analysis, the authors first studied the relation between Xmax and the radio LDF slope on the basis of CoREAS simulations of LOPES events. This confirmed the previous predictions [137] that the slope can be used to determine X_{max} . The relation found on the basis of CoREAS simulations was then used to determine X_{max} values from measured slope parameters (Fig. 39). The analysis method achieved an uncertainty of $\approx 50 \text{ g/cm}^2$ and the overall systematic uncertainty of the result was \approx 90 g/cm², which is not competitive with fluorescence and Cherenkov light detectors which provide a resolution of ~ 20 g/cm². Also, no independent measurement was available within LOPES to cross-check the validity of the determined X_{max} values. Nevertheless, this analysis can be seen as a proof of principle that such analyses are possible with radio detectors.

LOFAR has taken the approach of using the radio LDF for X_{max} reconstruction to the next level. In their analysis [124], the complete complex two-dimensional distribution of the radio emission on the ground is used to identify the best-fitting out of a large number of CoREAS simulations for each given event. In addition



Figure 39: Left: Distribution of the X_{max} values of air showers determined from the slopes of the radio lateral distribution functions measured with LOPES compared to the distributions expected for CoREAS simulations of proton and iron primaries. Adapted from [130]. Right: Mean X_{max} value as a function of energy as determined from the LDF and wavefront X_{max} analyses performed with LOPES. Adapted from [142].

to the LDF slope this approach also takes advantage of the asymmetries and the Cherenkov bump in the LDF. It turns out that the one parameter which governs the level of agreement between simulations and the LOFAR data is X_{max} , which can be determined with a resolution of on average 17 g/cm² (Fig. 40). Again, an independent cross-check with X_{max} information from an independent detector is not available in LOFAR, but the remarkable agreement between the simulations and data inspire confidence that the analysis is reliable and that radio detection can achieve an X_{max} resolution competitive with other techniques.

Finally, Tunka-Rex recently reported the first experimental comparison of an X_{max} reconstruction using the slope of the radio LDF and the reconstruction with an independent detector, in this case the Cherenkov-light detectors of Tunka-133 [139]. There is a very good correlation between the two reconstructions, as is shown in Fig. 41. The combined uncertainty of the two reconstructions currently amounts to ~ 50 g/cm², while the uncertainty of the Tunka-133 X_{max} reconstruction alone is specified as 28 g/cm². This first direct experimental proof of the X_{max} sensitivity of radio measurements is another important milestone.

The approaches discussed so far only used the radio LDF and thus the spatial distribution of signal amplitude or power, respectively. However, there are additional sensitivities of the radio signal to the source distance. As discussed in section 7.5, the radio wavefront is also sensitive to the distance of the radio source. A simulation study by the LOPES experiment [106] showed on the basis of CoREAS simulations of LOPES events



Figure 41: Atmospheric depth between observer location and the depth of shower maximum as determined with the Tunka-Rex radio measurement and the Tunka-133 Cherenkov detectors. Adapted from [139].

that a clear correlation exists between the zenith-anglecorrected opening angle of the asymptotic cone of the hyperbolic wavefront and X_{max} (Fig. 42). The method resolution in the absence of measurement uncertainties has been determined to be $\approx 30 \text{ g/cm}^2$, but the overall uncertainty in LOPES data was found to be 140 g/cm², probably limited by uncertainties in the determination of the pulse arrival times due to noise influence in the LOPES data. The method requires a high-quality timing



Figure 40: Left: Measured total power received at individual LOFAR antennas (colored circles) in comparison with the two-dimensional lateral distribution predicted by the best-fitting of a set of CoREAS simulations (background-color) for a particular air shower event. The depicted plane corresponds to the shower plane, defined by the axes along the direction of the Lorentz force and the one perpendicular to that. Middle: One-dimensional projection of the two-dimensional lateral distribution. Right: Quality of the agreement between the total power distribution measured with LOFAR and the one predicted by different CoREAS simulations of the air shower event. A clear correlation between the value of X_{max} and the quality of the fit is obvious. All diagrams adapted from [124].

calibration of the individual detector stations. The core position has significant impact in the analysis, which means that in principle it can also be determined in the course of a wavefront analysis (see section 7.6). As mentioned before, derived quantities such as the value of the opening angle depend on the exact definition of the signal arrival time (values determined with interferometric techniques are systematically different from those determined on the basis of the time of the pulse maximum, also remaining experimental characteristics in the deconvolved data can change the exact result). Therefore, comparisons between published results need to be performed with great care. The true potential lies in a combination of the LDF-based methods with a wavefront timing analysis (and polarisation information) to increase the accuracy of the radio-based X_{max} measurement even further. The mean X_{max} values as a function of energy determined with this approach are shown and compared with the values determined from the LDF analysis in Fig. 39, right. Both methods agree within their (fairly large) systematic uncertainties.

A third possibility to access information on the source distance and thus X_{max} is to study the radio pulse shape measured in individual antennas. Due to the geometrical time delays arising from the propagation of the radiating particles on the one hand and the radio emission on the other hand, the radio pulses become wider as the observer position moves away from the shower axis (with the exception of positions inside and near the Cherenkov ring where pulses are stretched and compressed, respectively). If this first-order effect can be corrected for, a second-order effect on the pulse width is given by the



Figure 42: Correlation between the opening angle of the hyperbolic wavefront ρ and the depth of shower maximum as predicted by CoREAS simulations for LOPES measurements. Adapted from [106].

distance of the emission region from the ground.

Instead of measuring the pulse width, also the slope of the frequency spectrum can be used [143]. (This relies only on the amplitude information, not the phases of the different frequency components.) Measurements of the frequency spectrum of air shower radio emission have proven to be difficult, though, with the only published result from a ground-based array so far from the LOPES experiment [144]. One reason for this is that the air shower radio signal is localized in time, but spread in the frequency domain, leading to a lower signal-tonoise ratio in the determination of frequency components. Another reason is the required very good understanding of the frequency-dependent gain of the antenna used to measure the radio pulses. When trying to use frequency spectra in the determination of X_{max} another complication is that the core position needs to be known rather precisely. On the other hand, the advantage of this method could be the use of single radio stations not necessarily requiring coincident detection in multiple radio detectors. Also, a combination with LDF and wavefront methods could be beneficial.

For the determination of X_{max} from high-frequency emission please see the next subsection.

7.9. High-frequency emission

Both EASIER [86] and CROME [84] have reported successful detections of GHz radiation associated with air showers, and CROME has been able to study the characteristics of the radio emission in the 3.4 to 4.2 GHz band in detail. There are clear indications that the radio emission is forward-beamed and polarised, which is not expected for "molecular bremsstrahlung". In fact, the CROME observations are compatible with the high-frequency radio emission expected from the interplay of geomagnetic and Askaryan radiation undergoing Cherenkov-like time-compression effects as described in section 3.4 and simulated here with CoREAS (Fig. 43). Even the changes in the emission pattern above 2 GHz as predicted by CoREAS simulations, cf. section 4.5, seem to be observed in the measurements (the lack of detected air showers along the north-south axis in Fig. 43, left).

Further support to the validity of the simulations at high frequencies is given by the results from the ANITA-I experiment [87] which has observed 16 impulsive radio signals in the frequency band from 200 to 1200 MHz. These pulses can be explained by geomagnetic and charge-excess radio emission along the Cherenkov angle, received either directly or reflected off the antarctic ice [145]. The fact that the radio pulses are very similar once normalized by amplitude (see Fig. 44) illustrates that this high-frequency emission is indeed observed very near the Cherenkov angle. From the spectral index of the frequency spectrum, the offaxis angle (which must be close to the Cherenkov angle) can be determined, and once this is known the energy can be estimated on the basis of simulations [57]. The mean energy of the reflected ANITA events corresponds to 2.9 EeV, a value significantly lower than the previously published energy estimate of 15 EeV [87] based on assumptions for the radio emission not including refractive index effects and thus estimating a significantly wider radiation pattern. Note that such an energy analysis would not be possible at lower frequencies, as it would be essentially unknown at which off-axis angle a detected signal was recorded.



Figure 44: Radio signals from 16 extensive air showers detected in the ANITA-I flight. 14 signals have been reflected off the antarctic ice, while 2 signals have been measured from Earth-skimming air showers. Adapted from [87].

Finally, LOFAR has observed air showers in the frequency range from 110 to 190 MHz with their highband mode. Again, these are in excellent agreement with CoREAS simulations, and clearly confirm the presence of a Cherenkov ring at higher frequencies (Fig. 45).



Figure 45: A clear Cherenkov ring is visible in the measurements of extensive air showers with the LOFAR high-band antennas in the frequency range from 110 to 190 MHz. CoREAS simulations reproduce the measurements very precisely. Adapted from [146].

An important fact to keep in mind is that highfrequency geomagnetic and charge-excess emission is only detectable at locations near the Cherenkov ring,



Figure 43: Left: Core positions of air showers measured in the 3.4-4.2 GHz band with CROME. All measured showers have their cores at distances of $\sim 70 - 100$ m from the antenna. Their distribution follows the prediction from CoREAS simulations, the total field-strength of which is shown in the background-color. Right: Signal polarisation measured with CROME in comparison to the one predicted with CoREAS. Adapted from [84].

where the radio emission from a large fraction of the shower evolution arrives simultaneously. To first order, this ring can be seen as the projection of a cone with an opening angle given by the Cherenkov angle starting from the shower maximum. Thus, the diameter of the Cherenkov ring is directly related to X_{max} (and the atmospheric density at X_{max}) and could also be used to determine the depth of shower maximum (see, e.g., [120]). However, successful detection requires a dense antenna spacing as only a very limited ring-like area is illuminated by the higher-frequency emission.

While there was great success in detecting and verifying high-frequency emission from the geomagnetic and charge-excess effects, time-compressed by the refractive index in the atmosphere, many searches for "molecular bremsstrahlung" (see section 5.3) were without success. Neither the air shower detectors CROME [84], EASIER, MIDAS and AMBER [86] nor the acceleratorbased experiments AMY [90], MAYBE [91] nor the Telescope Array Electron Light Source experiment [92] could find the emission at the level that was previously reported [83]. Modern calculations also showed the emission to be much weaker than originally presumed (see ref. [147] and references therein). The prospects to use this isotropic radio emission from air showers for a "radio-fluorescence"-like detection approach thus seem very pessimistic today. Interestingly, one experiment reported somewhat forward-beamed microwave radiation at 11 GHz from a 95 keV electron beam in air [148]. The measured emission power scales linearly with the number of particles in the shower,

and the authors interpret the radiation as arising from bremsstrahlung processes. It is not entirely clear how this measurement relates to the negative searches for molecular bremsstrahlung reported above. It might not be at tension because of the more forward-beamed nature of the observed emission, in contrast to the presumed isotropy of molecular bremsstrahlung radiation.

7.10. Influence of thunderstorms

It has been known since the 1970s that the radio emission from extensive air showers can be strongly influenced by atmospheric electric fields [12]. (In fact, the fear that radio measurements of extensive air showers could be unpredictable because they heavily rely on the state of unknown atmospheric electric fields was one of the reasons why activities in the field ceased in the 1970s.) Modern measurements with LOPES confirmed this influence [149], finding amplified radio emission from air showers measured in thunderstorm conditions. They also showed, however, that in fair weather and even rainy conditions the radio signal is unaffected. This means that, depending on the rate of thunderstorms at the location of a given experiment, reliable radio measurements are possible with duty cycles of more than 90 - 95%.

A simulation on the basis of (outdated) REAS2 simulations [150] confirmed that air showers can be influenced significantly by strong electric fields and that also the radio emission can be strongly changed. This means that radio emission from air showers in thunderstorms carries information on the electric fields that they propagated through. LOPES, however, had too few antennas and was too imprecise to actually exploit this information practically.

This has changed very recently with a study performed by LOFAR [151]. LOFAR had measured several air showers which could not be reproduced with CoREAS simulations, in strong contrast to the majority of events that can be described very well. It turned out that many of these events were recorded during thunderstorm activity within 150 km of LOFAR. In particular, the polarisation (Fig. 46) and amplitude distribution of these radio measurements were significantly different from those of air showers during fair weather. The authors used CoREAS, which is able to simulate the influence of electric fields on extensive air showers (Fig. 47) to probe possible atmospheric electric field configurations (Fig. 48) that rotate the electric field vector towards the direction observed in the measurements. A good agreement with both the measured polarisation and amplitude distribution could be achieved with two oppositely oriented atmospheric electric field layers of different amplitudes at heights from ground to 2.9 km and from 2.9 km to 8 km. While it remains to be seen how reliable the atmospheric electric field information is that can be extracted from air shower measurements, the prospect of measuring atmospheric electric fields in situ using radio detection of cosmic ray showers is very promising and has received a lot of media attention.

In addition to probing electric fields in thunderclouds, radio detectors also have the potential to study possible connections between lightning initiation and extensive air showers, as they can record both the air shower radio pulse and the process of lightning initiation, which produces characteristic radio signals. Such connections have been long presumed [152]. In particular, the scenario of a "runaway breakdown" [153] has received significant attention. Recent results indicating that indeed a combination of macroscopic ice particles in thunderclouds in combination with seed electrons from extensive air showers can initiate lightning at atmospheric electric field strengths observed in nature [154] provide strong motivation to intensify research in this direction.

7.11. Determination of an energy spectrum of cosmic rays

At this stage, the attentive reader might have wondered why no cosmic ray energy spectrum from radio measurements of extensive air showers has yet been discussed. The reason is that for the determination of an energy spectrum, the acceptance of the detector has to



Figure 46: LOFAR has measured air shower radio emission during thunderstorms which exhibit polarisation characteristics vastly different from the expectation of the geomagnetic emission mechanism (indicated by the arrow marked "normal") and its small modifications due to the charge-excess emission. Adapted from [151].



Figure 47: CoREAS simulation of the north-south electric field component for an observer 250 m north of the core of a 30° inclined 10¹⁶ eV air shower in the presence of various vertical atmospheric electric fields. Fair-weather electric fields have values $\lesssim 3$ V/cm. Electric field components perpendicular to the air shower axis influence the geomagnetic emission, while electric field components along the shower axis influence the charge-excess radiation. Adapted from [58].

be known very accurately, and in radio detection, an accurate determination of the detector acceptance is rather challenging. First, the complication arises that the detection threshold and thus the detector acceptance is strongly dependent on the air shower arrival direction, as the geomagnetic angle influences the radio emission



Figure 48: Agreement between CoREAS simulations including atmospheric electric fields and a LOFAR air shower measurement recorded during thunderstorm conditions when varying various parameters of the simulations. Left: Variation of X_{max} . Middle: Variation of the relative strength of the atmospheric electric field in the lower and upper layers. Right: Height at which the lower layer ends and upper layer starts. A specific set of these simulation parameters provided the best description of the measurement. Adapted from [151].

strength. However, as we have discussed in great depth, the physics of the radio emission has by now been wellunderstood, so that the direction dependence can be modelled with confidence. Another problem arises from the time-variation of the radio background. The Galactic noise is well-known, including its time-variation, and its impact on the detection threshold can thus be taken into account reliably. If other sources of noise are significant, however, they have to be monitored in detail (continuous noise with a periodic trigger, transient noise with a pass-through trigger) so that their influence can be quantified.

This discussion illustrates the difficulties in the determination of a cosmic ray energy spectrum from radio measurements. We stress, though, that while the determination of an energy spectrum requires significant effort, no principle problems are known to exist. Threshold-effects and the resulting detector acceptance can be determined precisely by Monte Carlo studies, which in fact very recently has been achieved by the ANITA collaboration for their first flight [57]. The determined flux at the mean event energy of 2.9 EeV is in good agreement with the one measured by the Pierre Auger Observatory and the Telescope Array, as is shown in Fig. 49. This demonstrates that flux measurements with radio detectors are feasible, and should encourage other collaborations to perform similar analyses on their radio data.

7.12. Measurements of the three-dimensional electric field vector

When radio detection of extensive air showers with digital techniques began in the early 2000s, the detec-



Figure 49: The cosmic ray flux determined from the 14 events measured with the ANITA-I balloon flight. Adapted from [57].

tors only sampled the electric field with single-polarised antennas at any given location (typically linearly polarised, except for CODALEMA-1 which used circularly polarised antennas). While the information gathered with this approach is of course valuable, it is nevertheless incomplete — it is not possible to reconstruct the electric field at the measurement locations from this information. To do so, at least a second component of the electric field vector needs to be measured, which is why the experiments soon moved towards dual-polarised antennas. The typical scheme was to measure the northsouth and east-west linear polarisations, i.e., the projection of the three-dimensional electric field vector onto the ground plane. As electromagnetic waves in the atmosphere are transverse waves and thus their electric field is polarised perpendicular to the propagation direction, this projection in combination with the arrival direction could be used to reconstruct the electric field vector.

This works well when the electric field vector is oriented such that the projected electric field is sizable, which is in particular fulfilled when the zenith angle of the air shower is small. For inclined air showers with zenith angles larger than 60° , however, the electric field can have a sizable component in the vertical polarisation. This component would thus not be accessible by the horizontally aligned antennas, increasing the detection threshold significantly.

This reasoning prompted the LOPES-3D experiment with its tripole measurements of the electric field [75]. The results of the experiment, unfortunately, were somewhat inconclusive [155]. In general, anthropic noise was much more present in the vertical component of the electric field. This was expected, but in the end made it very difficult to exploit the additional vertical measurement with a clear benefit. One lesson learnt from LOPES-3D is that the added cost of instrumenting a vertical detection channel should only be undertaken after a survey of the transient noise environment in the vertical component at the designated detection site. If the noise is much stronger than in the horizontal components, instrumentation of a third channel might not be justified.

8. Future directions

Here, we discuss possible and proposed applications of the radio detection technique in future applications and try to assess their potential.

8.1. Determination of the energy scale of cosmic rays

As discussed in section 7.7, radio emission allows a calorimetric determination of the energy in the electromagnetic cascade of extensive air showers, comparable to fluorescence detection. To derive the energy of the primary cosmic particle, the fraction of energy not going into the electromagnetic cascade (and thus not leading to radio or fluorescence light emission) needs to be estimated for both techniques. While this fraction does depend on models of hadronic interactions, data-driven techniques have been developed [136] wich reduce the systematic uncertainty arising from this correction to well below 5% [156]. In contrast to fluorescence detection, however, radio signals do not undergo any significant scattering or absorption in the atmosphere. Also, they can be observed with relatively simple detection setups. Hence, there is high potential for using radio detectors as an excellent tool to cross-calibrate cosmicray experiments. In particular, the determination of the energy in the radio signal by the Pierre Auger Collaboration [102] provides a transparent way to compare measurements at different detectors. It seems reasonable to deploy a small radio detector at every future cosmic ray detector for the sole reason of a precise crosscalibration.

In addition, as discussed in section 4.3, the radio signal from extensive air showers can be calculated with first-principle calculations. The accurate description of the electromagnetic cascade of an air shower plus a formalism implementing a discretized calculation of classical electrodynamics suffice to calculate the radio emission on an absolute scale. This is markedly different from the complex situation of fluorescence detection, in which the "fluorescence yield" has been a limiting source of systematic uncertainty for a long time (today, the fluorescence yield plays only a minor role [157]; signal propagation in the atmosphere, on the other hand, remains a challenging complication requiring very detailed atmospheric monitoring). The accurate absolute calibration of radio detectors will be the biggest challenge to overcome in this context, but there are many approaches that can be used to improve on the already good absolute calibration of today's experiments. For example, antennas can be optimized for independence from ground conditions, by design or by providing an appropriate ground shield (wire mesh, ...). External calibration sources can be improved further, and the crosscalibration with the Galactic noise, a well-understood, always-available calibration source, can be refined further. Galactic noise can even be used to monitor possible drifts of the absolute calibration effortlessly, although those are not expected to be important as radio detectors do not rely on hardware prone to aging effects such as photo-multiplier-tubes in the first place. Firstprinciple calculations can thus be used in combination with a well-calibrated radio detector to independently check the absolute energy scale of cosmic ray detectors.

Both the cross-calibration and independent energy scale determination can be realized in the near future, and they will have a significant impact on cosmic ray physics beyond the field of radio detection.

8.2. Large-scale measurements of inclined air showers

From the beginning the hope was that radio detection could be applied on the largest experimental scales. This seemed particularly attractive as radio antennas can be built fairly cheaply (the SALLA antenna used in Tunka-Rex can be built for 500 USD including all analog electronics [158]) and electronics get cheaper with each new generation. Also, the near-100% duty cycle of radio detectors marks a major advantage with respect to optical techniques such as fluorescence and Cherenkov-light detection with their typical duty cycles of $\sim 10\%$. However, it has become increasingly clear in recent years that the footprint of the radio emission is generally small, and stays small even as the energy of the primary particle is increased. The reason for this is of geometric nature, the forward-beamed emission is radiated in a narrow cone and thus typically subtends only regions with a few hundred metres in diameter. Radio detection arrays thus have to be fairly dense, with antenna spacings of order 300 metres or less to ensure coincident radio detection in several antennas. Instrumenting very large areas thus requires a very high number of radio detectors to be deployed. Even with cheap radio detectors, there is the problem of the cost of deployment and supporting infrastructure, in particular for power harvesting and communications. The current concepts can thus not easily be scaled to areas of hundreds of km². A radical rethinking of the design might still provide a solution, though (think pouring smartphone-like detectors out of an airplane for deployment ...).

The situation changes markably for inclined air showers, as was already illustrated in Fig. 11. Showers with zenith angles larger than 70° illuminate areas of several km². The main reason is that the radio source is geometrically much further away, so that the same amount of energy is distributed over a much larger area on the ground. As long as the signal is still detectable above the Galactic noise level, air showers can thus be detected in coincidence with antennas on very sparse grids of more than a kilometre. The threshold for detecting pulses in the presence of Galactic noise is predicted from simulations to be around $\sim 5 \cdot 10^{17} \text{ eV}$ [60]. Interferometric analysis approaches could lower this threshold considerably, since the radio pulses for very inclined air showers should in fact be very similar over many antennas (unlike for near-vertical air showers). The "classical" far-field interferometry as already exploited by LOPES is thus expected to work well for inclined air showers.

The intrinsic sensitivity for determination of X_{max} will likely be weak for very inclined air showers: the geometrically further away the source, the smaller the relative changes in geometry. However, coincident detection of radio emission and particles can yield composition information on the basis of the ratio between the electromagnetic and muonic cascade (particle detectors will register mostly muons for very inclined showers, the electromagnetic cascade has virtually died out when the shower reaches the ground). In fact, radio detector

tion is the only technique allowing a measurement of the electromagnetic component of very inclined extensive air showers with a favourable acceptance. There is thus strong potential in using radio detection specifically for the detection of inclined air showers, a prospect that was actually already realized early on [29].

The long-standing idea to detect near-horizontal neutrino-induced air showers with radio detection, unfortunately, does not seem very promising. The radio source will be close to the ground (this is the criterion with which a cosmic ray is excluded), but that means that the radio emission footprint will again be small and thus difficult to detect. The situation may be more favorable if tau-lepton-induced air showers from Earthskimming (upgoing) neutrinos or from neutrinos interacting in mountains are targeted, as is the goal of the proposed GRAND project [97].

In summary: While it currently seems unlikely that very-large-scale radio detectors focused on showers with zenith angles below 60° will be built in the near- to mid-term future, it seems a very realistic option to complement particle detectors such as those of the Pierre Auger Observatory with radio antennas focused on the detection of very inclined air showers for cosmic ray composition studies.

8.3. Super-hybrid measurements with integrated detectors

Radio detection has its strongest potential in combination with other detection techniques. This hybrid approach naturally solves the problem of triggering, and provides valuable additional information to reconstruct each individual air shower as well as possible. In particular, radio detection offers an excellent way to study the electromagnetic component of air showers (see previous subsection).

A large fraction of the cost involved in cosmic ray detection is in deployment, maintenance and "infrastructure". This is particularly true for radio detectors. Antennas can be built cheaply, also the cost for digital electronics is dropping continuously. The main cost of radio detectors is in fact incurred by power harvesting (solar panels are expensive, batteries age quickly and require regular replacement). High-bandwidth communications can also be problematic, although off-the-shelf components have recently become rather powerful.

The natural choice to decrease cost thus lies in integrating detectors. A "one-does-all" detector measuring particle content (preferably electromagnetic and muonic component separately), possibly fluorescence or Cherenkov light, and radio emission, seems like a very promising approach. First steps in such a direction have been followed in the framework of the AugerNext project [159] and with the TAXI prototype [160]. It seems very natural to proceed in this direction with increased efforts.

8.4. Ultimate precision: the Square Kilometre Array

As of 2020, the Square Kilometre Array will go into operation in western Australia. It will constitute the largest radio telescope ever built, with a rich programme in astrophysics and radio-astronomy, and its potential for cosmic ray detection was already considered over a decade ago [5].

If equipped with a suitable particle detector array for triggering purposes and adequate buffering capabilities at individual antennas, the dense core of the lowfrequency part (50-350 MHz) of SKA can be used for detection of extensive air showers in the energy range of $\gtrsim 10^{16}$ eV to $\gtrsim 10^{18}$ eV. An overwhelming number of 60,000 antennas will be deployed in a circular region with 750 m diameter, with a very homogeneous spacing. The results of LOFAR, in particular with respect to the reconstruction of the depth of shower maximum, were already impressive, but the level of detail measured with SKA-low will beat the one of LOFAR by far, as is obvious from Fig. 50. The current expectation is that the average resolution of SKA-low on measurements of Xmax will be below 10 g/cm² and thus significantly better than that of any other detector existing today. SKA-low can therefore be used for precision studies of the mass composition in the transition from Galactic to extragalactic cosmic rays, for the study of interaction and air shower physics at very high energies and in the extreme forward regime, and for studies of thunderstorm and lightning physics, including possible connections to cosmic rays [161].

Furthermore, with the detailed sampling of each individual air shower achieved by SKA-low, also "tomographic imaging" with near-field interferometry seems a very promising prospect. In principle, it should be possible to do a three-dimensional "tomography" of the extended source region of air shower radio emission. In other words, one should be able to make a threedimensional image of the electromagnetic component of the air shower. It will be a major challenge to devise this analysis technique. However, there is very high potential to extract much more information from the radio signals than just X_{max} and energy.

A complementary observation mode of the SKA for cosmic particles of the highest energies exists in detecting cosmic-ray showers (and also neutrino showers) via radio emission generated in the lunar regolith as opposed to the Earth's atmosphere [163, 164].

8.5. Balloon-borne and satellite-based detection

When the ANITA balloon-borne experiment, conceived to measure radio pulses from neutrinos interacting in the antarctic ice, measured more than a dozen radio pulses, it was quickly realized that these were caused by radio emission from cosmic rays, reflected off the ice (or transmitted directly in an Earth-skimming geometry). It was unclear for some time what the energy of the measured cosmic rays was. If the 16 detected events were of very high energy, then balloonborne cosmic ray detection could be a way to achieve very large exposures and hence collect statistics of cosmic rays at the very highest energies. Projects like EVA [165] and SWORD [166] have consequently been proposed.

A recent study by Motloch et al. [167], however, showed on the basis of CoREAS simulations that the radio emission is beamed in such a narrow cone around the air shower axis, that the effective acceptance reached by radio detectors on balloons or even satellites (let alone mountains [168]) in the end is not as large as one had hoped, see Fig. 51. This is not even remedied by measuring at frequencies below 100 MHz where the emission is not as focused on a Cherenkov ring as it is at higher frequencies.



Figure 51: Yearly exposure (acceptance) as a function of energy for a radio detector on a mountain (dotted line), a balloon (dashed line) and a satellite (solid line). The angular distributions of radio signals underlying these predictions are based on a SWORD model (black lines) and on CoREAS simulations (blue lines). For comparison, the exposure collected by the Surface Detector array of the Pierre Auger Observatory for air showers up to 55 degrees zenith angle in the period from Jan 2004 to Dec 2014 amounts to 42,500 km² sr y [169]. Adapted from [167].

This pessimistic view is confirmed by a recent publication of the ANITA collaboration [57] in which the average energy of the ANITA cosmic ray events has been determined at 2.9 EeV, significantly lower than the



Figure 50: CoREAS simulation of the radio emission footprint of an air shower with 30° zenith angle and an energy of 10^{18} eV sampled with LOFAR (top-left) and SKA-low (bottom, zoomed-in at top-right). Each point represents a measurement with an individual dual-polarised antenna. Even for an ideal core position, LOFAR only achieves an incomplete sampling of the radio signal. The SKA-low sampling, on the other hand, is extremely homogeneous and detailed, irrespective of the core position within the antenna array. The appearance of a Cherenkov ring in the SKA-low measurement is due to the measurement of higher-frequency components up to 350 MHz. Adapted from [162].

15 EeV [87] estimated originally on the basis of an incomplete understanding of the radio emission properties.

Based on today's knowledge of the physics of radio emission from extensive air showers, balloon- or satellite-based observations thus do not seem as promising as originally thought.

8.6. Low-frequency radio emission

Current experiments for air shower radio detection focus on the frequency range between the short-wave band and the FM band (typically 30-80 MHz). At lower frequencies, atmospheric noise quickly rises, as signals (e.g., lightning radio pulses) from very far-away are still measurable due to their reflection between the Earth's surface and the ionosphere. Radio emission from air showers at low MHz (and even kHz) frequencies have been performed before the renaissance of air shower radio detection, see ref. [170] and references therein. Successful detections were reported and attributed mostly to transition radiation of the air shower cascade entering the ground, but these activities did not gather significant momentum and were not independently confirmed. Today, two ideas, however might make low-frequency measurements an interesting topic to investigate once more.

First, there is a frequency window from $\sim 1 - 5$ MHz where, during day, the atmospheric noise is low, cf. Fig. 17. The reason is that the "D-layer" in the ionosphere absorbs radio emission at these frequencies during day-time. Simulations predict that radio signals from extensive air showers should be measurable over large areas at these frequencies, i.e., relatively sparse antenna arrays could be used for such measurements. However, timing information would be very coarse at such low frequencies, and the duty cycle would be limited to less than 50%.

Second, it has been discussed [171] that the nearinstantaneous stopping of the charged particles in an air shower when hitting the ground should lead to strong low-frequency radio emission that can be measured kilometres away from the impact point. While it is clear that this radio emission must occur (a large number of charged particles is decelerated very quickly), calculations presented so far have been somewhat incomplete. They described the emission from the fast deceleration of particles ("sudden death"), yet did not take into account the fact that the deceleration actually takes place in the Earth, that the signal has to be propagated through the Earth/air boundary and that the transmission of the signals along the Earth will quickly dampen at least those components of the electromagnetic waves polarised parallel to the Earth's surface. A consistent treatment of all these effects is imperative to judge the potential of this technique. By now, also experimental activities trying to measure this effect have been started in the EXTASIS project [72].

9. Conclusions

Radio detection of cosmic ray air showers has undergone an impressive decade of progress. The major breakthrough of the past years has been achieved with a detailed understanding of the radio emission physics, culminating in Monte Carlo simulations on the basis of first principles such as CoREAS and ZHAireS which can successfully explain every measurement made so far. Unlike ten years ago, this means that new experiments and analysis procedures can now be developed in a targeted fashion on a solid theoretical foundation. The field has clearly left the pioneering phase where many basic questions were unanswered. While the previous decade was focused on unerstanding the physics and detection techniques for air shower radio emission themselves, the next decade will clearly focus on studying cosmic rays using radio techniques.

Many of the promises initially made by radio enthusiasts could be fulfilled. Indeed, radio detection can measure the energy of cosmic ray particles with excellent resolution (17% having been achieved experimentally, with potential to go below 10%). The hoped-for sensitivity on X_{max} and hence the mass of cosmic rays has been demonstrated convincingly with simulations, and measurements with dense antenna arrays such as LO-FAR have already achieved a resolution of $\sim 17 \text{ g/cm}^2$ or better, i.e., at a level competitive with today's fluorescence and Cherenkov-light detectors. Furthermore, Tunka-Rex measurements have brought the experimental proof that X_{max} values derived with radio measurements are indeed in good agreement with those measured by other detectors, and similar endeavors are currently being followed within AERA.

Difficulties arose in the use of radio detectors as an autonomous detection technique not using any input from other detectors. Self-triggering of radio signals remains very challenging. Real-time interferometric triggering strategies could help. Yet self-triggering does not seem a goal of high priority, as the strength of radio detection does not lie in its isolated application but in its combination with other detection techniques, in particular particle detectors. The combination of these two techniques, both with near-100% duty cycle, can deliver very detailed information on individual air showers. This is especially true if the particle detectors provide a dedicated measurement of the muonic component of air showers, while the radio detectors provide accurate information on the electromagnetic component, including its longitudinal evolution with atmospheric depth. Such "radio-hybrid" measurements can thus contribute significantly to our understanding of air shower physics, for example in testing hadronic interaction models.

As the footprint of the radio emission for noninclined air showers is fairly limited, instrumentation of areas larger than a few dozen of km² still requires the development of concepts that can scale to thousands of individual detectors at moderate cost. The main challenge here lies in deployment and "infrastructure", in particular in power harvesting. But technology is progressing fast, and this potential should be borne in mind. For inclined air showers, on the other hand, already today's concepts could be used to instrument hundreds of km² and thus measure cosmic rays at energies well beyond 10¹⁸ eV up to the highest energies, as the radio detector spacing can be of order a km or larger. As no other detection technique can measure the electromagnetic component of air showers for very inclined air showers with a reasonable acceptance, this seems like a very promising area of application for large-scale radio detection, especially if detectors are integrated to share infrastructure. First activities in this direction are being followed in the frame of AERA at the Pierre Auger Observatory; in fact, a combination of radio detectors and the Auger surface detector array could at some point possibly extend the precision measurements targeted with the AugerPrime upgrade to zenith angles $\gtrsim 65^{\circ}$.

Dense radio detectors such as LOFAR and the upcoming SKA can access the energy range from \gtrsim 10^{16} eV to $\gtrsim 10^{18}$ eV. This is the region where transitions from Galactic to extragalactic cosmic rays already seem to take place. With the high duty cycle and good X_{max} resolution achievable with radio detectors, the mass composition in this energy range could be probed with high precision. With sufficient statistics, composition-sensitive anisotropy studies could be performed, and with those dense radio detectors could make a major contribution in studying the physics of cosmic rays in the transition region. Very significant potential also still lies in an improved analysis of the radio data, in particular in "imaging" approaches such as near-field interferometry applied to dense radio detectors. We are only using a fraction of the information in the radio signal so far, and imaging analyses could allow detailed insights in the physics of air showers that we have not even thought of today.

The biggest impact that radio detection is likely to

have already in the near future, however, lies in the accurate cross-calibration of the energy scale of cosmic ray detectors worldwide, as well as in the independent determination of the absolute energy scale of cosmic rays on the basis of first-principle calculations. Radio detection is uniquely well-suited for this goal, as the emission is well-predictable, the signal is not absorbed or scattered in the atmosphere, and the techniques have been developed to precisely calibrate radio detectors. It might well be that every cosmic ray detector will soon be equipped with a small radio antenna array, for the sole purpose of an accurate absolute energy calibration.

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References

- J. Blümer, R. Engel, J. R. Hörandel, Cosmic rays from the knee to the highest energies, Progress in Particle and Nuclear Physics 63 (2009) 293 – 338.
- [2] K.-H. Kampert, M. Unger, Measurements of the cosmic ray composition with air shower experiments, Astropart. Phys. 35 (2012) 660 – 678.
- [3] R. Engel, D. Heck, T. Pierog, Extensive air showers and hadronic interactions at high energy, Ann. Rev. Nucl. Part. Sci. 61 (2011) 467–489.
- [4] R. Engel, for the Pierre Auger Collaboration, Upgrade of the Pierre Auger Observatory, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)686.
- [5] H. Falcke, P. Gorham, R. J. Protheroe, Prospects for radio detection of ultra-high energy cosmic rays and neutrinos, New Astronomy Review 48 (2004) 1487–1510.
- [6] R. J. Nichol, for the ANITA Collaboration, Radio detection of high-energy particles with the ANITA experiment, Nucl. Instr. Meth. A 626–627, Supplement (2011) S30 – S35.
- [7] J. V. Jelley, J. H. Fruin, N. A. Porter, T. C. Weekes, F. G. Smith, R. A. Porter, Radio Pulses from Extensive Cosmic-Ray Air Showers, Nature 205 (1965) 327.
- [8] H. R. Allan, Radio Emission From Extensive Air Showers, Prog. in Element. Part. and Cos. Ray Phys. Vol. 10 (1971) 171– 302.
- [9] H. R. Allan, The Lateral Distribution of the Radio Emission and its Dependence on the Longitudinal Structure of the Air Shower, Proc. of the 12th ICRC, Tasmania, Australia Vol. 3 (1971) 1108.
- [10] J. H. Hough, Calculations on the radio emission resulting from geomagnetic charge separation in an extensive air shower,

Journal of Physics A: Mathematical, Nuclear and General Vol. 6 (1973) 892.

- [11] V. B. Atrashkevich, O. V. Vedeneev, H. R. Allan, et al., Electric field strength of radiofrequency radiation from extensive air showers, Sov. J. Nucl. Phys. 28 (1978) 366.
- [12] N. Mandolesi, G. Morigi, G. G. C. Palumbo, Radio pulses from extensive air showers during thunderstorms—the atmospheric electric field as a possible cause, Journal of Atmospheric and Terrestrial Physics 36 (1974) 1431 – 1435.
- [13] H. E. Bergeson, J. C. Boone, G. L. Cassiday, The Fly's Eye. A Novel Technique for Sensing Extensive Air Showers, Proc. 14th ICRC, Munich, Germany Vol. 8 (1975) 3059–3063.
- [14] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz, T. Thouw, CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers, FZKA Report 6019, Forschungszentrum Karlsruhe, 1998.
- [15] A. Aab, P. Abreu, M. Aglietta, E. Ahn, et al., Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events, Phys. Rev. D 91 (2015) 032003.
- [16] A. Aab, P. Abreu, M. Aglietta, et al., The Pierre Auger Cosmic Ray Observatory, Nucl. Instrum. Meth. A 798 (2015) 172–213.
- [17] H. Falcke, P. W. Gorham, Detecting radio emission from cosmic ray air showers and neutrinos with a digital radio telescope, Astropart. Phys. 19 (2003) 477–494.
- [18] O. Scholten, K. Werner, F. Rusydi, A macroscopic description of coherent geo-magnetic radiation from cosmic-ray air showers, Astropart. Phys. 29 (2008) 94–103.
- [19] F. D. Kahn, I. Lerche, Radiation from cosmic ray air showers, in: Proc. Roy. Soc., volume A-289, p. 206.
- [20] H. Schoorlemmer, Tuning in on cosmic rays, Ph.D. thesis, Radboud Universiteit Nijmegen, 2012.
- [21] K. D. de Vries, O. Scholten, K. Werner, Macroscopic geomagnetic radiation model; polarization effects and finite volume calculations, Nucl. Instr. Meth. A 662, Supplement 1 (2012) S175 – S178.
- [22] G. A. Askaryan, Excess negative charge of an electron-photon shower and its coherent radio emission, Soviet Phys. JETP 14 (1962) 441.
- [23] G. A. Askaryan, Coherent radio emission from cosmic showers in air and in dense media, Soviet Phys. JETP 21 (1965) 658.
- [24] J. Alvarez-Muñiz, A. Romero-Wolf, E. Zas, Practical and accurate calculations of Askaryan radiation, Phys. Rev. D 84 (2011) 103003.
- [25] T. Huege, M. Ludwig, C. W. James, Simulating radio emission from air showers with CoREAS, AIP Conf. Proc. (2013) 128– 132.
- [26] J. Alvarez-Muñiz, W. R. Carvalho Jr., E. Zas, Monte Carlo simulations of radio pulses in atmospheric showers using ZHAireS, Astropart. Phys. 35 (2012) 325 – 341.
- [27] K. D. de Vries, A. M. van den Berg, O. Scholten, K. Werner, Coherent Cherenkov Radiation from Cosmic-Ray-Induced Air Showers, Phys. Rev. Lett. 107 (2011) 61101.
- [28] C. W. James, H. Falcke, T. Huege, M. Ludwig, General description of electromagnetic radiation processes based on instantaneous charge acceleration in "endpoints", Phys. Rev. E 84 (2011) 056602.
- [29] T. Gousset, O. Ravel, C. Roy, Are vertical cosmic rays the most suitable to radio detection?, Astropart. Phys. 22 (2004) 103–107.
- [30] T. Huege, A. Haungs, Radio detection of cosmic rays: present and future, JPS Conference Proceedings (2015). Proceedings of the UHECR2014 conference, Springdale, USA, arXiv:1507.07769.
- [31] T. Huege, H. Falcke, Radio emission from cosmic ray air showers. Coherent geosynchrotron radiation, Astronomy & Astro-

physics 412 (2003) 19-34.

- [32] M. A. DuVernois, B. Cai, D. Kleckner, Geosynchrotron radio pulse emission from extensive air showers: Simulations with AIRES, in: Proc. of the 29th ICRC, Pune, India, pp. 311–+.
- [33] D. A. Suprun, P. W. Gorham, J. L. Rosner, Synchrotron radiation at radio frequencies from cosmic ray air showers, Astropart. Phys. 20 (2003) 157–168.
- [34] T. Huege, H. Falcke, Radio emission from cosmic ray air showers. Monte Carlo simulations, Astronomy & Astrophysics 430 (2005) 779–798.
- [35] T. Huege, H. Falcke, Radio emission from cosmic ray air showers: Simulation results and parametrization, Astropart. Phys. 24 (2005) 116.
- [36] S. Lafèbre, R. Engel, H. Falcke, et al., Universality of electronpositron distributions in extensive air showers, Astropart. Phys. 31 (2009) 243–254.
- [37] C. Rivière, F. Montanet, J. Chauvin, Radio Emission AIRES: Results and parameterization, in: Proc. of the 31st ICRC, Lodz, Poland, id 1519.
- [38] S. J. Sciutto, AIRES: A system for air shower simulations (Version 2.2.0) (1999). ArXiv:astro-ph/9911331.
- [39] J. Chauvin, C. Rivière, F. Montanet, et al., Radio emission in a toy model with point-charge-like air showers, Astropart. Phys. 33 (2010) 341–350.
- [40] T. Huege, M. Ludwig, O. Scholten, K. D. de Vries, The convergence of EAS radio emission models and a detailed comparison of REAS3 and MGMR simulations, Nucl. Instr. Meth. A 662 (2012) S179–S186.
- [41] J. D. Jackson, Classical Electrodynamics, John Wiley & Sons, New York, second edition, 1975.
- [42] K. Werner, O. Scholten, Macroscopic Treatment of Radio Emission from Cosmic Ray Air Showers based on Shower Simulations, Astropart. Phys. 29 (2008) 393–411.
- [43] N. N. Kalmykov, A. A. Konstantinov, Macroscopic model of radio emission from extensive air showers, Physics of Atomic Nuclei 74 (2011) 1019–1031.
- [44] M. Ludwig, T. Huege, O. Scholten, K. de Vries, A detailed comparison of MGMR and REAS3 simulations, in: Proceedings of the 32nd ICRC, Beijing, volume 2, pp. 23–26.
- [45] K. D. de Vries, O. Scholten, K. Werner, The EVA code; macroscopic modeling of radio emission from air showers based on full MC simulations including a realistic index of refraction, AIP Conf. Proc. 1535 (2013) 133–137.
- [46] K. Werner, K. D. de Vries, O. Scholten, A realistic treatment of geomagnetic Cherenkov radiation from cosmic ray air showers, Astropart. Phys. 37 (2012) 5–16.
- [47] R. Engel, N. N. Kalmykov, A. A. Konstantinov, Simulation of Radio Signals from 1-10 TeV Air Showers using EGSnrc, in: Int.J.Mod.Phys. A; Proc. of the ARENA2005 conference, DESY Zeuthen, Germany, 21S1, World Scientific, 2006, pp. 65–69.
- [48] N. N. Kalmykov, A. A. Konstantinov, R. Engel, Radio emission from extensive air showers as a method for cosmic-ray detection, Physics of Atomic Nuclei 73 (2010) 1191–1202.
- [49] I. Kawrakow, E. Mainegra-Hing, D. W. O. Rogers, et al., The EGSnrc Code System: Monte Carlo Simulation of Electron and Photon Transport, NRCC Report PIRS-701, National Research Council, Ottawa, Canada, 2010. http://www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html.
- [50] M. Ludwig, T. Huege, REAS3: Monte Carlo simulations of radio emission from cosmic ray air showers using an "end-point" formalism, Astropart. Phys. 34 (2011) 438–446.
- [51] E. Zas, F. Halzen, T. Stanev, Electromagnetic pulses from high-energy showers: Implications for neutrino detection, Phys. Rev. D 45 (1992) 362–376.

- [52] J. Alvarez-Muñiz, A. Romero-Wolf, E. Zas, Cerenkov radio pulses from electromagnetic showers in the time domain, Phys. Rev. D 81 (2010) 123009.
- [53] K. Belov, Radio emission from Air Showers. Comparison of theoretical approaches., AIP Conf. Proc. 1535 (2013) 157.
- [54] V. Marin, B. Revenu, Simulation of radio emission from cosmic ray air shower with SELFAS2, Astropart. Phys. 35 (2012) 733 – 741.
- [55] K. Belov, K. Mulrey, A. Romero-Wolf, et al., Accelerator measurements of magnetically-induced radio emission from particle cascades with applications to cosmic-ray air showers, Phys. Rev. Lett. (2015). in press, arXiv:1507.07296.
- [56] A. Zilles, K. Belov, K. Bechtol, et al., Modelling of radio emission in the SLAC T-510 experiment using microscopic Geant4 simulations, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)313.
- [57] H. Schoorlemmer, K. Belov, A. Romero-Wolf, et al., Energy and Flux Measurements of Ultra-High Energy Cosmic Rays Observed During the First ANITA Flight, Astropart. Phys. (2015). in press, arXiv:1506.05396.
- [58] T. Huege, Theory and simulations of air shower radio emission, AIP Conf. Proc. (2013) 121–127.
- [59] J. Alvarez-Muñiz, W. R. Carvalho Jr., D. García-Fernández, et al., Simulations of reflected radio signals from cosmic ray induced air showers, Astropart. Phys. 66 (2015) 31 – 38.
- [60] T. Huege, C. W. James, Full Monte Carlo simulations of radio emission from extensive air showers with CoREAS, Proceedings of the 33rd ICRC, Rio de Janeiro, Brazil, id 0548 (2013).
- [61] D. Ardouin, A. Bellétoile, D. Charrier, et al., Radio-detection signature of high-energy cosmic rays by the CODALEMA experiment, Nucl. Instr. Meth. A 555 (2005) 148–163.
- [62] H. Falcke, W. D. Apel, A. F. Badea, et al., Detection and imaging of atmospheric radio flashes from cosmic ray air showers, Nature 435 (2005) 313–316.
- [63] W. D. Apel, J. C. Arteaga, A. F. Badea, et al., The KASCADE-Grande experiment, Nucl. Instr. Meth. A 620 (2010) 202–216.
- [64] F. G. Schröder, T. Asch, L. Bähren, et al., New method for the time calibration of an interferometric radio antenna array, Nucl. Instr. Meth. A 615 (2010) 277–284.
- [65] J. Schulz, for the Pierre Auger Collaboration, Status and Prospects of the Auger Engineering Radio Array, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)615.
- [66] A. Aab, P. Abreu, M. Aglietta, E. Ahn, et al., Nanosecondlevel time synchronization of autonomous radio detector stations for extensive air showers, JINST (2016) in press. arXiv:1512.02216.
- [67] W. D. Apel, J. C. Arteaga-Velázquez, L. Bähren, et al., Comparing LOPES measurements of air-shower radio emission with REAS 3.11 and CoREAS simulations, Astropart. Phys. 50-52 (2013) 76–91.
- [68] ITU, Recommendations and reports of the CCIR (1982) Rep 670: Worldwide minimum external noise levels, 0.1 Hz to 100 GHz, volume I (Spectrum utilization and monitoring).
- [69] D. Ardouin, A. Bellétoile, D. Charrier, et al., Radioelectric field features of extensive air showers observed with CO-DALEMA, Astropart. Phys. 26 (2006) 341–350.
- [70] D. Ardouin, A. Bellétoile, C. Berat, et al., Geomagnetic origin of the radio emission from cosmic ray induced air showers observed by CODALEMA, Astropart. Phys. 31 (2009) 192–200.
- [71] B. Revenu, for the CODALEMA Collaboration, First results of the Standalone Antenna Array of the CODALEMA Radio Detection Experiment, in: Proceedings of the 32nd ICRC, Beijing, volume 1, p. 299.
- [72] R. Dallier, J. L. Béney, H. Carduner, et al., Multi-scale and

multi-frequency studies of cosmic ray air shower radio signals at the CODALEMA site, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)293.

- [73] W. D. Apel, J. C. Arteaga, T. Asch, et al., Lateral distribution of the radio signal in extensive air showers measured with LOPES, Astropart. Phys. (2010) 294–303.
- [74] P. G. Isar, W. D. Apel, J. C. Arteaga, T. Asch, et al., Operation of LOPES-30 for Polarization Measurements of the Radio Emission of Cosmic Ray Air Showers, in: Proceedings of the 30th ICRC, Merida, Mexico, volume 5, pp. 1093–1096.
- [75] W. D. Apel, J. C. Arteaga, L. Bähren, et al., LOPES-3D, an antenna array for full signal detection of air-shower radio emission, Nucl. Instr. Meth. A 696 (2012) 100–109.
- [76] H. Gemmeke, W. D. Apel, A. F. Badea, et al., Advanced Detection Methods of Radio Signals from Cosmic Rays for KAS-CADE Grande and Auger, International Journal of Modern Physics A 21 (2006) 242–246.
- [77] P. Schellart, A. Nelles, S. Buitink, et al., Detecting cosmic rays with the LOFAR radio telescope, Astronomy & Astrophysics 560 (2013) A98.
- [78] P. A. Bezyazeekov, N. M. Budnev, O. A. Gress, et al., Measurement of cosmic-ray air showers with the Tunka Radio Extension (Tunka-Rex), Nucl. Instr. Meth. A 802 (2015) 89–96.
- [79] S. Acounis, D. Charrier, T. Garçon, et al., Results of a selftriggered prototype system for radio-detection of extensive air showers at the Pierre Auger Observatory, JINST 7 (2012) P11023.
- [80] S. Thoudam, S. Buitink, A. Corstanje, et al., LORA: A scintillator array for LOFAR to measure extensive air showers, Nucl. Instr. Meth. A 767 (2014) 339 – 346.
- [81] O. Krömer, H. Gemmeke, W. D. Apel, et al., New Antenna for Radio Detection of UHECR, in: Proceedings of the 31st ICRC, Lodz, Poland, 1232.
- [82] P. Abreu, M. Aglietta, M. Ahlers, et al., Antennas for the detection of radio emission pulses from cosmic-ray induced air showers at the Pierre Auger Observatory, JINST 7 (2012) 11P.
- [83] P. W. Gorham, N. G. Lehtinen, G. S. Varner, et al., Observations of microwave continuum emission from air shower plasmas, Phys. Rev. D 78 (2008) 032007.
- [84] R. Šmída, F. Werner, R. Engel, et al., First Experimental Characterization of Microwave Emission from Cosmic Ray Air Showers, Phys. Rev. Lett. 113 (2014) 221101.
- [85] J. Alvarez-Muñiz, A. Berlin, M. Bogdan, M. Boháčová, C. Bonifazi, W. R. Carvalho, J. R. T. de Mello Neto, P. Facal San Luis, J. F. Genat, N. Hollon, E. Mills, M. Monasor, P. Privitera, L. C. Reyes, B. Rouille d'Orfeuil, E. M. Santos, S. Wayne, C. Williams, E. Zas, J. Zhou, Search for microwave emission from ultrahigh energy cosmic rays, Phys. Rev. D 86 (2012) 051104.
- [86] K. Louedec, for the Pierre Auger Collaboration, Radiodetection of extensive air showers at the Pierre Auger Observatory - Results and next enhancements, in: Proceedings of The European Physical Society Conference on High Energy Physics (EPS-HEP 2013). Stockholm, Sweden., p. 27.
- [87] S. Hoover, J. Nam, P. W. Gorham, et al., Observation of Ultrahigh-Energy Cosmic Rays with the ANITA Balloon-Borne Radio Interferometer, Phys. Rev. Lett. 105 (2010) 151101.
- [88] D. Saltzberg, P. Gorham, D. Walz, et al., Observation of the Askaryan Effect: Coherent Microwave Cherenkov Emission from Charge Asymmetry in High-Energy Particle Cascades, Phys. Rev. Lett. 86 (2001) 2802–2805.
- [89] P. W. Gorham, S. W. Barwick, J. J. Beatty, et al., Observations of the Askaryan Effect in Ice, Phys. Rev. Lett. 99 (2007) 171101.

- [90] J. Alvarez-Muñiz, M. Bohacova, G. Cataldi, et al., The Air Microwave Yield (AMY) experiment to measure the GHz emission from air shower plasmas, in: European Physical Journal Web of Conferences, volume 53, p. 8011.
- [91] C. Williams, M. Boháčová, C. Bonifazi, et al., First results from the microwave air yield beam experiment (MAYBE): Measurement of GHz radiation for ultra-high energy cosmic ray detection, in: European Physical Journal Web of Conferences, volume 53, p. 8008.
- [92] T. Yamamoto, I. Ohota, Y. Inome, et al., Search for isotropic microwave radiation from electron beam in the atmosphere, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)579.
- [93] S. Böser, for the IceCube Collaboration, A Radio Air-Shower Test Array (RASTA) for IceCube, Nucl. Instr. Meth. A 662, Supplement 1 (2012) S66 – S68.
- [94] I. Petrov, S. Knurenko, Z. Petrov, et al., Yakutsk array radio emission registration results in the energy range of 3*10¹⁶ – 5*10¹⁸ eV, Proceedings of the 32nd ICRC, Rio de Janeiro, Brazil (2013) id 181.
- [95] D. Ardouin, C. Cârloganu, D. Charrier, et al., First detection of extensive air showers by the TREND self-triggering radio experiment, Astropart. Phys. 34 (2011) 717 – 731.
- [96] O. Brusova, L. Anchordoqui, T. Huege, et al., Radio Detection of Neutrinos from Behind a Mountain, in: Proceedings of the 30th ICRC, Merida, Mexico, volume 5, pp. 1585–1588.
- [97] O. Martineau-Huynh, K. Kotera, D. Charrier, et al., The Giant Radio Aray for Neutrino Detection, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)1143.
- [98] P. M. S. Blackett, A. C. B. Lovell, Proc. Roy. Soc. A-177 (1940) 183.
- [99] I. Myers, J. Belz, Telescope Array Radar (TARA): First Measurement of EAS Radar Cross-section Upper Limit, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)434.
- [100] J. Stasielak, R. Engel, S. Baur, et al., Is radar detection of extensive air showers feasible?, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)316.
- [101] F. G. Schröder, W. D. Apel, J. C. Arteaga, et al., On noise treatment in radio measurements of cosmic ray air showers, Nucl. Instr. Meth. A 662, Supplement 1 (2012) S238 – S241.
- [102] A. Aab, P. Abreu, M. Aglietta, et al., Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory, Phys Rev. D (2015). submitted, arXiv:1508.04267.
- [103] F. G. Schröder, K. Link, W. D. Apel, et al., New results of the digital radio interferometer LOPES, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)317.
- [104] T. Huege, W. D. Apel, J. C. Arteaga, et al., The LOPES experiment - recent results, status and perspectives, Nucl. Instr. Meth. A (2012) S72–S79.
- [105] A. Romero-Wolf, S. Hoover, A. G. Vieregg, et al., An interferometric analysis method for radio impulses from ultra-high energy particle showers, Astropart. Phys. 60 (2015) 72 – 85.
- [106] W. D. Apel, J. C. Arteaga-Velázquez, L. Bähren, et al., The wavefront of the radio signal emitted by cosmic ray air showers, JCAP (2014) 025.
- [107] P. Schellart, S. Buitink, A. Corstanje, et al., Polarized radio emission from extensive air showers measured with LOFAR, JCAP 10 (2014) 14.
- [108] V. Radhakrishnan, Polarisation, in: Proceedings of the 1990 URSI General Assembly, Prague, Czechoslovakia.
- [109] A. Schmidt, Realization of a Self-triggered Detector for the Radio Emission of Cosmic Rays, Ph.D. thesis, Karlsruhe Institute of Technology, 2012. http://nbn-

resolving.org/urn:nbn:de:swb:90-309570.

- [110] D. Torres Machado, for the CODALEMA Collaboration, Latest upgrades and results from the CODALEMA experiment, Proceedings of the 33rd ICRC, Rio de Janeiro, Brazil, id 0013 (2013).
- [111] G. Burke, A. Poggio, Numerical Electromagnetics Code (NEC) method of moments, Technical Report, Lawrence Livermore National Laboratory, Livermore U.S.A., 1977-1983.
- [112] S. Nehls, A. Hakenjos, M. J. Arts, et al., Amplitude calibration of a digital radio antenna array for measuring cosmic ray air showers, Nucl. Instr. Meth. A 589 (2008) 350–361.
- [113] W. D. Apel, J. C. Arteaga-Velázquez, L. Bähren, et al., Improved absolute calibration of LOPES measurements and its impact on the comparison with REAS 3.11 and CoREAS simulations, Astropart. Phys. 75 (2015) 72–74.
- [114] A. Nelles, J. R. Hörandel, T. Karskens, et al., Calibrating the absolute amplitude scale for air showers measured at LOFAR, JINST 10 (2015) P11005.
- [115] R. Hiller, N. M. Budnev, O. A. Gress, et al., The Tunka-Rex antenna station, Proceedings of the 33rd ICRC, Rio de Janeiro, Brazil (2013). arXiv:1308.0917.
- [116] J. R. Prescott, J. H. Hough, J. Pidcock, Nature Phys. Science 233 (1971) 109.
- [117] V. Marin, for the CODALEMA Collaboration, Charge excess signature in the CODALEMA data. Interpretation with SELFAS2., Proc. 32nd ICRC, Beijing, China 1 (2011) 291.
- [118] A. Bellétoile, R. Dallier, A. Lecacheux, et al., Evidence for the charge-excess contribution in air shower radio emission observed by the CODALEMA experiment, Astropart. Phys. 69 (2015) 50–60.
- [119] A. Aab, P. Buchholz, N. Förster, et al., Probing the radio emission from cosmic-ray-induced air showers by polarization measurements, Phys. Rev. D 89 (2014) 052002.
- [120] K. D. de Vries, O. Scholten, K. Werner, The air shower maximum probed by Cherenkov effects from radio emission, Astropart. Phys. 45 (2013) 23 – 27.
- [121] K. Link, T. Huege, W. D. Apel, et al., Revised absolute amplitude calibration of the LOPES experiment, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)311.
- [122] P. Abreu, M. Aglietta, E. J. Ahn, et al., Advanced functionality for radio analysis in the Offline software framework of the Pierre Auger Observatory, Nucl. Instr. Meth. A 635 (2011) 92–102.
- [123] F. G. Schröder, for the Pierre Auger Collaboration, Radio detection of air showers with the Auger Engineering Radio Array, Proceedings of the 33rd ICRC, Rio de Janeiro, Brazil (2013). id 0899.
- [124] S. Buitink, A. Corstanje, J. E. Enriquez, et al., Method for high precision reconstruction of air shower X_{max} using twodimensional radio intensity profiles, Phys. Rev. D 90 (2014) 082003.
- [125] J. Petrovic, W. D. Apel, T. Asch, et al., Radio emission of highly inclined cosmic ray air showers measured with LOPES, Astronomy & Astrophysics 462 (2007) 389–395.
- [126] F. G. Schröder, W. D. Apel, J. C. Arteaga, et al., Cosmic ray measurements with LOPES: Status and recent results, AIP Conf. Proc. 1535 (2013) 78–83.
- [127] F. G. Schröder, W. D. Apel, J. C. Arteaga-Velazquez, et al., Investigation of the radio wavefront of air showers with LOPES measurements and CoREAS simulations (ARENA 2014), Proceedings of the ARENA2014 Conference, Annapolis, USA (2015). arXiv:1507.07753.
- [128] A. Corstanje, P. Schellart, A. Nelles, et al., The shape of the radio wavefront of extensive air showers as measured with LO-

FAR, Astropart. Phys. 61 (2015) 22 - 31.

- [129] S. Lafèbre, H. Falcke, J. R. Hörandel, et al., Prospects for determining air shower characteristics through geosynchrotron emission arrival times, Astropart. Phys. 34 (2010) 12–17.
- [130] W. D. Apel, J. C. Arteaga-Velázquez, L. Bähren, et al., Reconstruction of the energy and depth of maximum of cosmic-ray air showers from LOPES radio measurements, Phys. Rev. D 90 (2014) 062001.
- [131] C. Glaser, for the Pierre Auger Collaboration, Energy estimation for cosmic rays measured with the Auger Engineering Radio Array, AIP Conf. Proc. 1535 (2013) 68–72.
- [132] D. Kostunin, P. A. Bezyazeekov, R. Hiller, et al., Reconstruction of cosmic ray air shower parameters using the lateral distribution of the radio emission, Astropart. Phys. 74 (2015) 79– 86.
- [133] A. Nelles, S. Buitink, H. Falcke, et al., A parameterization for the radio emission of air showers as predicted by CoREAS simulations and applied to LOFAR measurements, Astropart. Phys. 60 (2015) 13 – 24.
- [134] A. Nelles, S. Buitink, A. Corstanje, et al., The radio emission pattern of air showers as measured with LOFAR—a tool for the reconstruction of the energy and the shower maximum, JCAP (2015) 018.
- [135] J. Alvarez-Muñiz, W. R. Carvalho Jr., H. Schoorlemmer, E. Zas, Radio pulses from ultra-high energy atmospheric showers as the superposition of askaryan and geomagnetic mechanisms, Astropart. Phys. 59 (2014) 29 – 38.
- [136] M. Tueros, for the Pierre Auger Collaboration, Estimate of the non-calorimetric energy of showers observed with the fluorescence and surface detectors of the Pierre Auger Observatory, Proceedings of the 33rd ICRC, Rio de Janeiro, Brazil (2013). arXiv:1307.5059.
- [137] T. Huege, R. Ulrich, R. Engel, Dependence of geosynchrotron radio emission on the energy and depth of maximum of cosmic ray showers, Astropart. Phys. 30 (2008) 96–104.
- [138] K. D. de Vries, A. M. van den Berg, O. Scholten, K. Werner, The lateral distribution function of coherent radio emission from extensive air showers: Determining the chemical composition of cosmic rays, Astropart. Phys. 34 (2010) 267 – 273.
- [139] P. A. Bezyazeekov, N. M. Budnev, O. A. Gress, et al., Radio measurements of the energy and the depth of the shower maximum of cosmic-ray air showers by Tunka-Rex, JCAP (2016). In press, arXiv:1509.05652.
- [140] S. Thoudam, S. Buitink, A. Corstanje, et al., Measurement of the cosmic-ray energy spectrum above 10¹⁶ eV with the LO-FAR Radboud Air Shower Array, Astropart. Phys. 73 (2015) 34–43.
- [141] W. D. Apel, J. C. Arteaga, L. Bähren, et al., Experimental Evidence for the sensitivity of the air-shower radio signal to the longitudinal shower development, Phys Rev. D 85 (2012) 071101(R).
- [142] F. G. Schröder, W. D. Apel, J. C. Arteaga-Velázquez, et al., LOPES - Recent Results and Open Questions on the Radio Detection of Air Showers, J. Phys.: Conf. Ser. 632 (2015) 012102.
- [143] S. Grebe, for the Pierre Auger Collaboration, Spectral index analysis of the data from the Auger Engineering Radio Array, AIP Conf. Proc. 1535 (2013) 73.
- [144] A. Nigl, W. D. Apel, J. C. Arteaga, et al., Frequency spectra of cosmic ray air shower radio emission measured with LOPES, Astronomy & Astrophysics 488 (2008) 807–817.
- [145] J. Alvarez-Muñiz, W. R. Carvalho, A. Romero-Wolf, et al., Coherent radiation from extensive air showers in the ultrahigh frequency band, Phys. Rev. D 86 (2012) 123007.
- [146] A. Nelles, P. Schellart, S. Buitink, et al., Measuring a

Cherenkov ring in the radio emission from air showers at 110-190 MHz with LOFAR, Astropart. Phys. 65 (2015) 11 – 21.

- [147] I. Al Samarai, O. Deligny, D. Lebrun, et al., An estimate of the spectral intensity expected from the molecular Bremsstrahlung radiation in extensive air showers, Astropart. Phys. 67 (2015) 26 – 32.
- [148] E. Conti, G. Collazuol, G. Sartori, Experimental study of the microwave emission from electrons in air, Phys. Rev. D 90 (2014) 071102.
- [149] S. Buitink, W. D. Apel, T. Asch, et al., Amplified radio emission from cosmic ray air showers in thunderstorms, Astronomy & Astrophysics 467 (2007) 385–394.
- [150] S. Buitink, T. Huege, H. Falcke, J. Kuijpers, Simulation of radio emission from air showers in atmospheric electric fields, Astropart. Phys. 33 (2010) 296–306.
- [151] P. Schellart, T. N. G. Trinh, S. Buitink, et al., Probing Atmospheric Electric Fields in Thunderstorms through Radio Emission from Cosmic-Ray-Induced Air Showers, Phys. Rev. Lett. 114 (2015) 165001.
- [152] J. R. Dwyer, M. A. Uman, The physics of lightning, Physics Reports 534 (2014) 147 – 241.
- [153] A. V. Gurevich, A. N. Karashtin, Runaway Breakdown and Hydrometeors in Lightning Initiation, Phys. Rev. Lett. 110 (2013) 185005.
- [154] A. Dubinova, C. Rutjes, U. Ebert, et al., Prediction of Lightning Inception by Large Ice Particles and Extensive Air Showers, Phys. Rev. Lett. 115 (2015) 015002.
- [155] D. Huber, W. D. Apel, J. C. Arteaga-Velázquez, et al., LOPES-3D - studies on the benefits of EAS-radio measurements with vertically aligned antennas, Proceedings of the ARENA2014 Conference, Annapolis, USA (2015). in press.
- [156] V. Verzi, for the Pierre Auger Collaboration, The energy scale of the Pierre Auger Observatory, Proc. 33rd ICRC, Rio de Janeiro, Brazil (2013).
- [157] M. Ave, M. Bohacova, E. Curry, et al., Precise measurement of the absolute fluorescence yield of the 337 nm band in atmospheric gases, Astropart. Phys. 42 (2013) 90–102.
- [158] F. G. Schröder, P. Bezyazeekov, N. M. Budnev, et al., Tunka-Rex: the Cost-Effective Radio Extension of the Tunka Air-Shower Observatory, JPS Conference Proceedings (2015). Proceedings of the UHECR2014 conference, Springdale, USA, arXiv:1504.01541.
- [159] A. Haungs, for the Pierre Auger Collaboration, AugerNext: R&D studies at the Pierre Auger Observatory for a next generation ground-based ultra-high energy cosmic ray experiment, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)593.
- [160] T. Karg, A. Haungs, M. Kleifges, et al., Introducing TAXI: a Transportable Array for eXtremely large area Instrumentation studies, Proceedings of the ARENA2014 Conference, Annapolis, USA (2015). arXiv:1410.4685.
- [161] T. Huege, J. D. Bray, S. Buitink, et al., Precision measurements of cosmic ray air showers, Proceedings of Science (2014) PoS(AASKA14)148.
- [162] T. Huege, J. Bray, S. Buitink, et al., High-precision measurements of extensive air showers with the SKA, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)309.
- [163] J. D. Bray, J. Alvarez-Muñiz, S. Buitink, et al., Lunar detection of ultra-high-energy cosmic rays and neutrinos with the Square Kilometre Array, Proceedings of Science (2014) PoS(AASKA14)144.
- [164] C. W. James, J. D. Bray, J. Alvarez-Muñiz, et al., The lunar Askaryan technique with the Square Kilometre Array, in:

Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)291.

- [165] P. W. Gorham, F. E. Baginski, P. Allison, et al., The Exa-Volt Antenna: A large-aperture, balloon-embedded antenna for ultra-high energy particle detection, Astropart. Phys. 35 (2011) 242 – 256.
- [166] A. Romero-Wolf, P. Gorham, K. Liewer, J. Booth, R. Duren, Concept and Analysis of a Satellite for Space-based Radio Detection of Ultra-high Energy Cosmic Rays, ArXiv e-prints (2013). arXiv:1302.1263.
- [167] P. Motloch, N. Hollon, P. Privitera, On the prospects of Ultra-High Energy Cosmic Rays detection by high altitude antennas, Astropart. Phys. 54 (2014) 40 – 43.
- [168] C.-C. Chen, C.-H. Chen, C.-W. Chen, et al., Taiwan Astroparticle Radiowave Observatory for Geo-Synchrotron Emissions (TAROGE), in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)663.
- [169] I. Valino, for the Pierre Auger Collaboration, The flux of ultrahigh energy Cosmic rays after ten years of operation of the Pierre Auger Observatory, in: Proceedings of the 34th ICRC, The Hague, The Netherlands, PoS(ICRC2015)271.
- [170] R. Baishya, P. Datta, P. M. Kalita, et al., On the production mechanism of MF-HF radiopulses associated with large extensive air showers, Il Nuovo Cimento C 16 (1993) 17–22.
- [171] B. Revenu, V. Marin, Radio emission from the air shower sudden death, ArXiv e-prints (2012). arXiv:1211.3305.