LOPES — Recent Results and Open Questions on the Radio Detection of Air Showers

Journal of Physics: Conference Series **632** (2015) 012102 doi:10.1088/1742-6596/632/1/012102

LOPES – Recent Results and Open Questions on the Radio Detection of Air Showers

F G Schröder[1], W D Apel[1], J C Arteaga-Velázquez[2], L Bähren[3], K Bekk[1], M Bertaina[4], P L Biermann[5,1], J Blümer[1,6], H Bozdog[1], I M Brancus[7], E Cantoni[4,8], A Chiavassa[4], K Daumiller[1], V de Souza[9], F Di Pierro[4], P Doll[1], R Engel[1], H Falcke[10,3,5], B Fuchs[6], H Gemmeke[11], C Grupen[12], A Haungs[1], D Heck[1], J R Hörandel[10], A Horneffer[5], D Huber[6], T Huege[1], P G Isar[13], K-H Kampert[14], D Kang[6], O Krömer[11], J Kuijpers[10], K Link[6], P Łuczak[15], M Ludwig[6], H J Mathes[1], M Melissas[6], C Morello[8], J Oehlschläger[1], N Palmieri[6], T Pierog[1], J Rautenberg[14], H Rebel[1], M Roth[1], C Rühle[11], A Saftoiu[7], H Schieler[1], A Schmidt[11], S Schoo[1], O Sima[16], G Toma[7], G C Trinchero[8], A Weindl[1], J Wochele[1], J Zabierowski[15] and J A Zensus[5]

[1] Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), Germany
[2] Instituto de Física y Matemáticas, Universidad Michoacana, Morelia, Mexico
[3] ASTRON, Dwingeloo, The Netherlands
[4] Dipartimento di Fisica, Università degli Studi di Torino, Torino, Italy
[5] Max-Planck-Institut für Radioastronomie, Bonn, Germany
[6] Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie (KIT), Germany
[7] National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[8] Osservatorio Astrofisico di Torino, INAF Torino, Italy
[9] Universidade São Paulo, Instituto de Física de São Carlos, São Carlos, Brasil
[10] Department of Astrophysics, Radboud University Nijmegen, The Netherlands
[11] Institut für Prozessdatenverarbeitung und Elektronik, KIT, Germany
[12] Faculty of Natural Sciences and Engineering, Universität Siegen, Germany
[13] Institute for Space Sciences, Bucharest-Magurele, Romania
[14] Fachbereich C, Physik, Universität Wuppertal, Germany
[15] Department of Astrophysics, National Centre for Nuclear Research, Łódź, Poland
[16] Department of Physics, University of Bucharest, Bucharest, Romania

E-mail: `frank.schroeder@kit.edu`

Abstract. LOPES was a digital antenna array operating for approximately 10 years until spring 2013 at the Karlsruhe Institute of Technology (KIT). Triggered by the co-located KASCADE-Grande air-shower experiment, it measured the radio signal of around 1000 cosmic-ray air showers with energies $E \gtrsim 10^{17}\,\mathrm{eV}$ in an effective band of $43 - 74\,\mathrm{MHz}$. Using the interferometric technique of cross-correlation beamforming, LOPES could reconstruct the shower direction with an accuracy $< 0.7°$, the shower energy with a precision $< 20\,\%$, and the atmospheric depth of the shower maximum, X_{max}, with a precision $< 95\,\mathrm{g/cm^2}$. In particular the reconstruction of the shower maximum suffers from significant measurement uncertainties due to the radio-loud environment of the site. This article summarizes our latest results on the reconstruction of the shower maximum, using two independent methods: the steepness of the hyperbolic radio wavefront and the slope of the lateral distribution of the radio amplitude. Moreover, we show vectorial measurements of the electric field with the tripole antennas of the latest LOPES setup. Finally, we discuss open questions as well as the potential impact of the lessons learned at LOPES for future antenna arrays.

1. Introduction

LOPES, the LOFAR prototype station, was a pathfinder experiment for digital detection of the radio emission by cosmic-ray air showers at MHz frequencies. Operating from 2003 until 2013 in different configurations, LOPES provided proof-of-principle for the capability to detect air showers with digital antenna arrays [1], and developed several technical methods, e.g., for amplitude and time calibration [2],[3]. Moreover, it demonstrated the feasibility for the offline reconstruction of air-shower properties from the digital radio signal, in particular, the direction [4],[5], the energy [6],[7], and the position of the shower maximum [8],[6],[5] which provides a statistical estimator for the mass composition of the primary particles. Finally, LOPES contributed to the understanding of the physics relevant for the radio emission by comparing the measured electric field with model predictions [9],[10], and by confronting Monte Carlo simulations with detailed measurements of the lateral distribution and the wavefront [11],[5].

All these results can be found in the various publications, and rather complete descriptions of the current understanding of the radio emission are available as well, see e.g., Ref. [12] for a recent summary. For this reason, we summarize just the latest results of LOPES, comparing for the first time our results on the shower maximum obtained with two different methods – namely the slope of the radio lateral distribution, and the steepness of the hyperbolic radio wavefront. Furthermore, the last section is devoted to open issues, which should be answered by future measurements and corresponding analysis methods with the new generation of radio arrays.

2. Experimental Setup and Measurements

LOPES was built as the radio extension of KASCADE-Grande [13] at the Karlsruhe Institute of Technology (KIT), Germany, where most of its antennas were located inside of the original KASCADE scintillator array [14]. As such LOPES was externally triggered by KASCADE-Grande which turned out to be a successful approach: by this all LOPES events are automatically hybrid measurements with the particle detector array, and we were able to study correlations with the air-shower properties measured by KASCADE-Grande. We also installed a few self-triggered antennas [15], but distinguishing air-shower pulses from background was close to impossible in the noisy environment of a research center. Even at areas which are more radio quiet, it is still questionable whether the additional effort required for self-triggering is justified, since hybrid measurements might be required anyway for most science goals, e.g., for determining the cosmic-ray composition with high accuracy.

In different periods LOPES consisted of 10 to 30 antennas placed in an area smaller than $200 \times 200\,\mathrm{m}^2$. Thus, LOPES can be considered a relatively dense array, since the distance between antennas is significantly smaller than both the radius of the Cherenkov ring and the typical decay distance of the lateral distribution, which both are in between 100 and 200 m. Consequently, we make two reasonable assumptions for the analysis of our measurements: First, if there is a significant radio signal detected by LOPES, then all antennas should have measured it, though, it could be lower than the noise level at some of the antennas. Second, the signal shape is approximately the same in all antennas, i.e., we neglect the known dependence of the pulse shape on the distance to the shower axis [16],[17].

Under these assumptions cross-correlation beamforming is a very powerful technique: Using the air-shower core and direction reconstructed by KASCADE-Grande as starting values, we digitally shift all recorded radio signals in time according to the calculated arrival time of the radio wavefront at each antenna. Then, we determine the cross-correlation and maximize it by slightly varying the direction and the shape of the wavefront using a simplex fit. In our latest analyses we assumed a hyperbolic shape for the wavefront and vary in particular the angle of the asymptotic cone of the hyperbola. By this interferometric technique we can reconstruct many events which have no significant signal in individual antennas, but still show a sufficiently high signal-to-noise ratio in the cross-correlation beam.

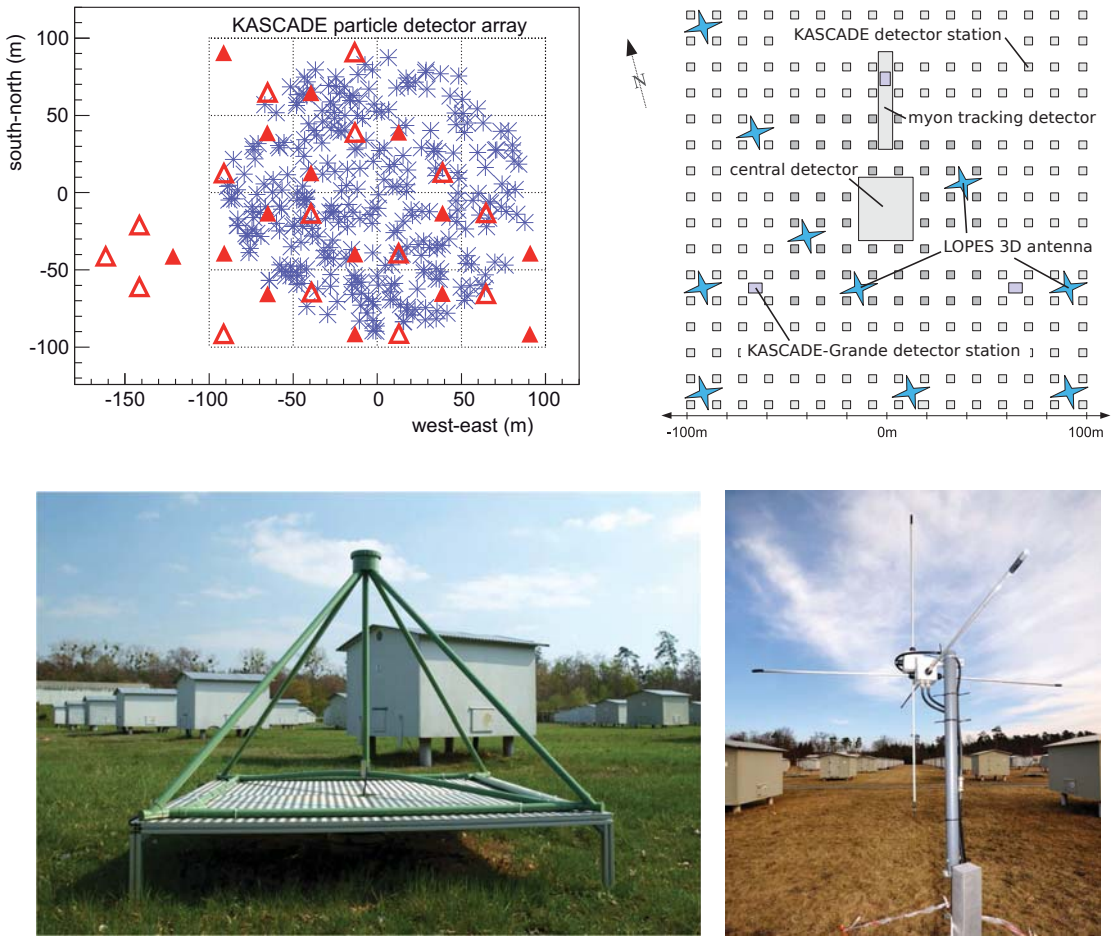

Figure 1. Left (top and bottom): LOPES setup from 2005-2009 and a photo of the inverted-V-shape dipole antenna used at this time. Filled triangles indicate the positions of 15 east-west aligned antennas present in the full data set; open triangles indicate 15 antennas present in about one third of the used data set. The shower cores of the events selected for a typical analysis are marked as stars (reconstructed from KASCADE data only). Right (top and bottom): LOPES-3D setup in operation from 2010 until spring 2013 consisting of 10 tripole antennas (photo) [18]. Apart from the antennas and preamplifiers, the analog and digital electronics was the same in both setups, providing an effective bandwidth of $43 - 74\,\mathrm{MHz}$.

Using this technique, we detected more than 1000 events during the whole live time of LOPES. For our recent analyses, though, we used only approximately 300 events recorded with $15 - 30$ east-west aligned antennas from 2005-2009, with energies $E > 10^{17}\,\mathrm{eV}$, zenith angles $\theta < 40°$, and shower core inside of the fiducial area of the KASCADE array. In earlier years the calibration was not yet finished. In later years we tested different types of antenna for the reconstruction of the electric field vectors [18]. These tripole antennas forming the LOPES-3D setup could have been beneficial in particular for inclined showers, but unfortunately we discovered that the background at the research center increases dramatically towards the horizon. Thus, after reasonable quality cuts, LOPES-3D would have increased the total LOPES statistics only marginally, and we decided to use only the former dipole antennas for our standard analyses.

Figure 1 shows photos of the two antenna types and maps of the different setups. The shower cores of a typical data selection are also plotted.

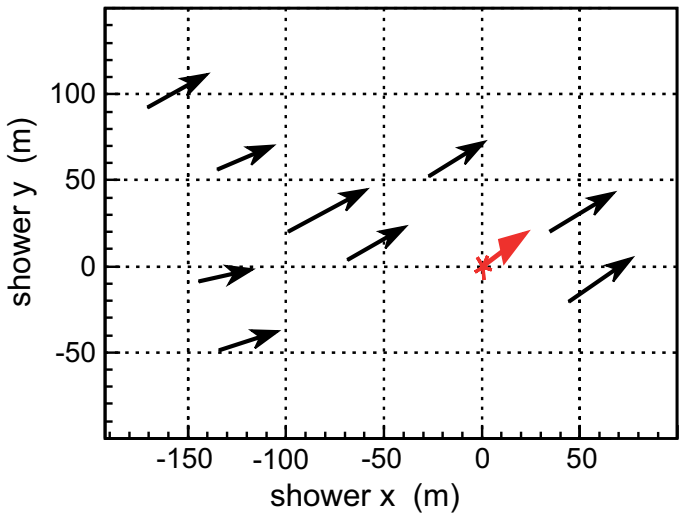

Figure 2. LOPES-3D event featuring a signal-to-noise ratio sufficient for the reconstruction of the electric field vector in the individual antennas. Each black arrow indicates the reconstructed direction and amplitude of the electric field vector at the position of one antenna, and the red arrow denotes the direction predicted for geomagnetic radio emission [10].

3. Results

Our most recent results are on the reconstruction of the shower maximum, and on the measurement of the electric field vector with the tripole antennas of the LOPES-3D setup. Despite the high background in the vertical polarization, LOPES-3D could confirm that a vertically aligned antenna increases the sensitivity for inclined showers [19],[10]. This could be important for future large-scale arrays, since inclined showers have very large footprints and make sparse and economic arrays feasible [20].

Moreover, we could confirm earlier results [9] that the measured polarization or, in this case, the reconstructed direction of the electric field vector, is compatible with the direction of the geomagnetically induced transverse currents in the air shower (see figure 2 for an example). This means that the vectorial measurements of LOPES-3D provide another evidence that the radio emission from air-showers is dominated by the geomagnetic effect. However, the sensitivity of LOPES-3D is insufficient to distinguish the contribution of the sub-dominant Askaryan effect. Nevertheless, indications for the Askaryan effect have been found at other experiments in regions with lower background [21],[22],[23].

While the high background is a problem for some analyses, for others it is not so relevant. Thanks to the interferometric beamforming, LOPES achieves a competitive accuracy for the air shower direction of better than 0.7°. Also the energy precision is competitive to other air shower techniques, namely at least as good as the precision of the KASCADE particle-detector array, i.e., better than 20 %. Since the radio technique provides a calorimetric measurement of the shower energy, both energy and arrival direction are first-order effects, and thus relatively easy to reconstruct: The arrival direction determines in first-order the arrival time of the radio signal at each antenna, and the shower energy determines in first-order the amplitude of the radio signal.

In contrast, the position of the shower maximum is a second-order effect on these observables: the distance from the radio array to the shower maximum determines by how much the arrival times deviate from a plane wavefront, and how fast the amplitude of the radio signal changes with distance to the shower axis. In other words: The closer the shower maximum, the steeper the

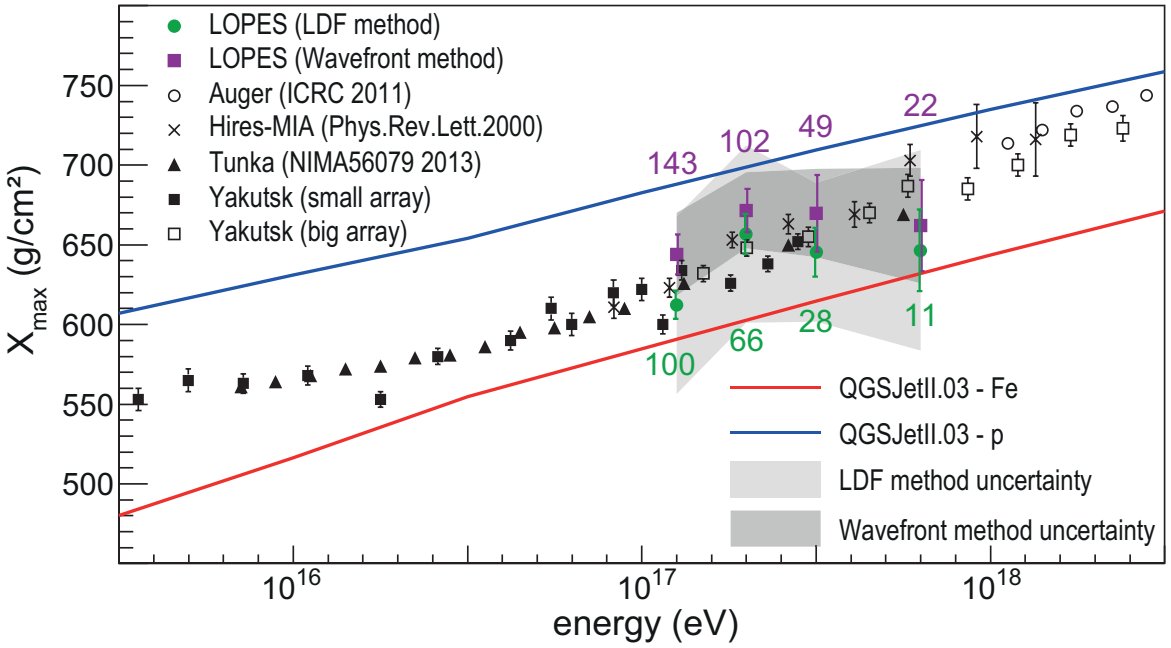

Figure 3. Measurements of different experiments of the mean atmospheric depth of the shower maximum, $X_{\max}$, in different energy bins. The bands around the LOPES values are for both methods the average deviation between the true and reconstructed $X_{\max}$ values of the CoREAS simulations, but not the total systematic uncertainty, which is not known. The indicated numbers of events per bin deviate between both methods due to different quality cuts. For references to the data points see Refs. [6] and [5].

radio wavefront, and the steeper the lateral distribution of the radio amplitude. Consequently, the reconstruction of the atmospheric depth of the shower maximum, $X_{\max}$, is more challenging than the reconstruction of the energy and the shower direction. This is because any measurement uncertainties generally have a larger effect on the second-order effects relevant for $X_{\max}$ than on the first-order effects relevant for energy and arrival direction. Still, we were able to provide a practical proof-of-principle for both methods, performing a reconstruction of $X_{\max}$ using high-quality LOPES events of the years 2005 to 2009 [5],[6].

First, we could show that the radio wavefront is approximately of hyperbolic shape. According to CoREAS simulations [24], the steepness of the asymptotic cone of the hyperbola is clearly correlated with the distance to the shower maximum [5]. CoREAS simulations predict that under ideal conditions, i.e., negligible noise and measurement uncertainties, a precision of better than $30\,\mathrm{g/cm^2}$ for $X_{\max}$ should be possible for a LOPES-like experiment. With LOPES measurements, however, we achieved a precision of $140\,\mathrm{g/cm^2}$. Nevertheless, we could demonstrate that the method in principle works, since we experimentally confirmed expected correlations of the wavefront steepness with other observables, e.g., the shower age reconstructed by the KASCADE array.

Second, we exploited the dependence of the slope of the lateral distribution on the shower development, for which we already had found experimental evidence [8]. Again, we used CoREAS simulations to study for different zenith angles how exactly the lateral slope depends on the shower maximum. Then, we used the input of the simulations to reconstruct $X_{\max}$ for measured events. Although the predicted precision for the ideal case without measurement uncertainties is only $50\,\mathrm{g/cm^2}$ and, thus, worse than for the wavefront method, the practically

achieved precision at LOPES is better than for the wavefront method, namely better than $95\,\mathrm{g/cm^2}$ [6].

In figure 3 we compare the reconstructed mean $X_{\max}$ obtained with both methods to measurements of other experiments. The event selections for both methods are not identical, since both methods require slightly different quality cuts. Moreover, we have not studied the effect of a potential selection bias, and we do not yet know the total systematic uncertainty of the LOPES measurements (e.g., due to varying atmospheric conditions). In any case, the total uncertainty will be larger than the pure statistical uncertainties. Consequently, the results of both methods are compatible with each other and in agreement with the results of independent experiments using other methods, namely air-fluorescence and air-Cherenkov measurements.

4. Open questions

4.1. Absolute scale

The general features of the radio emission by air showers seem to be understood: The latest generation of several simulation codes and models for the radio emission of air showers, e.g., ZHAires [25], EVA [26], SELFAS2 [27], and CoREAS [28],[24], yield comparable results and agree in the features of the radio signal [17]. For simplicity and due to limited resources we have compared LOPES data only to CoREAS simulations and its predecessor REAS 3.11. Results from AERA [29] indicate that qualitatively similar results could be expected for other simulation codes.

The radio extension CoREAS of the CORSIKA simulation package for air showers incorporates the present state of knowledge, and is able to reproduce the experimentally observed features of the lateral distribution and the wavefront within the measurement accuracy. Earlier published results indicated that the LOPES measurements would be in better agreement with REAS 3.11 than with CoREAS, which predicted a lower amplitude scale [11]. Using new input provided by the company which produced our external calibration source, we started to re-analyze the absolute amplitude calibration of LOPES. The new calibration indeed leads to a lower amplitude scale, moving the measurements closer to the CoREAS simulations. At the present state of analysis we cannot yet say, in which way this will alter conclusions for the comparison of measurements and simulations.

4.2. Subtraction of external noise

The detection of the air-shower radio signal at MHz frequencies suffers significantly from external noise, which is mainly composed of galactic and anthropogenic noise in the frequency range relevant for LOPES. Already galactic noise exceeds thermal noise by an order of magnitude. Including rural areas, anthropogenic background can be even higher [30]. Thus, sophisticated techniques for the reduction of background could significantly improve the performance of the radio technique. The detection threshold could be lowered by almost an order of magnitude if external noise could be completely suppressed.

At LOPES we successfully demonstrated that the detection threshold can be lowered by cross-correlation beamforming, exploiting the correlation of the air-shower signal arriving in different antennas at different times. In principle, also the background should be correlated, but this is not yet exploited: Most of the background, be it galactic or anthropogenic, is the sum of the radio emission originating from many different individual sources. This means that the background recorded by individual antennas is composed of many signals arriving from different directions. In principle, each antenna records the same background contributions just at different times, depending on the position of the antenna and the direction of the individual background signals. Consequently, using background observations before and after the air-shower signal, it should be in principle possible to predict and calculate the background in each antenna from the background measured at other antennas. This requires that the array consists of a sufficient

number of antennas to split the sky in a sufficient number of direction bins, or alternatively, when working in the Fourier domain, a sufficient number of different baselines. Once the background at one antenna is predictable from the measurements in other antennas (at least to a certain precision), it can be subtracted and the signal-to-noise ratio can be improved.

Such a method for rejection of directional background has not yet been tried. It corresponds to the solution of a multi-dimensional equation system for the time series recorded at the individual antennas, and requires sufficient computing power. Since all triggered events are stored on disk, this offers the opportunity to later increase the efficiency of the already terminated experiment, once the technique for noise reduction becomes available. Moreover, this method could be applied to radio astronomy whenever background cannot be reduced by integration, e.g., when observing fast transients.

4.3. Feasibility for large observatories

At the start of LOPES there was hope that the radio technique could be extended at reasonable cost to very large scale arrays of several 1000 km^2, which are necessary for the detection of ultra-high energy cosmic rays. Scaling the radio technique to huge areas would be economically feasible only when the array is much sparser than LOPES, or when the costs per station is reduced significantly. However, the methods and techniques developed for LOPES cannot be applied to an arbitrary large antenna spacing, for two reasons: First, we achieve the highest precision for the reconstructed shower energy using the radio amplitude at a distance to the shower axis of approximately 100 m. Second, interferometric beamforming requires several antennas with signal. This means that several antennas have to be placed within the radio footprint, which has a diameter of at most a few 100 m, except for very inclined showers.

Consequently, the LOPES technique requires an antenna spacing of not more than 100 to 200 m. At the present state of technology this might be too expensive for huge areas, in particular when a ns-timing precision is required for interferometry. This does not mean that radio detection would be completely unfeasible at the highest energies. However, certain modification compared to LOPES would be necessary when applying the radio technique to huge areas. Perhaps one could focus on inclined showers with large footprints or better exploit the information contained in the pulse shape and polarization measured at a single station. Balloons or satellites might be an alternative to ground arrays, which is currently under investigation by ANITA [31]. Finally, other target materials than the Earth's atmosphere could be observed, e.g, the moon [32].

5. Conclusion

With LOPES we could demonstrate that digital radio arrays are a suitable extension to particle detector arrays for air showers at energies $E \gtrsim 10^{17}\,\mathrm{eV}$. Regarding the precision of the shower direction and energy, radio measurements can compete with other detection techniques, even in the noisy environment of the LOPES site. Furthermore, the position of the shower maximum can be reconstructed from the radio measurements. But for X_{max}, the precision of LOPES is not competitive and just sufficient to distinguish on average the extreme cases of protons and iron nuclei as primary particles. Nevertheless, LOFAR has demonstrated a competitive precision for the shower maximum with a denser array at a site with lower ambient background. Still, it is not yet clear, if only the background level, or also the antenna density is essential for the precision. This question will be answered by the currently running, sparser radio arrays AERA [33] and Tunka-Rex [34], which are located at radio quiet sites, but have a larger antenna spacing in the order of 200 m.

Even if for larger radio arrays only the arrival direction and the shower energy could be determined with decent precision, this could still make it worth to build such arrays. The combination of a particle detector array providing a measurement of the muonic component,

and a complementary radio array providing a precise measurement of the energy of the electromagnetic component, together could bring a significant step in accuracy, e.g., for an energy spectrum distinguishing different mass groups. This would be an essential input for the open questions with respect to the transition from galactic to extra-galactic cosmic rays at energies larger than 10^{17} eV, i.e., exactly in the energy range where the radio technique becomes efficient.

Acknowledgments

Acknowledgement LOPES and KASCADE-Grande have been supported by the German Federal Ministry of Education and Research. KASCADE-Grande is partly supported by the MIUR and INAF of Italy, the Polish Ministry of Science and Higher Education and by the Romanian Authority for Scientific Research UEFISCDI (PNII-IDEI grant 271/2011). This research has been supported by grant number VH-NG-413 of the Helmholtz Association. The present study is supported by the 'Helmholtz Alliance for Astroparticle Physics - HAP' funded by the Initiative and Networking Fund of the Helmholtz Association, Germany.

References

[1] Falcke H *et al* - LOPES Coll 2005 *Nature* **435** 313–316
[2] Nehls S, Hakenjos A, Arts M J *et al.* 2008 *Nucl. Instr. and Meth. A* **589** 350 – 361
[3] Schröder F G, Asch T, Bähren L *et al.* 2010 *Nucl. Instr. and Meth. A* **615** 277 – 284
[4] Nigl A *et al* - LOPES Coll 2008 *Astronomy & Astrophysics* **487** 781–788
[5] Apel W D *et al* - LOPES Coll 2014 *J. Cosmol. Astropart. Phys.* JCAP09(2014)025
[6] Apel W D *et al* - LOPES Coll 2014 *Phys. Rev. D* **90** 062001
[7] Schröder F G *et al* - LOPES Coll 2013 *JPCS* **409** 012075
[8] Apel W D *et al* - LOPES Coll 2012 *Phys. Rev. D* **85** 071101(R)
[9] Isar P G *et al* - LOPES Coll 2009 *Nucl. Instr. and Meth. A* **604, Supp. 1** S81–S84
[10] Huber D 2014 PhD Thesis URL `digbib.ubka.uni-karlsruhe.de/volltexte/1000043289`
[11] Apel W D *et al* - LOPES Coll 2013 *Astroparticle Physics* **50-52** 76–91
[12] Huege T 2013 *Proc. of 33rd ICRC* #1294 arxiv.org:1310.6927
[13] Apel W D *et al* - KASCADE-Grande Coll 2010 *Nucl. Instr. and Meth. A* **620** 202–216
[14] Antoni T *et al* - KASCADE Coll 2003 *Nucl. Instr. and Meth. A* **513** 490–510
[15] Asch T, Forschungszentrum Karlsruhe 2009 *FZKA Report* **7459**
[16] Grebe S *et al* -Pierre Auger Coll 2013 *Proc. of 5th ARENA 2012, AIP Conf. Proc.* **1535** 73–77
[17] Huege T 2013 *Proc. of 5th ARENA 2012, AIP Conf. Proc.* **1535** 121–127
[18] Apel W D *et al* - LOPES Coll 2012 *Nucl. Instr. and Meth. A* **696** 100–109
[19] Huber D *et al* - LOPES Coll 2014 *Proc. of 6th ARENA 2014, submitted to AIP Conf. Proc.*
[20] Holt D 2013 Diploma Thesis, Karlsruhe Institute of Technology (KIT), Germany
[21] Marin V *et al* - CODALEMA Coll 2011 *Proc. of the 32nd ICRC, Beijing, China* vol 1 p #0942
[22] Pierre Auger Coll 2014 *Phys. Rev. D* **89** 052002
[23] Schellart P *et al* - LOFAR Coll 2014 *JCAP* **10** 014
[24] Huege T and Ludwig M 2013 *Proc. of 5th ARENA 2012, AIP Conf. Proc.* **1535** 128–132
[25] Alvarez-Muñiz J *et al* 2012 *Astroparticle Physics* **35** 325–341
[26] Werner K *et al* 2012 *Astroparticle Physics* **37** 733–741
[27] Marin V *et al* 2012 *Astroparticle Physics* **35** 733–741
[28] Ludwig M and Huege T 2011 *Astroparticle Physics* **34** 438–446
[29] Schröder F G *et al* - Pierre Auger Coll 2013 *Proc. of 33rd ICRC* #0899 arxiv.org:1307.5059
[30] CCIR (International Radio Consultative Committee), ITU, Geneva, Switzerland 1990 *CCIR Report* **670**
[31] Hoover S *et al* - ANITA Coll *Phys. Rev. Letters* **105** 151101
[32] James C W *et al* - LUNASKA 2010 *Phys. Rev. D* **81** 042003
[33] Pierre Auger Coll 2012 *Journal of Instr.* **7** P10011
[34] Kostunin D *et al* - Tunka-Rex Coll 2014 *Nucl. Instr. and Meth. A; Proc. of RICAP 2013* **742** 89–94