Radio detection of cosmic rays: present and future

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Digital radio detection of cosmic rays has made tremendous progress over the past decade. It has become increasingly clear where the potential — but also the limitations — of the technique lie. In this article, we discuss roads that could be followed in future radio detection efforts and try to evaluate the associated prospects and challenges.

KEYWORDS: UHECR 2014, radio detection, cosmic rays

1. Introduction

Over the past decade, tremendous progress has been made in the field of digital radio detection of cosmic ray air showers — for an overview we kindly refer the reader to the short review and references presented in [1]. Based on promising results achieved with the first-generation experiments LOPES [2] and CODALEMA [3], a second generation of experiments including in particular AERA [4], LOFAR [5] and Tunka-Rex [6] has been set up with the goal to evaluate and exploit the true potential of the detection technique.

In parallel to the experimental activities, the needed simulation codes and analysis strategies have been developed. Based on a solid understanding of the underlying radio emission physics, analyses have been devised to reliably extract the geometry, energy and even depth of shower maximum of air showers measured with radio antennas. In parallel to these achievements, however, some intrinsic limitations of the detection of radio emission from air showers on large scales have become increasingly clear.

Based on the current state of the field, we try to evaluate where the most promising potential of radio detection of cosmic rays in future cosmic ray research lies. We stress that this is our personal view which might not necessarily be shared by the whole community. Nevertheless, this contribution can certainly act as a good starting point for further discussions.

2. The promises of radio detection

Renewed interest in radio detection of cosmic rays at the beginning of the millennium had been sparked by several promising aspects of the technique. We give a concise overview here and try to summarize shortly to what extent these promises have indeed been fulfilled.

- Radio emission gives information complementary to particle detectors: This is true in the sense that radio detection purely measures the electromagnetic component of an air shower, while particle detectors can be sensitive to various components of the cascade. Complementarity can be maximized in particular if particle detectors specifically measure the muonic component of air showers.
- Radio measurements provide a calorimetric energy measurement: The radio signal at MHz frequencies is coherent and thus its amplitude scales linearly with the number of particles, which is in turn roughly proportional to the energy of the primary particle. As there is no absorption of
the radio signal in the atmosphere, indeed the radio signal provides a calorimetric measurement of energy in the electromagnetic component of an air shower [2]. Furthermore, energy estimators can be chosen which are hardly influenced by shower-to-shower fluctuations. Intrinsically (without accounting for experimental uncertainties) the energy resolution achievable with radio detectors should be better than 10%, potentially even as good as 5% [2, 7].

- The depth of the air shower maximum (Xmax) can be measured with the radio technique: Due to the forward-beamed nature of the radio emission, the distance of the radio source, closely correlated with the depth of the shower maximum, leaves an imprint in several observables, in particular the slope of the radio lateral distribution function [2, 7, 8], the opening angle of the hyperbolical wavefront [9] and the pulse shape. Xmax resolutions of 20 g/cm² or better can in principle be achieved, although the experimental confirmation with independent cross-checks using, e.g., the fluorescence detectors of the Pierre Auger Observatory or the Cherenkov-light detectors of Tunka has yet to be performed.

- Radio has a near-100% duty cycle: It has been established that radio emission is strongly influenced during thunderstorm conditions [10]. In fair weather conditions, however, measurements can be made day and night. Depending on the location, duty cycles of ≈ 95% seem to be achieved. This high duty cycle is coupled with a field-of-view of nearly 2π, which is considerably larger than the one usually achieved with particle, fluorescence light and Cherenkov light detectors. (It should be noted, though, that the radio detection threshold depends significantly on the arrival direction.)

- A high angular direction resolution is achievable: Even small arrays such as LOPES have demonstrated an angular resolution below 1°. The angular resolution is expected to be better than 0.5° for more sophisticated and larger arrays.

- The detectors can be built cheaply: This depends on two main aspects, the cost of an individual radio detector element and the needed density of these elements. Of the current experiments, only Tunka-Rex has been designed with the explicit goal of cost-effectiveness. Tunka-Rex has been built with a cost of only 500 USD per antenna [6] — however, significant infrastructure of the existing Tunka array was used in the process. It is clear that antennas and digital electronics can certainly be built at much lower prices than those of particle detectors. The difficulty for a cheap radio detector arises, however, when the needed spacing of the detectors is considered, which we will discuss below.

We will now discuss the potential for various specific implementations of radio detection of cosmic rays in more detail.

3. Potential of sparse arrays

Radio detection of cosmic rays in the frequency range of ≈ 30 – 80 MHz has started with small-scale radio detection setups covering areas of less than 0.1 km². With those it was established that the detection threshold for radio emission lies approximately at 10¹⁷ eV, where the radio signal starts to dominate over the Galactic Noise. Although the details depend on the local magnetic field configuration, the arrival direction, the altitude of the experiment and the analysis technique (interferometry can improve the signal-to-noise ratio), this threshold can be considered an adequate rule of thumb.

From the beginning, the interest in radio detection was to extend the energy reach of the measurements, ideally to be able to measure at the highest energies up to 10²⁰ eV. As the cosmic ray flux drops very dramatically with primary particle energy, this requires the instrumentation of very large areas. To keep instrumentation cost-effective, radio antennas have to be spaced as far apart as possible while still ensuring efficient detection. Hence, one of the goals was to make arrays as “sparse” as possible.
The Auger Engineering Radio Array (AERA) has pursued this approach with a graded array layout, which can be seen in comparison with LOPES-3D, Tunka-Rex and LOFAR in Fig. 1. The spacing of the AERA stations has been set to grids of 144 m, 250 m and 375 m and in the last phase 750 m. It has become increasingly clear that the size of the “radio footprint” illuminated by an air shower is dominated completely by one parameter: the zenith angle of the air shower. For near-vertical showers the footprint is very small due to the closeness of Xmax to the ground. A spacing of 375 m is probably already too sparse for coincident detection of near-vertical showers with at least three antennas. When more inclined geometries are considered, the picture changes dramatically, as is illustrated in Fig. 2. For the detection of showers with zenith angles of 70° or more, a grid of 750 m or even 1.5 km (the baseline grid of the Pierre Auger Observatory) can be sufficient.

A very important fact to realize is that the energy of the primary particle will not mitigate the effect of the small footprints for near-vertical air showers. While the electric field amplitudes do grow linearly with primary particle energy, the steepness of the lateral distribution function still limits the extent of the radio emission footprint to small areas.

Two consequences arise from these simple considerations (which, in fact have already been hinted at in the review article of Allan in 1971 [12]): A radio detection array focused at air showers with zenith angles below ≈ 60° zenith angle will need to be fairly dense if coincident detection in three or more antennas is foreseen. A spacing of ≈ 300 m seems to be adequate. If the goal is to cover large areas, this requires very many antennas to be deployed. To reach the same yearly exposure as the Auger Fluorescence detector, an area of ≈ 300 km² would need to be covered (a tenth of the area with roughly ten-fold duty cycle). At a spacing of ≈ 300 m this requires of order 3000 – 5000 antennas. This would be a tremendous effort. A very significant cutting of the cost of individual antenna stations with respect to those of current-generation detectors such as in AERA is certainly possible. Consider that a modern-day smartphone has many of the capabilities needed by a radio detector, and that by Moore’s law, the needed digital electronics drops in price very significantly year by year. Wireless communication of the acquired data could profit from new developments like LTE-Advanced in which the capability to form ad-hoc mesh networks receives special attention. Communications thus seems a solvable problem. The biggest challenge in fact seems to be power.
Fig. 2. Radio emission footprints in the 30-80 MHz frequency band as simulated with CoREAS [11]. The detection threshold typically lies at \( \approx 1-2 \, \mu V/m/MHz \). While the radio emission footprint is small for air showers with zenith angles up to \( \approx 60^\circ \), it becomes very large for inclined showers with zenith angles of 70\(^\circ\) or larger. The white rectangle characterizes the size of the 50\(^\circ\) inset. The dramatic increase of the illuminated area with the shower zenith angle is caused by the increasing geometrical distance between the shower maximum and the ground.

harvesting: solar power is expensive and requires expensive buffering with batteries. Maybe cheap wind turbines could be an option if they can be made reliable and radio-quiet. However, even if the cost per detector station is reduced to a few hundred USD, another problem would be the manpower needed for deployment and maintenance, which would have to be kept to an absolute minimum. This seems to call for a visionary (or crazy?) approach such as "deploy by airplane", i.e. pour a huge number of cheap autonomous radio detectors out of an airplane or helicopter while flying over the area to be instrumented. While none of this seems impossible per se, it seems clear that the concepts developed so far can not simply be scaled to areas much bigger than a few dozens of km\(^2\) area.

This, however, is certainly not to say that radio detection on the scales achieved today cannot make important contributions to cosmic ray physics. Very strong potential exists in independent cross-checks of the energy scale of existing particle and fluorescence detectors. This is because radio emission can be predicted from first principles on the basis of the pure electromagnetic cascade of an air shower. There are no uncertainties such as an unknown “yield” and there is no absorption in the atmosphere. The biggest challenge is a precise absolute calibration of the radio detectors, in particular the antenna response. Once this is available, radio detection can be used as a very precise technique to independently measure the absolute energy scale of cosmic ray measurements and to precisely determine the energy on an event-to-event basis. Also, Xmax reconstruction on an event-to-event basis with arrays such as AERA seems to be promising, although the actual resolution still has to be established experimentally.

Another direction that seems promising to pursue is the detection of inclined air showers with zenith angles of 70\(^\circ\) or more. Here, sparse radio detection arrays with grid spacings of a km or more should suffice. As these scales are comparable to those on which particle detectors are deployed, an
integration of radio detectors with particle detectors seems very attractive — this allows re-use of much of the infrastructure for power harvesting and wireless communications, making the additional cost rather small. The benefit would be that while particle detectors for such inclined air showers basically measure pure muons (the electromagnetic component has died out when the shower reaches the ground), radio detection would provide a precise measurement of the electromagnetic component of the air shower. Combined, this can be a powerful tool for mass composition and/or air shower physics studies, in which not only the energy scale but also further details could be probed.

Finally, one should not forget another option, which is to make use of the information provided by the radio detection of an air shower with only one antenna. If the geometry of the air shower (in particular the core position) is known precisely from another detector such as a particle detector array, even a single radio antenna measurement can provide a wealth of additional information. The best option for an optimal local hybrid detector as well as the analysis techniques for this approach have yet to be developed, though. Of course, the probability to detect an air shower with even one antenna still depends strongly on the density of detectors, especially for near-vertical showers.

4. Potential of dense arrays

A complementary approach to trying to instrument the largest possible area with the smallest possible number of antennas is to instrument a given area very densely with radio antennas. The Low Frequency Array (LOFAR) can be considered such a dense array. In particular, in its dense core hundreds of antennas are spaced in an area with a diameter of only 400 m. The layout of the LOFAR antennas inside and outside this core was optimized for interferometric observations of astronomical radio sources and is not ideal for cosmic ray radio detection, as there are very densely instrumented “stations” with large gaps in between. Nevertheless, LOFAR has shown very impressively how much detail can be extracted from radio measurements of air showers with a dense antenna array. In particular, an Xmax resolution of better than 20 g/cm² has been achieved with room for further optimisation of the analysis technique [8]. (It should be noted, though, that this Xmax reconstruction so far purely rests on simulations of the radio emission from extensive air showers. LOFAR lacks the capability for independent experimental cross-check of this result as it does not have access to Xmax information measured with another detection technique. This experimental verification will have to be achieved with AERA and Tunka-Rex in the near future.)

Fig. 3. Antenna layouts for LOFAR (left), AERA (middle) and a simulation of the core region of the SKA (right) (axes denote distances in metres). The background colors represent the radio emission footprint of an air shower with a zenith angle of 55° as simulated with CoREAS [11]. Both LOFAR and SKA sample the footprint with hundreds of antennas simultaneously, but at SKA the coverage will be much more uniform. Diagrams are from [13].
While the concept of such dense arrays does not scale to the large detection areas needed for the study of ultra-high-energy cosmic rays, there is strong potential for “precision studies” of air shower and cosmic ray physics at energies from $10^{17}$ eV to $\approx 10^{19}$ eV, i.e., in the region of transition from Galactic to extragalactic cosmic rays. In particular, the low-frequency part of the coming Square Kilometre Array (SKA) will instrument a significantly larger area than LOFAR with a very dense homogeneous array of radio antennas sensitive in the frequency range from 50 to 350 MHz, see Fig. 3. Activities are ongoing to ensure the needed particle triggering and buffering capabilities to use SKA-Low as an air shower detector in parallel to astronomical observations [13]. With the SKA, precision studies of the mass composition in the transition region, with $X_{\text{max}}$ resolutions on the level of up to $\approx 10 \text{ g/cm}^2$ could be pursued. Also, the SKA could be used to study particle interactions at the highest energies by precise measurements of the electromagnetic component of extensive air showers. Using (yet-to-be-developed) near-field interferometric analysis techniques it should be possible to reconstruct a three-dimensional “tomography” of the electromagnetic component of the air shower, offering a wealth of information for the study of air shower and thus particle physics. Considering the relatively small design changes needed to use the SKA for such studies and the potential scientific gain it is clear that this is a highly attractive option for the future application of radio detection of air showers.

A way with which dense arrays can be used for the observation of cosmic rays up to the highest energies is to not use the atmosphere as interaction medium but rather use the moon as active volume. In this scheme, which has been followed for decades with various projects, but without successful detection to date, several “beams” are placed simultaneously on the lunar limb to search for Askaryan-effect radio pulses arising from particle cascades initiated in the lunar regolith. The advantage of using the moon is that the detection volume is tremendous. The disadvantage is that the source is very far away and thus the radio pulses become very weak, requiring a very sensitive radio telescope to pick them out. With the SKA, for the first time detection of cosmic rays at energies below $10^{20}$ eV should become feasible. Such observations would allow pin-pointing of the sources of cosmic rays, and there is even a moderate energy resolution expected [14]. Consequently, this is another way of cosmic ray detection using dense radio arrays which is being followed very actively. At the same time, this technique can also be used to search for ultra-high energy neutrinos, exploiting the vast detection volume available for neutrino interactions in the moon.

5. Potential of radio-only detectors

From the start of digital radio detection activities, one prominent question was how a stand-alone radio detector could be realized. Significant effort has been made to develop a “self-triggered radio detector” and some successes have been achieved [15]. In principle, it is of course possible to trigger read-out of radio detectors on the basis of pulses measured in the radio signals themselves. However, it has turned out to be very challenging indeed to reliably identify cosmic ray air showers among the triggered signals. The problem is that there are ample sources of pulsed radio signals, in particular of anthropogenic origin. This reaches from faulty isolation in power lines or transformers kilometres away over airplanes passing above the detector to lightning in thunderclouds many kilometres away from the detector. The rate of such “transient RFI” is what limits self-triggering capabilities, while the “continuous noise”, in particular the Galactic noise, governs the overall detection threshold. It is thus not sufficient to survey a location by taking a spectrum analyzer and having a look at the frequency spectrum of the measured noise, as has sometimes been done in the past. The one site that remains to seem particularly promising for self-triggering of radio detectors is the south pole, which seems to be virtually free of transient RFI at MHz frequencies according to measurements by the RASTA project [16].

A self-triggered radio detector is certainly not impossible. Some successes have been achieved,
and the radio signal exhibits enough peculiarities that should allow identification of air showers even in the presence of anthropogenic RFI (the lateral distribution of the radio signals over the antennas, the hyperbolic wavefront, the peculiar polarization). However, the power of radio detection does not lie in isolated measurements without any other detector. The true potential lies in combining different detectors in the most complementary way, for example using muon detectors in combination with radio antennas. Not only does this provide a completely different quality of the measurement, it is also attractive from a cost point of view since much of the infrastructure can be shared by the different detectors. It is so much easier to then use the trigger provided by the particle detectors, which exhibits virtually no false positives and also is able to achieve a significantly lower trigger threshold than is possible on the basis of the radio signals alone. In other words, while a self-triggered radio detector is not impossible to build, this is so much harder to achieve than triggering by particle detectors, and there is so little convincing reason to do so that the question seems to have become purely academic today.

6. Potential of high- and low-frequency observations

There were great hopes to use radio detection at GHz frequencies for “fluorescence-like” detection of air showers 24 hours a day with off-the-shelf hardware. This would be possible if there were isotropic radio emission at GHz frequencies by the “molecular bremsstrahlung” effect that was originally invoked to explain measurements at the Argonne Wakefield Accelerator and SLAC [17]. Several experiments have by now attempted to measure this isotropic microwave emission, but to no avail. If it exists, it is much weaker than originally expected, and probably too weak to be exploited in practice. The most convincing detection of GHz radio emission has been made by the CROME experiment [18], but these results are fully consistent with forward-beamed radio emission arising from the very same geomagnetic and charge excess radiation seen at MHz frequencies undergoing a Cherenkov-like time compression due to the refractive index gradient of the atmosphere. The special condition to be able to observe this emission is that the antennas need to be located on the “Cherenkov ring” that is illuminated by high-frequency emission on the ground. While the GHz emission provides interesting information (e.g., the diameter of the ring provides information on the distance of the source and thus Xmax), this is a very constrained geometry for detection which requires an even denser array than MHz observations. From this point of view, high frequency emission alone does not seem an attractive scheme. If low-frequency detectors can easily be extended to higher frequencies than the 80 MHz typically used today, this could however be attractive.

While the radio emission from air showers extends to frequencies below 30 MHz, detection at such low frequencies suffers from the presence of very strong atmospheric noise. It could be feasible to exploit a frequency window at $\approx 1$–10 MHz which is relatively quiet during day because of absorption effects in the ionosphere. At these frequencies, one could potentially also observe radio emission from another mechanism, the near-instantaneous deceleration of charged shower particles entering the ground. This effect has been predicted by simulations and has been dubbed “sudden-death radiation” [19]. While it is clear that the sudden stopping of charged particles will cause a radio pulse, it is, however, currently rather unclear how much of the emission exits the ground-air boundary and if indeed it will be observable by antennas situated directly on the ground. Experimental efforts to test this detection scheme are ongoing in the EXTASIS project.

7. Potential of balloon-/satellite-based observations

Another option that was and still is being discussed in various scenarios is to use radio detectors high up in the atmosphere to identify air showers in large volumes of the atmosphere by their radio pulses. ANITA has already achieved this by detecting both direct (up-going) air showers and radio
emission from air showers that has been reflected off the antarctic ice [20].

However, recent calculations [21] indicate that the strong forward-beaming of the radio emission strongly limits the achievable apertures. Even with satellite-based observations, apertures of at most \( \sim 20,000 \text{ km}^2 \) sr can be achieved, which means that they will not be able to surpass the existing large ground-based detector arrays such as the Pierre Auger Observatory. This is true even at MHz frequencies where the beam pattern is much broader than the ring-shaped beam pattern at hundreds of MHz observed by the ANITA balloon. Considering the efforts involved in realizing a satellite-based experiment and the relatively short times over which balloons can operate, these approaches do not seem to be as attractive as was previously hoped.

8. Conclusions

Radio detection of cosmic ray air showers has made tremendous progress over the past decade. It can contribute in many important ways to cosmic ray research, in particular by independent measurements of the energy scale and the mass composition of cosmic rays. Limitations exist in particular in the size of the radio emission footprint which requires antennas to be spaced on grids not larger than \( \approx 300 \text{ m} \) — except if one concentrates on inclined air showers or only strives to complement particle detector measurements with radio measurements in single antennas. Very dense arrays of radio detectors, in particular the upcoming SKA, on the other hand, will be able to do high precision studies of air shower physics and the mass composition in the transition region. Radio detection may thus not fulfill all hopes that were originally expressed, but it certainly has the potential to provide very valuable additional information in hybrid detector concepts within existing and future cosmic ray observatories.

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