Radio Detection of Ultra-High Energy Cosmic Rays

HEINO FALCKE[1,2] FOR THE LOPES COLLABORATION
[1]*Department of Astrophysics, Institute for Mathematics, Astrophysics and Particle Physics, Radboud University, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
[2]*ASTRON, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands*
h.falcke@astro.ru.nl

Abstract: The radio technique for the detection of cosmic particles has seen a major revival in recent years. New and planned experiments in the lab and the field, such as GLUE, Anita, LUNASKA, Codalema, LOPES as well as sophisticated Monte Carlo experiments have produced a wealth of new information and I review here briefly some of the main results with the main focus on air showers. Radio emission of ultra-high energy cosmic particles offers a number of interesting advantages. Since radio waves suffer no attenuation, radio measurements allow the detection of very distant or highly inclined showers, can be used day and night, and provide a bolometric measure of the leptonic shower component. The LOPES experiment has detected the radio emission from cosmic rays, confirmed the geosynchrotron effect for extensive air showers, and provided a good calibration fomula to convert the radio signal into primary particle energy. Moreover, Monte Carlo simulations suggest that also the shower maximum and the particle composition can be measured. Future steps will be the installation of radio antennas at the Auger experiment to measure the composition of ultra-high energy cosmic rays and the usage of the LOFAR radio telescope (and later the SKA) as a cosmic ray detector. Here an intriguing additional application is the search for low-frequency radio emission from neutrinos and cosmic rays interacting with the lunar regolith. This promises the best detection limits for particles above 10^{21} eV and allows one to go significantly beyond current ground-based detectors.

Introduction

Radio astronomy has always been closely connected to cosmic ray physics. Already the very first cosmic radio emission detected by Carl Jansky in 1932 originated from cosmic ray constituents in the Milky Way. We now know that at low radio frequencies the diffuse Galactic radio emission is mainly produced through synchrotron radiation of relativistic electrons. They are propagating through the interstellar medium and the Galactic magnetic field and were most likely accelerated in supernova explosions.

Also, the brightest radio sources discovered thereafter, like quasars and radio galaxies (active galactic nuclei) and supernova remnants, are today the main suspects for the origin of cosmic rays. So, without the advent of radio telescopes, we probably would not know much about the non-thermal universe today.

It is therefore no surprise that radio antennas were early on also considered for directly detecting cosmic ray air showers. In fact the huge Lovell radio telescope in Jodrell Bank was initially built in order to detect cosmic ray radar reflection [14, 27] — it did not succeed but detected the radar reflection of Sputnik instead and made history.

Radio detection of air showers has a number of advantages: the detector material itself, a simple wire, is cheap, radio emission is not absorbed in the atmosphere and can thus see the entire shower, and interferometric techniques should allow relatively precise localization. But does this work in practice and how does the radio signal actually look like?

I will here mainly summarize some of the main recent results and not recall the entire history of this field. Here one can point to the well-known review by Allan from 1971 [1] and a brief summary of the early results given by Falcke & Gorham [20]. Main points were the prediction of radio Cherenkov radiation by Askaryan [6, 7] and the discovery of CR related radio pulses through Jelley et al. in 1965 [39] (a nice historical recount of the discovery was given by Trevor Weekes [67]).

Despite many experimental problems at the time, quite a number of basic properties of air shower were established within a decade culminating in the empirical "Allan formula" [1].

A long hiatus of this field began in the 1970's, as witnessed by a quote from Alan Watson in his 1975 ICRC rapporteur talk in Munich, where he observed that "Apart from work at 2 MHz which is planned for Yakutsk, it is clear that experimental work on radio signals has been terminated elsewhere."

Occasional attempts with single or few radio antennas at EAS-TOP and CASA/MIA [26] did not lead to further radio detections in the 1990's, making some colleagues (unjustifiably) even doubt the reality of the earlier results in private conversations.

Only in recent years, the technique has seen an astounding revival. A good overview is probably found in references [59, 20, 21, 52].

Scientifically, this started with attempts to detect radio emission from neutrinos hitting the moon by Hankins, Ekers, & O'Sullivan [29] and Gorham et al. [25]. For air showers, the realization that the emission can be understood as geosynchrotron emission by Falcke & Gorham [20] and Huege & Falcke [32] also inspired new efforts.

Technologically, the revival is certainly due to high-dynamic range digital radio receivers and post-processing capabilities that are now available. There is also a general revival in low-frequency radio astronomy as seen in a number of projects such as LOFAR[22], MWA[15], LWA[44] and GMRT[64].

In the following we will give a summary of some of the results in this field, with particular emphasis on radio emission from air showers and results obtained with LOPES.

Theory

After the experimental realization in the late 1960's that the Earth magnetic field is a factor in radio air shower emission, early theoretical modeling by Kahn & Lerche considered the Lorentz boosted lateral current induced by the geomagnetic field [41], an approach that has been revisited very recently by Werner & Scholten [68, 63].

A different approach was presented by Falcke, Gorham, and Huege [20, 32] where the radio emission was explained in terms of "geosynchrotron emission". This approach takes an important extra factor into account, namely the curvature of the trajectories of the individual electron/positron pairs in the geomagnetic field. The fact that the emission region is smaller than a wavelength (and optically thin) allows a relatively simple coherent addition of the radio waves. This "single-particle approach" makes it straightforward to combine the radio emission with Monte Carlo calculations [33, 36]. The overall level of the geosynchrotron component seems to be sufficient to explain the bulk of the observed radio emission [34]. After all, geosynchrotron subsumes most of the "lateral current interpretation".

However, also in the geosynchrotron picture a couple of extra effects still need to be taken into account, such as the current induced by the change in charges through creation, annihilation and recombination[63, 49]. The recombination of electrons may also lead to an additional Bremsstrahlung component [49]. Also, the non-zero refractive index of air and the original Askaryan effect through Cherenkov emission from the charge excess [18, 50] will play a role at some level. The static Coulomb contribution should also be looked at [50] as well as optical depth effects that could become relevant for air showers around 10^{20} eV (proposed in the context of radio radar experiments [23]).

Hence, while major progress has been made, there is still room for improvement. Nonetheless, the predictive power of current Monte Carlo codes, if coupled with air shower simulations, is probably already quite significant. This requires knowledge of the lepton evolution in the showers and adequate shower libraries [47].

Calculations with the REAS2 code and CORSIKA code by Huege et al. have recently shown some interesting results [35]: If measured at a characteristic radius of $\sim$ 300 m from the shower core the radio signal is tightly correlated with the primary particle energy (Fig. 1). Shower-to-shower

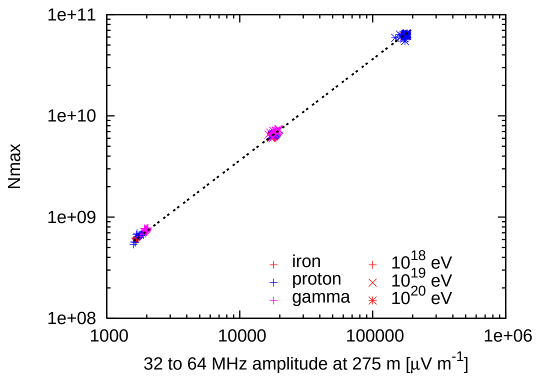

Figure 1: Integrated 32-64 MHz radio flux measured at 275 m from REAS2 simulations as function of energy for different primary particles and showers with 60° zentith angle. Shower-to-shower fluctuations are only 5%. Figure taken from reference [35].

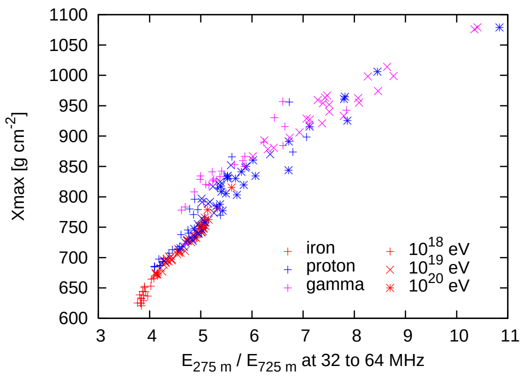

Figure 2: Location of shower maximum, $X_{\max}$, vs. lateral slope of radio emission from REAS2 simulations. The tight correlation suggests that perhaps $X_{\max}$ should be measurable with radio antennas and showers with 60° zentith angle. Figure taken from reference [35].

fluctuations and different elemental composition of the primaries induce just 5% variations in the radio flux. This is due to the fact that the radial radio distribution on the ground pivots around a few hundred m for different $X_{\max}$, depending a bit on shower geometry. This also means that measuring the radial slope of the radio emission should give clues for the location of the shower maximum (Fig. 2) and together with the absolute radio flux allow one to separate primaries of different elemental composition. This tantalizing prediction naturally requires experimental confirmation but already shows how important the theoretical work is.

LOPES

Quite a few experiments have been built or have been discussed in the last couple of years that employ the radio detection method. We will try to briefly discuss them here in turn.

A very productive experiment has been the LOFAR PrototypE Station (LOPES), which made use of early prototype hardware developed for the LOFAR radio telescope (see below) and helped to bring about the current renaissance in radio detection techniques[19].

LOPES [30, 19] was a collaboration of radio astronomers involved in LOFAR and the groups involved in the KASCADE[45] and KASCADE Grande array[53]. The idea was to put a significant amount of radio antennas – allowing for interferometric measurements – near a well-developed air shower array. This facilitates a cross correlation between conventional air shower measurements and radio observations.

LOPES consisted initially of 10 single dipole antennas (LOPES10) that were then expanded to 30 antennas (LOPES30). In the last phase LOPES was again rearranged to have 20 antennas of which 10 are in a dual polarization mode (Fig. 3). Polarization investigations are now underway (see Isar et al.[37]).

The LOPES antennas digitize the incoming radio waves with a 12 bit A/D converter operating at 80 MHz. An analog filter restricts the observable frequency range to 40-80 MHz, i.e. the second Nyquist zone. All antennas share a joint clock distribution and have a 6.7 second ring-buffer which is triggered and read-out roughly twice a minute by the KASCADE array (Fig. 3).

LOPES itself is restricted to the dimensions of KASCADE (200 m), but with the help of KAS-

CADE Grande events out to 500 m can be seen [3].

The energies of cosmic rays seen in the radio at KASCADE is typically a few times 10^{17} eV. Inclusion of KASCADE Grande provides information up to 10^{18} eV. Below 10^{17} eV the radio signal vanishes in the noise.

Clearly, the Forschungszentrum Karlsruhe, where LOPES is located, is not an ideal location of radio observations due to an enormous man-made radio background noise (Radio Frequency Interference, RFI). This can be overcome somewhat in the post-processing through digital filtering methods.

Also, in addition to the LOPES antennas a few additional log-periodic antennas ("Christmas trees") with new electronics have been added in order to develop a self-triggering algorithm [5]. Here the background noise is an even more severe problem. On the other hand, studying self-triggering under these conditions, will allow one to self-trigger almost everywhere else in the world as well.

Codalema

Parallel to LOPES the CODALEMA experiment was set-up[4], which initially had a complementary approach: set up particle detectors near an existing radio astronomy telescope at Nancay (France) and try self-triggering. This had the advantage of a radio quiet site — much better than LOPES — and well-calibrated antennas, but the disadvantage of having to calibrate a new particle-detector array and to trigger on a yet not understood radio signal. In the latest version the CODALEMA array is now completely independent and employs a set of 16 wide-band active dipoles aligned on two 600 meter long baselines in the North-South and East-West directions. The radio array is triggered by a ground detector array of 240 meters square containing 13 plastic scintillator stations. The recording bandwidth is 1-200 MHz, but signal detection is mainly done around 50 MHz, where also LOPES operates. Hence, the two experiments are now quite compatible.

LOFAR

A next big step in radio detection of air showers will be the LOFAR array which was planned as a large radio astronomy experiment [22, 58]. In the summer 2007 the project had to be downsized due to financial shortfalls, however, it will still be a major step forward. According to the current plans, LOFAR will consist of 36 antenna fields ("stations") in the Netherlands plus a number of stations across Europe (E-LOFAR: Germany, UK, France, Sweden, Italy, Poland, Ukraine). The first 20 stations are expected to operate early 2009.

Most of the antennas will be in a central concentration ("core") of 2 km diameter, where 18 stations are foreseen. Each station has two sets of receiver systems operating from 10-90 MHz (low-band antennas, LBA, Fig. 4) and 110-240 MHz (high-band antenna tiles, HBA). The LBA field consist of 48 dual-polarization inverted-V antennas, while the HBA fields consist of two sub-fields of 24 dual-polarization tiles. Each tile consists again of 16 bowtie-shaped fat dipoles (Fig. 5).

This means that in the inner 2 km there will be more than 800 dual-polarization low-frequency antennas and about $\sim 14,000$ high-frequency antennas (> 800 tiles) that will be able to observe bright radio events and deliver unprecedented detailed information about radio shower properties. LBAs and HBAs share one receiver, so each LBA/HBA pair cannot observe at the same time, however, it is well-possible to have one half of the receivers observe at the low-frequencies, while the other half observes at higher frequencies.

For normal radio astronomical observations the radio data from one station is combined into one data-stream ("digital beam-forming") to look in a predetermined direction. However, every antenna is also connected to a one second ring-buffer with FPGA-based processing and triggering capability. This allows one to trigger on the raw radio data stream in an intelligent way. Since 8 antennas share one memory board (with 4 FPGAs), there is the possibility to trade the number of antennas for triggering power or buffer length.

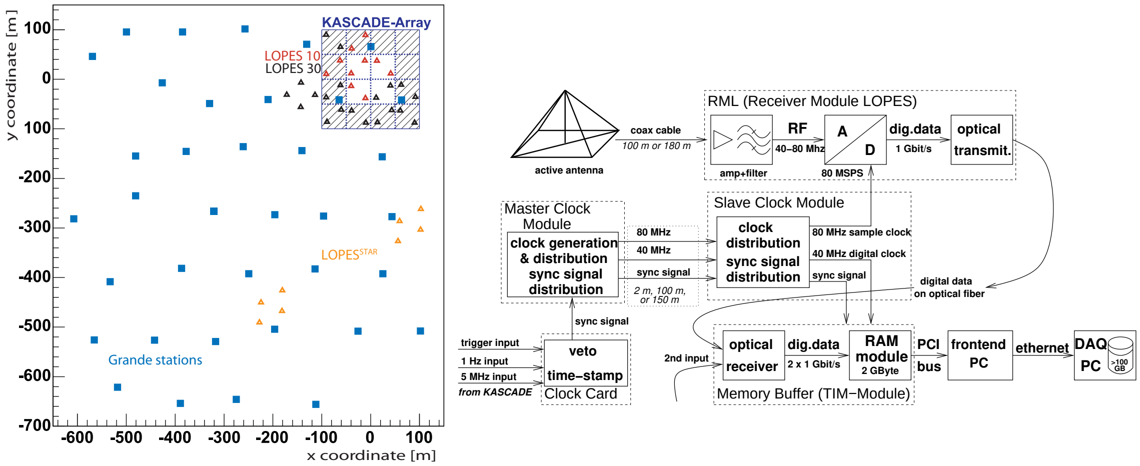

Figure 3: Left: LOPES and KASCADE Grande Layout. Right: Schematic of LOPES Electronics

Figure 4: LOFAR Low-Band Antennas

Figure 5: Inside of a LOFAR High-Band Antenna (HBA) tile, showing one crossed bow-tie antenna.

SKA

As a next step in radio astronomy at the low frequencies the Square Kilometre Array (SKA) project is planned for $>$ 2015 (www.skatelescope.org), which will provide even more opportunities for radio detection of cosmic rays and neutrinos [21]. The SKA will employ a mix of receptor technologies (dipoles, tiles, small dishes) depending on the frequency range (70 MHz- 10 GHz) and have a phased roll-out. The first phases will concentrate below 1 GHz and will be of high interest for radio particle detection as discussed here.

Auger Radio

In the spirit of the LOPES experiment, putting radio antennas next to existing cosmic ray experiments, it makes sense to also place radio antennas at today's largest cosmic ray array, the Pierre Auger observatory [66, 8]. This has been attempted recently with a few prototype radio antennas (van den Berg et al. [65]), including some LOPES antennas. The medium-term goal is to cover a 20 km^2 region with self-triggering radio antennas. In the same region an infill array and an upgrade to a fluorescence telescope will lower the energy threshold of Auger. This will nicely connect to the LOPES and CODALEMA measurements in energy and allow for the first time triple coincidences between radio, particle detectors, and fluorescence and hopefully further dramatically increase the quality of the data.

Radio in Ice and from the Moon

Apart from the radio air shower experiments a high level of attention has also been attracted by the possibility to detect showers generated in solid media, such as ice, salt or the lunar regolith. This goes back to the original suggestion by Askaryan [6, 7]. Further theoretical progress in the 1990's by Alvarez-Muniz and Zas et al. [2, 69, 12] and successful accelerator experiments, validating the theory, breathed new life into this field [60, 24].

One idea is to use the huge detector volume of the moon and observe it with sensitive ground-based radio telescopes in search for nanosecond pulses which are dispersed by the Earth ionosphere. First such experiments were made with the Parkes radio telescope [29] and the 64 m Kalyazin radio telescope [13]. An experiment (GLUE) using the NASA deep space network antenna at Goldstone received wide attention and produced interesting limits on the ultra-high-energy neutrinos flux [25]. Currently extensive experiments, LUNASKA and NuMoon, are progressing at the Australia Telescope Compact Array (ATCA, James et al. [38]) and the Westerbork Synthesis Radio Telescope (WSRT, Scholten et al. [62]). Later LOFAR and the SKA could be used to further improve the current upper limits to interesting levels or even detections [61, 21]. Even a detection of neutrinos using radio *on* the moon has been considered[40].

Instead of looking up, one can also look down on the Earth and use for example the large ice sheet of Antarctica or salt domes as detector targets. While salt domes [51] are currently not pushed very strongly due to high drilling costs, experiments involving Antarctica are flourishing.

For quite some time already the RICE experiment [46] has radio antennas in the ice near the IceCube array [42] and a major extension of IceCube with radio antennas is actively discussed [42, 43]. Alternatively radio antennas have been tested at the Ross ice shelve in Antarctica (ARIANNA) which is logistically more conveniently located [9, 11].

An alternative approach to embedding a large number of radio antennas in the detector volume is to just fly over it and use the long range capability of radio detection. Gorham et al.[48] have used a military satellite (FORTE) to search for neutrino induced radio pulses from the ice. Recently the dedicated balloon experiment ANITA [10] was launched for the first time to circle Antarctica and to detect there distant radio pulses from up-going neutrinos. Unfortunately the flight was cut short by unfortunate wind conditions, but nonetheless the data analysis is proceeding.

This brief summary already shows that the number and breadth of radio experiments for cosmic ray and neutrino detection is rather large already.

Experimental Results & Calibration

In the following we will summarize some of the important experimental conclusions concerning the air shower radio properties that have been found recently, here mainly focused on air showers and based on the LOPES results.

First of all one has to realize that the simplicity of the antenna comes at the cost of more complicated calibration. The sensitivity of a dipole depends on frequency, direction, and polarization. For LOPES the absolute calibration has been performed as part of the PhD thesis of S. Nehls [54] using an elevated calibrated reference antenna. On the other hand, given the simple structure of the antenna, it is also possible to calculate the expected beam pattern on the sky using standard antenna simulation packages.

An example is shown on Fig. 6, which shows that the beam shape is elongated and even not peaking towards the zenith for frequencies above the resonance frequency of the LOPES dipoles (~ 60 MHz). The elongated structure is related to the orientation of the dipoles (EW) and would be rotated by $90°$ for the other (NS) polarization. In turn this also means that the crossed-dipole, if uncalibrated, will always produce highly polarized signals.

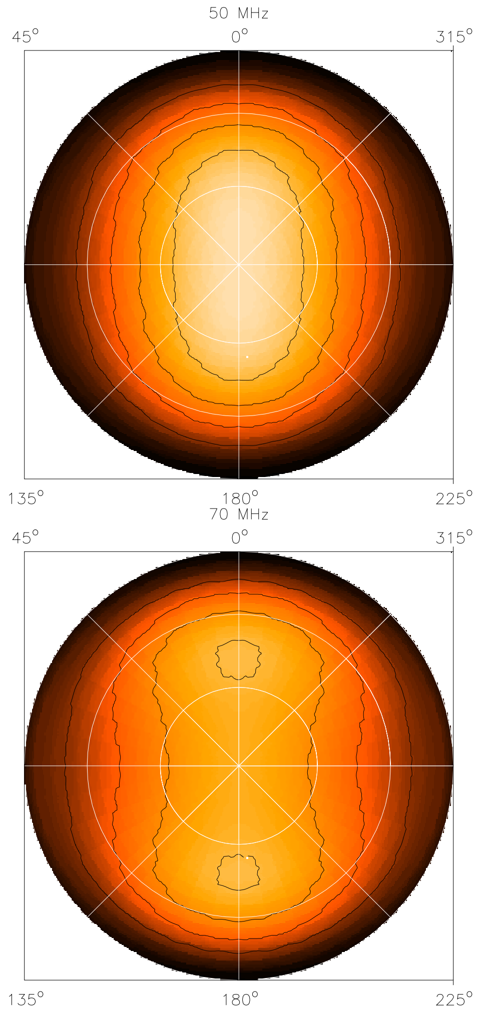

Figure 6: Gain pattern of a LOPES antenna at 50 MHz (top) and 70 MHz (bottom) showing the entire sky. The color scale goes from a gain of 0 (black)to 5 (white).

Energy Calibration

In addition to the antenna dependencies, the radio emission will also depend on the shower geometry. The main factors that have been identified are the particle energy, $E_{\rm p}$, the angle between shower axis and geomagnetic field ("geomagnetic angle"), α, the zenith angle, θ', and the distance from the shower core, r. For an east-west polarized antenna one finds that the radio emission for showers at the same energy and distance is proportional to $1 - \cos\alpha$ (Fig. 7a), the signal drops exponentially with radius (Fig. 7b), and increases linearly with primary particle energy (Fig. 7c).

Altogether this has been nicely parametrized in Horneffer's formula [31] (at the moment valid only for the EW polarization):

$$\epsilon_{\rm est} = (11 \pm 1.)\,((1.16 \pm 0.025) - \cos\alpha)\cos\theta$$
$$\exp\left(-\frac{r}{(236{\pm}81)\,{\rm m}}\right)\left(\frac{{\rm E_p}}{10^{17}{\rm eV}}\right)^{(0.95\pm0.04)}\left[\frac{\mu{\rm V}}{\rm m\,MHz}\right] \quad (1)$$

We note that the exponential decay of the radio signal is also seen by the CODALEMA experiment [4].

This prescription can now be inverted to predict the energy of the incoming particle. Comparison between the energy predicted from radio with the energy estimated from KASCADE Grande, shows a scatter of 27% between the two methods for $E_{\rm p} > 10^{17}$ eV. This is very encouraging, given that shower-to-shower fluctuations in the KASCADE Grande estimate alone should produce a 25% scatter. Hence, the scatter in the radio measurements should be much less.

This would support the claims from Monte Carlo simulations [35] that radio is a good tracer of the energy. The main reason why one suspects lower scatter in the radio measurements with respect to particle detection on the ground is the fact that radio emission in not absorbed in the atmosphere. Hence, radiation from every particle is visible on the ground — it is in that sense a bolometric measurement. Variations in the location of the shower maximum will be less dramatic compared to measurements of particles on the ground which are just a fractional tail of a quickly declining function, whose values are quite sensitive to $\rm X_{max}$.

Spectrum

One topic that had been difficult to tackle in the past has been the spectral shape of the radio signal, i.e. how much power is emitted at which frequency? Historic experiments were relatively narrow band and non-simultaneous data had to be combined. Modern broad-band receivers allow one to study the instantaneous spectral index, but require careful bandpass calibration.

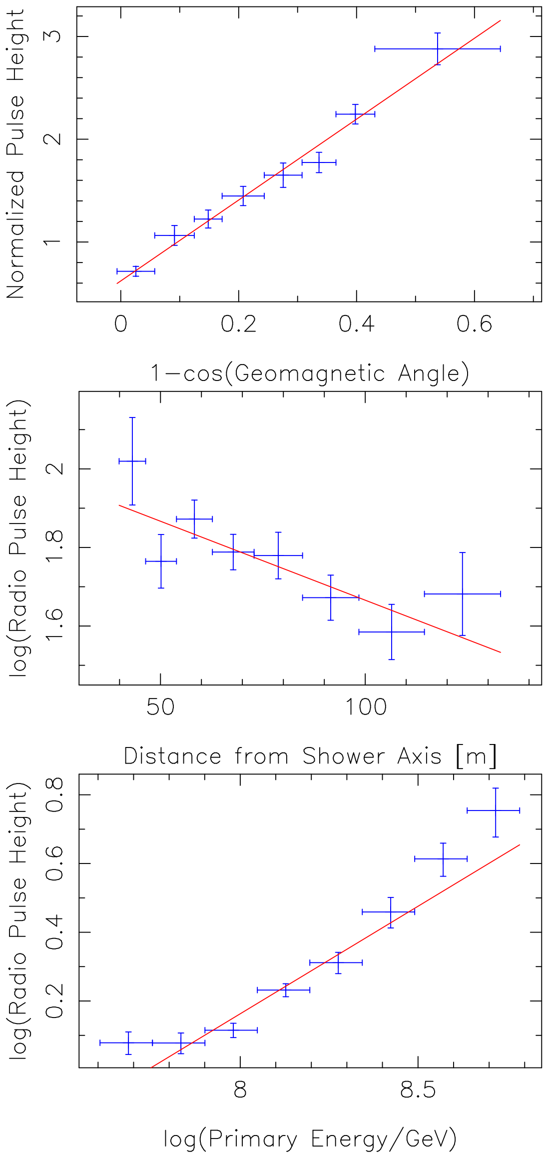

Figure 7: Calibration results of LOPES showing the normalized radio voltage vs. air shower parameters where the other parameters have been divided out. Each point represents the average and spread of all events in that bin. Panels a-c are from top to bottom.

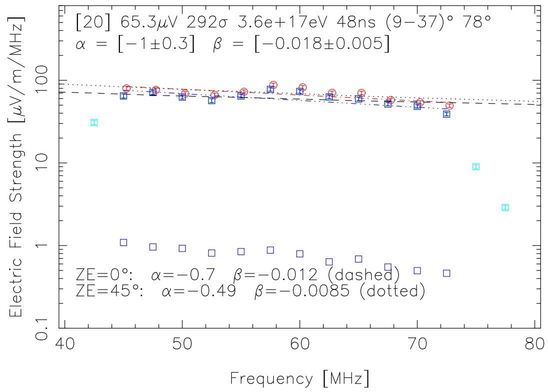

Figure 8: Example spectrum of a LOPES event for two different methods of beam-forming. The measured spectral slope is $\epsilon \propto \nu^{-1}$. The lines represent two spectra from Monte Carlo simulations. Also shown is the noise spectrum that has been corrected.

Nigl et al. [56] employed two methods to get the spectral shape (Fig. 8): Fourier transform of the (not squared) electric field around the pulse position and measurements of the pulse heights after applying narrow-band digital filters to the signal. Both methods give consistent results.

The spectra can be represented by a power-law function or an exponential decay. For the narrow frequency range of LOPES, extending only a factor of two, we cannot distinguish between the two prescriptions. For a power-law function the average spectral index is $\nu^{-1\pm0.3}$. This would mean that the power of the signal falls of with ν^{-2}. This is consistent with the simple expectations of coherent geosynchrotron [20] and only slightly steeper than the Monte Carlo simulations suggest [34]. Also, the Codalema experiment finds powerlaw spectra with spectral indices in the range -1.5 to 0. LOPES sees spectral indices in the range -1.5 to -0.4, so there is some agreement, but more detailed investigations have to be performed in the future.

Direction & Imaging

The next question then is, how well can we localize the radio emission? This has become of particular importance given the finding of anisotropies and correlations between cosmic ray arrival directions and nearby extragalactic objects [8].

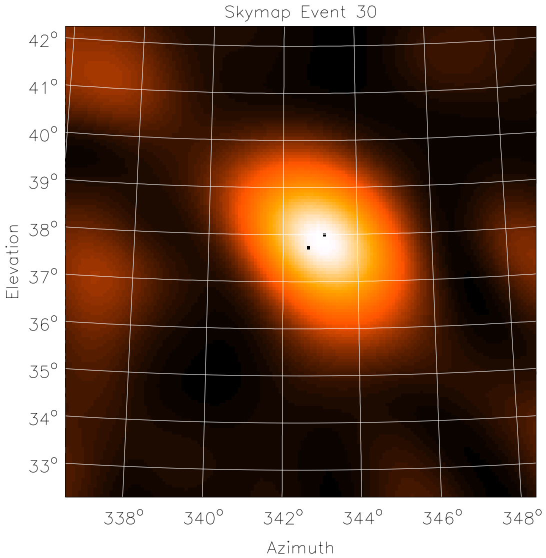

Figure 9: Image of a bright radio flash at the time of maximum. The dark dots mark the fitted LOPES position and the direction found by KASCADE. The size of the ellipse is determined by the expected image resolution.

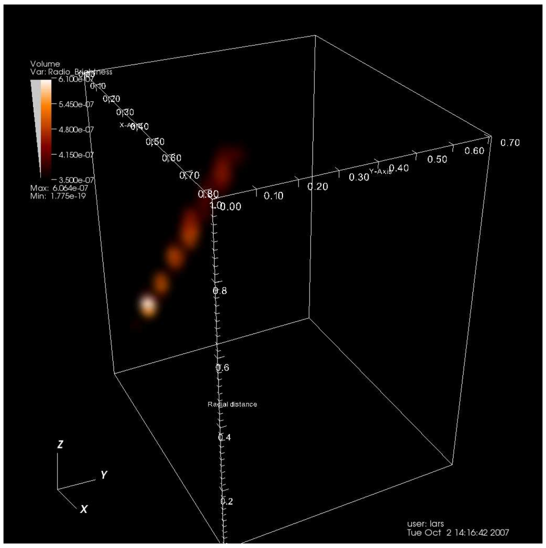

Figure 10: Three dimensional view of the radio emission from a cosmic ray air shower detected with LOPES. 3D sidelobes have been "cleaned" by only displaying high-brightness regions. The peak at 3 km height appears to be real, but the extended structure along the axis is strongly affected by remaining sidelobes.

Using radio astronomical imaging techniques, we can actually image the radio flash from the air shower. For LOPES L. Bähren has developed a special tool ("skymapper") which can actually do this on the tens of nanosecond (i.e., the sampling rate) level (see Fig. 9) and in three dimensions (Fig. 10).

This issue of the positional accuracy has then been further investigated by Nigl et al. [55] using LOPES data. Conventional interferometry is very sensitive to positional changes. For point sources one expects an angular error $\Delta\alpha_{min} = \pm\frac{1}{2}\frac{1}{\mathrm{SNR}}\frac{\lambda}{D}$ in the azimuthal direction, where SNR is the signal-to-noise ratio, D the separation of the antennas, and λ the observing wavelength. For high SNR images the positional accuracy for point sources is always better than the image resolution. Hence, for an SNR of 10 for an antenna separation of 100 m and observing frequencies around 60 MHz, as in LOPES, one expects an error of only 0.15°, while the point-spread function of the interferometer has a much larger width of about 2-3° in azimuth.

Comparisons of the shower direction (assuming a fixed shower core) between KASCADE and LOPES, actually shows an average offset of 1.3° (Fig. 11), which does decrease with increasing signal level (and increasing SNR). This is not bad compared to the imaging resolution of LOPES, but we would have expected better results still. So, what is the dominating source of error?

Some insight can be obtained from Fig. 12 which shows that the location of the radio centroid on the sky is also a function of the distance or radius of curvature. One has to remember that the shower maximum of the showers that LOPES sees is just a few km high. This is still in the near field of the interferometer. This means that radio waves emitted in the shower maximum will not appear as a plane wave, but will show a curvature with a radius corresponding to the distance from the observer. In the real world, the wave front will be even more complicated, since the emission is not constrained to a small region but extends along the shower axis. In principle one has then a wavefront that is the

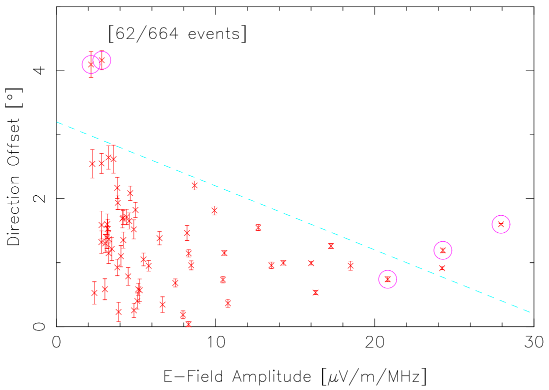

Figure 11: Offsets on the sky between the direction of the air shower axis as measured with KASCADE and LOPES vs the radio pulse amplitude. Events with circles were taken during thunderstorm conditions.

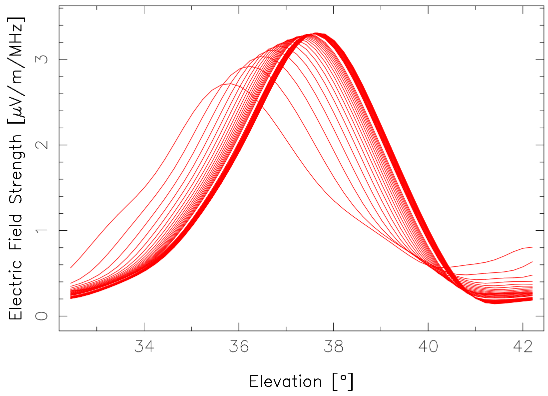

Figure 12: Cross section along the elevation axis in an image of a cosmic ray radio flash for different radii of curvature. The maximum field strength is found around a radius of 3km.

superposition of many spherical waves emitted at different positions.

In a proper 3D imaging process one would try to deconvolve the data and put together a 3D image cube. We are not yet able to do this. So, all we can do at present is to try different radii of curvature and search for the maximum in the emission. This is what Fig. 12 shows: different cross sections of a radio image focused at different distances in steps of 250m. The maximum is found at a distance of about 3 km. This is 30 times farther than the typical baselines on the ground and only possible due to the good SNR. What is clear from the figure is that not only the emission level changes but also the position of the maximum. The problem is that for small radii of curvature a small change in radius is similar to an inclination of a plane wave. Inclining the (virtual) receptor plane implies a positional shift on the sky. As seen in this example, the shift can be up to 3°. Hence, an error in the radius of curvature determination or – perhaps more important – a non-spherical wavefront will propagate into an positional error!

This requires that radio shower parameters are really derived from a 4 (or 6) dimensional data cube, consisting of time, 3 spatial coordinates, and potentially 2 shower core location parameters [3].

So, any experiment will improve its spatial accuracy not only with greater baselines but also with increasing the number of antennas. In addition we need to understand the exact geometry of the radio shower front. Here, further simulations and the detailed observations with the many antennas of LOFAR should clarify that issue. This may make further dramatic improvements in the astrometry of radio air showers possible.

Electric Fields and Lightning

One other important factor that has been looked at with some worries, is the influence of the atmospheric electric field on the radio emission. While the Earth magnetic field is very stable, the electric field can change significantly from 1-10 V/cm during fair weather, to 100 V/cm in heavy rain clouds (Nimbostratus), and up to 1000 V/cm in severe thunderstorms. If the radio emission is affected by the electric field one would not be able to interpret the radio signal quantitatively, since measuring precisely the instantaneous electric field structure is almost impossible.

To get a first idea of the importance of the electric field, we could simply look at the Lorentz force, $F = e(\vec{E} + \vec{v}/c \times \vec{B})$ in *cgs*, which is driving the geosynchrotron emission. For a relativistic parti-

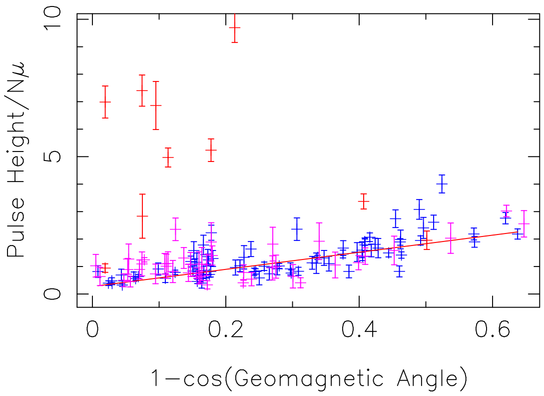

Figure 13: Radio pulse height (normalized by energy) versus the geomagnetic angle. Blue dots are taken during clear weather, purple during nimbostratus, and red points during thunderstorm conditions.

cle ($v/c \simeq 1$) the electric field will then dominate if $E > B \simeq 150\mathrm{V\,cm^{-1}}(B/0.5\,\mathrm{G})$. Hence, from this simple approximation one would expect only for severe weather a modification of the radio signal.

Buitink et al. [16] investigated radio pulse heights with LOPES under different weather conditions. They selected time slots where the local weather station recorded clear weather, heavy rain, or thunderstorms and compared the three (Fig. 13). Within the errors, the radio pulses followed the previously found correlation with the geomagnetic angle (if normalized to the same energy and radius). However, significant outliers are found in the thunderstorm data set – and only there. The amplification of the radio signal can be a factor ten.

This seems to confirm the simple estimate we made above and the fact that the Lorentz force is dominating. Further verification comes from Monte Carlo simulations. Buitink et al. [17] have now included electric fields in the CORSICA and REAS2 codes, allowing one to model the E-field influence in detail. The simulations have calculated radio pulses for different values of the electric field. Again a significant amplification is seen as soon as the E-field reaches 1000 V/cm, while at 100 V/cm the radio emission shows only little differences.

The CORSIKA simulations also show a modification of the electron/positron energy distribution and the shower structure. Many pairs are deflected significantly from the shower axis, which might be detectable with particle detectors.

Finally, we note that besides the radio pulse height also other parameters are impacted by thunderstorm electric fields. For example, in the investigation of the emitted radio spectrum one bright radio event stood out with a much steeper radio spectral index. It was found to be a thunderstorm event.

Moreover, also in the positional offsets between LOPES and KASCADE thunderstorm events stand out. In Fig. 11 all outliers are events measured during thunderstorms. Whether this is due to an actual deflection or an asymmetry in the radio emission is not yet clear.

In summary, we can state that air showers passing through the strong fields of thunderstorm clouds are brighter, further offset from the shower core measured on the ground, and have a steeper radio spectrum. For the measurement of cosmic rays this means that radio — at least at frequencies above 40 MHz — remains a reliable technique as along as data taken during thunderstorm is discarded.

On the other hand, the current results strongly suggest that in high E-fields not just the radio emission is altered, but the entire shower (at least the electronic part). This point may warrant further investigation for its own sake. Moreover, it has been speculated that cosmic ray air showers could play a role in initiating lightning through a runaway breakdown effect [28].

Radio methods could help to investigate this connection experimentally, since both – the lightning strike and the air shower – would be detectable by the same instrument. Also, further Monte Carlo simulations will investigate whether there is enough energy gain through the electric field or ionization through the air shower to actually start the runaway breakdown process. The LOFAR project will try to address some of these issues.

Self-triggering

Overall, the current results have provided a very comprehensive picture of the radio properties. However, whether the radio detection will mature into a standard technique depends on whether it is possible to actually trigger on the radio signal. This has been attempted but the final breakthrough still stands out. Recent attempts were made for example by the CODALEMA experiment [57]. Within LOPES, LOPES$^{\mathrm{STAR}}$ [5] has been designed specifically to investigate this issue in more detail.

We do now understand where the challenges lie. In many cases, disturbing radio interference has actually been generated by the devices and electronics of the cosmic ray experiments themselves. So, designing radio quiet electronics, power supplies and data communication is an important first step. Also, radio contains an enormous amount of information (as witnessed by every FM receiver) and many processes of the modern world produce wanted and unwanted radio signals. So, filtering out the correct information is more complicated then just looking for a peak in the electric field.

In a broad-band receiver the biggest contribution of the basic noise level typically comes from narrow-band RFI transmitters. Hence, a digital filter to cut these signals out – which is currently only employed in the post-processing, is a crucial step in the triggering electronics. Moreover, the characteristics of the pulse itself need to be considered as well. For a human eye it is quite simple to distinguish a cosmic ray pulse from those generated by a passing 1970 Chevrolet. Hence pulse shape parameters need to be used in the triggering. This will in any case require a bit more intelligence on the trigger board, than with conventional experiments. Such a pulse-shape parameter search to implement self-triggering in hardware is currently under way at LOPES$^{\mathrm{STAR}}$ showing some interesting progress recently. These techniques will eventually be tested at Auger and one can be hopeful that this last and crucial step will be achieved in the not too distant future.

Radio Pulses from the Moon

The main focus of this article was on the detection of radio emission of air showers. However, we want to end with a few comments on the prospects for radio emission from ultra-high energy cosmic rays with upcoming radio telescopes, in particular with LOFAR. Here the atmospheric detection will be implemented in the project — with the "transient buffer board" being at the heart of this new technique. It turns out that this buffer-board may also improve the detection of cosmic rays hitting the moon.

Scholten et al. [61] have shown that the 100-200 MHz range is ideal for detecting cosmic rays above 10^{20} eV hitting the lunar surface. In LOFAR any such event could be detected in a beam formed towards the moon. This detection could be used to trigger the buffer boards and download the raw data from all LOFAR antennas. With the raw data of the individual antennas the exact nature and origin of the pulse could be determined much more precisely, if one uses some of the offline processing steps known from the air shower detection.

The question is how sensitive is this technique? The originally planned LOFAR would have been very favorable for this [61], however, due to the downsize of LOFAR the sensitivity has decreased. K. Singh has now recalculated the expected sensitivity with the latest available station layout. The result is shown in Fig. 14. With the lower sensitivity, the minimum energy that can be detected has moved up above 10^{21} eV, which will decrease the expected count rate.

For comparison we also show the latest Auger spectrum with an extrapolation of the power law with three spectral indices through the GZK cut-off. For a powerlaw of E^{-3} LOFAR could in principle reach this extrapolation with a total observing time of 30 days, if a large number of tied-array beams can be formed – a mode that still needs to be tested.

While strong evidence for a GZK cut-off above $10^{19.6}$ eV has been seen by Auger, it cannot be excluded that there will be some recovery of the spectrum from local sources or neutrinos. Hence, it is still worth looking in this regime. Radio will probably be the only technique that can deliver at least very meaningful upper limits in this energy range.

Future expansions of LOFAR, such as the SKA, can improve these limits even more, actually reaching down to the GZK cut-off with the clear expectation of actual detections. This will then probably provide the ultimate detection experiment for

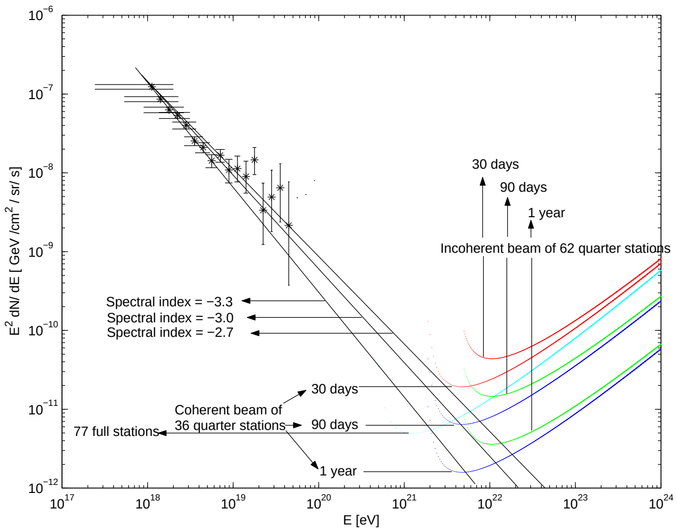

Figure 14: Expected LOFAR sensitivities for detecting ultra-high energy cosmic rays hitting the moon."Full stations" here relate to the originally planned 96 tiles. 36 quarter stations are the currently planned layout for the central LOFAR core. "Coherent" and "incoherent" relate to the two methods of combining the data from different stations.

cosmic ray particles at the highest energies we can ever measure.

Conclusions

The radio detection technique for cosmic particles has seen quite some ups and downs in the last decades. Pronounced dead in the 1970's it has now risen from the ashes. But is it here to stay? The chances are good at least.

First of all, we have made major progress in understanding the emission mechanism. For radio in solid media (Cherenkov emission) codes have been developed and accelerator experiments have been performed, giving trust in the reality of the effect. For radio emission from air showers (geosynchrotron) good Monte Carlo codes and solid experimental verification are now available and more and more details are being worked in.

The LOPES experiment, and in some areas also CODALEMA, has given us already detailed information about the radio air shower properties and performed a very useful cross-calibration between particle and radio detectors. Moreover, major experiments have embraced the technique. The large LOFAR radio telescope has the cosmic ray detection built in, the Auger collaboration is testing it, ANITA has flown, and also the IceCube collaboration is seriously preparing radio experiments.

A few issues still need to be solved: how does an optimal trigger system look like for radio antennas? What is the optimal layout for a large radio array? Nonetheless, there is a good chance that radio detection will become common place over the next few years.

It will be interesting to see in which direction this will develop. The simulations for air showers indicate that the addition of radio may increase energy resolution and directional accuracy. Also composition information (through $X_{\rm max}$) seems to be encoded in the radio signal. After the breakthrough of the hybrid technique with Auger, maybe we will see "tri-brid" detectors in the future. More and better data is almost always better in physics. If cosmic ray air shower arrays are to continue in the next decades, they will likely include radio antennas. For the highest energy events, the new generation of low-frequency radio telescopes provides hope that even particles above 10^{21} eV could in principle be detected in the future — if they exist.

References

[1] H. R. Allan. *Prog. in Element. Part. and Cos. Ray Phys.*, Vol. 10:171, 1971.

[2] J. Alvarez-Muñiz, R. A. Vázquez, and E. Zas. Calculation methods for radio pulses from high energy showers. *Phys. Rev. D*, 62:63001, 2000.

[3] W. D. Apel, T. Asch, A. F. Badea, L. Bähren, K. Bekk, A. Bercuci, M. Bertaina, P. L. Biermann, J. Blümer, H. Bozdog, I. M. Brancus, S. Buitink, M. Brüggemann, P. Buchholz, H. Butcher, A. Chiavassa, F. Cossavella, K. Daumiller, F. di Pierro, P. Doll, R. Engel, H. Falcke, H. Gemmeke, P. L. Ghia, R. Glasstetter, C. Grupen, A. Haungs, D. Heck, J. R. Hörandel, A. Horneffer, T. Huege, K. H. Kampert, Y. Kolotaev, O. Krömer, J. Kuijpers, S. Lafebre, H. J. Mathes, H. J. Mayer, C. Meurer, J. Milke, B. Mitrica, C. Morello, G. Navarra, S. Nehls, A. Nigl, R. Obenland, J. Oehlschläger, S. Ostapchenko, S. Over, M. Petcu, J. Petrovic, T. Pierog, S. Plewnia, H. Rebel, A. Risse, M. Roth, H. Schieler, O. Sima, K. Singh, M. Stümpert, G. Toma, G. C. Trinchero, H. Ulrich, J. van Buren, W. Walkowiak, A. Weindl, J. Wochele, J. Zabierowski, J. A. Zensus, and D. Zimmermann. Progress in air shower radio measurements: Detection of distant events. *Astroparticle Physics*, 26:332–340, 2006.

[4] D. Ardouin, A. Bellétoile, D. Charrier, R. Dallier, L. Denis, P. Eschstruth, T. Gousset, F. Haddad, J. Lamblin, P. Lautridou, A. Lecacheux, D. Monnier-Ragaigne, O. Ravel, T. Saugrin, and S. Valcares. Radioelectric field features of extensive air showers observed with CODALEMA. *Astroparticle Physics*, 26:341–350, 2006.

[5] T. Asch and et al. (LOPES collaboration). Trigger Strategy for Radio Detection in Atmospheric Air Showers with LOPESstar. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0923], 2007.

[6] G. A. Askaryan. *Soviet Phys. JETP*, 14:441, 1962.

[7] G. A. Askaryan. Coherent Radio Emission from Cosmic Showers in Air and in Dense Media. *Soviet Journal of Experimental and Theoretical Physics*, 21:658, 1965.

[8] Auger Collaboration. Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects. *Science*, 318:938, 2007.

[9] S. W. Barwick. ARIANNA: A New Concept for UHE Neutrino Detection. *ArXiv Astrophysics e-prints*, astro-ph/0610631, 2006.

[10] S.W. Barwick. ANITA: First Flight Overview and Detector Performance. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [1095], 2007.

[11] S.W. Barwick. ARIANNA: A New Concept for UHE Neutrino Detection. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [1163], 2007.

[12] A. R. Beresnyak. Expected properties of radio pulses from lunar EeV neutrino showers. *ArXiv Astrophysics e-prints*, astro-ph/0310295, 2003.

[13] A. R. Beresnyak, R. D. Dagkesamanskii, I. M. Zheleznykh, A. V. Kovalenko, and V. V. Oreshko. Limits on the Flux of Ultrahigh-Energy Neutrinos from Radio Astronomical Observations. *Astronomy Reports*, 49:127–133, 2005.

[14] P. M. S. Blackett and A. C. B. Lovell. Radio Echoes and Cosmic Ray Showers. *Royal Society of London Proceedings Series A*, 177:183–186, 1941.

[15] J. D. Bowman, D. G. Barnes, F. H. Briggs, B. E. Corey, M. J. Lynch, N. D. R. Bhat, R. J. Cappallo, S. S. Doeleman, B. J. Fanous, D. Herne, J. N. Hewitt, C. Johnston, J. C. Kasper, J. Kocz, E. Kratzenberg, C. J. Lonsdale, M. F. Morales, D. Oberoi, J. E. Salah, B. Stansby, J. Stevens, G. Torr, R. Wayth, R. L. Webster, and J. S. B. Wyithe. Field Deployment of Prototype Antenna Tiles for the Mileura Widefield Array Low Frequency Demonstrator. AJ, 133:1505–1518, 2007.

[16] S. Buitink, W. D. Apel, T. Asch, F. Badea, L. Böhren, K. Bekk, A. Bercuci, M. Bertaina, P. L. Biermann, J. Blümer, H. Bozdog,

I. M. Brancus, M. Brüggemann, P. Buchholz, H. Butcher, A. Chiavassa, F. Cossavella, K. Daumiller, F. di Pierro, P. Doll, R. Engel, H. Falcke, H. Gemmeke, P. L. Ghia, R. Glasstetter, C. Grupen, A. Haungs, D. Heck, J. R. Hörandel, A. Horneffer, T. Huege, K.-H. Kampert, Y. Kolotaev, O. Krömer, J. Kuijpers, S. Lafebre, H. J. Mathes, H. J. Mayer, C. Meurer, J. Milke, B. Mitrica, C. Morello, G. Navarra, S. Nehls, A. Nigl, R. Obenland, J. Oehlschläger, S. Ostapchenko, S. Over, M. Petcu, J. Petrovic, T. Pierog, S. Plewnia, H. Rebel, A. Risse, M. Roth, H. Schieler, O. Sima, K. Singh, M. Stümpert, G. Toma, G. C. Trinchero, H. Ulrich, J. van Buren, W. Walkowiak, A. Weindl, J. Wochele, J. Zabierowski, J. A. Zensus, and D. Zimmermann. Amplified radio emission from cosmic ray air showers in thunderstorms. A&A, 467:385–394, 2007.

[17] S. Buitink and et al. (LOPES collaboration). Radio emission of air showers in electric fields. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0902], 2007.

[18] R. Engel and et al. Simulation Cherenkov and Synchrotron Radio Emission in EAS. In *International Cosmic Ray Conference*, volume 6 of *International Cosmic Ray Conference*, page 9, 2005.

[19] H. Falcke, W. D. Apel, A. F. Badea, L. Bähren, K. Bekk, A. Bercuci, M. Bertaina, P. L. Biermann, J. Blümer, H. Bozdog, I. M. Brancus, S. Buitink, M. Brüggemann, P. Buchholz, H. Butcher, A. Chiavassa, K. Daumiller, A. G. de Bruyn, C. M. de Vos, F. di Pierro, P. Doll, R. Engel, H. Gemmeke, P. L. Ghia, R. Glasstetter, C. Grupen, A. Haungs, D. Heck, J. R. Hörandel, A. Horneffer, T. Huege, K.-H. Kampert, G. W. Kant, U. Klein, Y. Kolotaev, Y. Koopman, O. Krömer, J. Kuijpers, S. Lafebre, G. Maier, H. J. Mathes, H. J. Mayer, J. Milke, B. Mitrica, C. Morello, G. Navarra, S. Nehls, A. Nigl, R. Obenland, J. Oehlschläger, S. Ostapchenko, S. Over, H. J. Pepping, M. Petcu, J. Petrovic, S. Plewnia, H. Rebel, A. Risse, M. Roth, H. Schieler, G. Schoonderbeek, O. Sima, M. Stümpert, G. Toma, G. C. Trinchero, H. Ulrich, S. Valchierotti, J. van Buren, W. van Cappellen, W. Walkowiak, A. Weindl, S. Wijnholds, J. Wochele, J. Zabierowski, J. A. Zensus, and D. Zimmermann. Detection and imaging of atmospheric radio flashes from cosmic ray air showers. Nature, 435:313–316, 2005.

[20] H. Falcke and P. Gorham. Detecting radio emission from cosmic ray air showers and neutrinos with a digital radio telescope. *Astropart. Phys.*, 19:477–494, 2003.

[21] H. Falcke, P. Gorham, and R. J. Protheroe. Prospects for radio detection of ultra-high energy cosmic rays and neutrinos. *New Astronomy Review*, 48:1487–1510, 2004.

[22] H. D. Falcke, M. P. van Haarlem, A. G. de Bruyn, R. Braun, H. J. A. Röttgering, B. Stappers, W. H. W. M. Boland, H. R. Butcher, E. J. de Geus, L. V. Koopmans, R. P. Fender, H. J. M. E. Kuijpers, G. K. Miley, R. T. Schilizzi, C. Vogt, R. A. M. J. Wijers, M. W. Wise, W. N. Brouw, J. P. Hamaker, J. E. Noordam, T. Oosterloo, L. Bähren, M. A. Brentjens, S. J. Wijnholds, J. D. Bregman, W. A. van Cappellen, A. W. Gunst, G. W. Kant, J. Reitsma, K. van der Schaaf, and C. M. de Vos. A very brief description of LOFAR – the Low Frequency Array. *Highlights of Astronomy*, 14:386–387, 2007.

[23] P. W. Gorham. On the possibility of radar echo detection of ultra-high energy cosmic ray- and neutrino-induced extensive air showers. *Astroparticle Physics*, 15:177–202, 2001.

[24] P. W. Gorham, S. W. Barwick, J. J. Beatty, D. Z. Besson, W. R. Binns, C. Chen, P. Chen, J. M. Clem, A. Connolly, P. F. Dowkontt, M. A. Duvernois, R. C. Field, D. Goldstein, A. Goodhue, C. Hast, C. L. Hebert, S. Hoover, M. H. Israel, J. Kowalski, J. G. Learned, K. M. Liewer, J. T. Link, E. Lusczek, S. Matsuno, B. Mercurio, C. Miki, P. Miočinović, J. Nam, C. J. Naudet, J. Ng, R. Nichol, K. Palladino, K. Reil, A. Romero-Wolf, M. Rosen, L. Ruckman, D. Saltzberg, D. Seckel, G. S. Varner, D. Walz, and F. Wu. Observations of the Askaryan Effect in Ice. *Physical Review*

Letters, 99(17):171101, 2007.

[25] P. W. Gorham, C. L. Hebert, K. M. Liewer, C. J. Naudet, D. Saltzberg, and D. Williams. Experimental Limit on the Cosmic Diffuse Ultrahigh Energy Neutrino Flux. *Physical Review Letters*, 93(4):041101, 2004.

[26] K. Green, J. L. Rosner, D. A. Suprun, and J. F. Wilkerson. A prototype system for detecting the radio-frequency pulse associated with cosmic ray air showers. *Nuclear Instruments and Methods in Physics Research A*, 498:256–288, 2003.

[27] A. G. Gunn. Jodrell Bank and the pursuit of cosmic rays. In L. I. Gurvits, S. Frey, and S. Rawlings, editors, *EAS Publications Series*, volume 15 of *EAS Publications Series*, pages 15–26, 2005.

[28] A. V. Gurevich and K. P. Zybin. High energy cosmic ray particles and the most powerful discharges in thunderstorm atmosphere. *Physics Letters A*, 329:341–347, 2004.

[29] T. H. Hankins, R. D. Ekers, and J. D. O'Sullivan. A search for lunar radio Cerenkov emission from high-energy neutrinos. MNRAS, 283:1027–1030, 1996.

[30] A. Horneffer, T. Antoni, W. D. Apel, F. Badea, K. Bekk, A. Bercuci, M. Bertaina, H. Blümer, H. Bozdog, I. M. Brancus, M. Brüggemann, P. Buchholz, C. Büttner, A. Chiavassa, K. Daumiller, C. M. de Vos, P. Doll, R. Engel, J. Engler, H. Falcke, F. Fessler, P. L. Ghia, H. J. Gils, R. Glasstetter, A. Haungs, D. Heck, J. R. Hörandel, T. Huege, K.-H. Kampert, G. W. Kant, H. O. Klages, Y. Kolotaev, G. Maier, H. J. Mathes, H. J. Mayer, J. Milke, C. Morello, M. Müller, G. Navarra, R. Obenland, J. Oehlschläger, S. Ostapchenko, M. Petcu, S. Plewnia, H. Rebel, A. Risse, M. Roth, H. Schieler, J. Scholz, M. Stümpert, T. Thouw, G. C. Trinchero, H. Ulrich, S. Valchierotti, J. van Buren, W. Walkowiak, A. Weindl, J. Wochele, J. Zabierowski, and S. Zagromski. LOPES: detecting radio emission from cosmic ray air showers. In J. Hough and G. H. Sanders, editors, *Gravitational Wave and Particle Astrophysics Detectors. Edited by Hough, James; Sanders, Gary H. Proceedings of the SPIE, Volume 5500, pp. 129-138 (2004).*, volume 5500 of *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, pages 129–138, 2004.

[31] A. Horneffer and et al. (LOPES collaboration). Primary Particle Energy Calibration of the EAS Radio Pulse Height. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0119], 2007.

[32] T. Huege and H. Falcke. Radio emission from cosmic ray air showers. Coherent geosynchrotron radiation. A&A, 412:19–34, 2003.

[33] T. Huege and H. Falcke. Radio emission from cosmic ray air showers. Monte Carlo simulations. A&A, 430:779–798, 2005.

[34] T. Huege and H. Falcke. Radio emission from cosmic ray air showers: Simulation results and parametrization. *Astroparticle Physics*, 24:116–136, 2005.

[35] T. Huege, R. Ulrich, and R. Engel. Energy and composition sensitivity of geosynchrotron radio emission from EAS. *30th ICRC, Merida, Mexico, ArXiv e-prints*, astro-ph/0707.3761:[0889], 2007.

[36] T. Huege, R. Ulrich, and R. Engel. Monte Carlo simulations of geosynchrotron radio emission from CORSIKA-simulated air showers. *Astroparticle Physics*, 27:392–405, 2007.

[37] P.G. Isar and et al. (LOPES collaboration). Operation of LOPES-30 for Polarization Measurements of the Radio Emission of Cosmic Ray Air Showers. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0961], 2007.

[38] C. W. James, R. M. Crocker, R. D. Ekers, T. H. Hankins, J. D. O'Sullivan, and R. J. Protheroe. Limit on ultrahigh energy neutrino flux from the Parkes Lunar Radio Cherenkov experiment. MNRAS, 379:1037–1041, 2007.

[39] J. V. Jelley, J. H. Fruin, N. A. Porter, T. C. Weekes, F. G. Smith, and R. A. Porter. *Nature*, 205:327, 1965.

[40] S. Jester and H. Falcke. Science with a lunar low-frequency array: From the dark ages of the Universe to nearby exoplanets. *in prep.*, 2008.

[41] F. D. Kahn and I. Lerche. In *Proc. Roy. Soc.*, volume A-289, page 206, 1966.

[42] A. Karle, J. Ahrens, J. N. Bahcall, X. Bai, T. Becka, K.-H. Becker, D. Z. Besson, D. Berley, E. Bernardini, D. Bertrand, F. Binon, A. Biron, S. Böser, C. Bohm, O. Botner, O. Bouhali, T. Burgess, T. Castermans, D. Chirkin, J. Conrad, J. Cooley, D. F. Cowen, A. Davour, C. de Clercq, T. Deyoung, P. Desiati, J.-P. Dewulf, B. Dingus, R. Ellsworth, P. A. Evenson, A. R. Fazely, T. Feser, T. K. Gaisser, J. Gallagher, R. Ganugapati, A. Goldschmidt, J. Goodman, A. Hallgren, F. Halzen, K. Hanson, R. Hardtke, T. Hauschildt, M. Hellwig, P. Herquet, G. C. Hill, P. O. Hulth, K. Hultgvist, S. Hundertmark, J. Jacobsen, G. S. Japaridze, A. Karle, L. Köpke, M. Kowalski, J. I. Lamoureux, H. Leich, M. Leuthold, P. Lindahl, I. Liubarsky, J. Madson, P. Marciniewski, H. S. Matis, C. P. McParland, Y. Minaeva, P. Miočinović, R. Morse, R. Nahnhauer, T. Neunhöffer, P. Niessen, D. R. Nygren, H. Ogelman, P. Olbrechts, C. Pérez de Los Heros, A. C. Pohl, P. B. Price, G. T. Przybylski, K. Rawlins, E. Resconi, W. Rhode, M. Ribordy, S. Richter, H.-G. Sander, T. Schmidt, D. Schneider, D. Seckel, M. Solarz, L. Sparke, G. M. Spiczak, C. Spiering, T. Stanev, D. Steele, P. Steffen, R. G. Stokstad, P. Sudhoff, K.-H. Sulanke, G. W. Sullivan, T. Sumners, I. Taboada, L. Thollander, S. Tilav, C. Walck, C. Weinheimer, C. H. Wiebusch, C. Wiedemann, R. Wischnewski, H. Wissing, K. Woschnagg, and S. Yoshida. IceCube - the next generation neutrino telescope at the South Pole. *Nuclear Physics B Proceedings Supplements*, 118:388–395, 2003.

[43] A. Karle and et al. A radio air shower detector as an extension for IceCube and IceTop. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0293], 2007.

[44] N. E. Kassim, T. E. Clarke, A. S. Cohen, P. C. Crane, T. Gaussiran, C. Gross, P. A. Henning, B. C. Hicks, W. Junor, W. M. Lane, T. J. W. Lazio, N. Paravastu, Y. M. Pihlstrom, E. J. Polisensky, P. S. Ray, K. P. Stewart, G. B. Taylor, and K. W. Weiler. Exploring the Last Electromagnetic Frontier with the Long Wavelength Array (LWA). *Long Wavelength Astrophysics, 26th meeting of the IAU, Joint Discussion 12, 21 August 2006, Prague, Czech Republic, JD12, #56*, 12, 2006.

[45] H. O. Klages, W.-D. Apel, and K. Bekk. The KASCADE experiment. *Nuclear Physics B Proceedings Supplements*, 52:92–102, 1997.

[46] I. Kravchenko, C. Cooley, S. Hussain, D. Seckel, P. Wahrlich, J. Adams, S. Churchwell, P. Harris, S. Seunarine, A. Bean, D. Besson, S. Graham, S. Holt, D. Marfatia, D. McKay, J. Meyers, J. Ralston, R. Schiel, H. Swift, J. Ledford, and K. Ratzlaff. RICE limits on the diffuse ultrahigh energy neutrino flux. Phys. Rev. D, 73(8):082002, 2006.

[47] S. Lafebre, T. Huege, H. Falcke, and J. Kuijpers. The LOFAR Air Shower Front Evolution Library. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0181], 2007.

[48] N. G. Lehtinen, P. W. Gorham, A. R. Jacobson, and R. A. Roussel-Dupré. FORTE satellite constraints on ultrahigh energy cosmic particle fluxes. Phys. Rev. D, 69(1):013008, 2004.

[49] Q. Luo. Coherent synchrotron emission from cosmic ray air showers. MNRAS, 370:2071–2078, 2006.

[50] N. Meyer-Vernet, A. Lecacheux, and D. Ardouin. Radio pulses from cosmic ray air showers - Boosted Coulomb and Cherenkov fields. *ArXiv e-prints*, 712, 2007.

[51] R. Milincic, P. W. Gorham, P. Miocinovic, M. Rosen, D. Saltzberg, and G. Varner. The Status of Hawaii Askaryan Salt Radi Array (HASRA) experiment. *Journal of Physics Conference Series*, 81:2007, 2007.

[52] R. Nahnhauer and S. Böser, editors. *Acoustic and Radio EeV Neutrino Detection Activities*. World Scientific Publisher, 2006.

[53] G. Navarra, T. Antoni, W. D. Apel, F. Badea, K. Bekk, A. Bercuci, M. Bertaina, H. Blümer, H. Bozdog, I. M. Brancus, M. Brüggemann, P. Buchholz, C. Büttner, A. Chiavassa, P. Doll, R. Engel, J. Engler, F. Feßler, P. L. Ghia, H. J. Gils, R. Glasstetter, A. Haungs, D. Heck, J. R. Hörandel, A. Iwan, K.-H. Kampert, H. O. Klages, Y. Kolotaev, G. Maier, H. J. Mathes, H. J. Mayer, J. Milke,

C. Morello, M. Müller, R. Obenland, J. Oehlschläger, S. Ostapchenko, M. Petcu, S. Plewnia, H. Rebel, M. Roth, H. Schieler, J. Scholz, T. Thouw, G. C. Trinchero, H. Ulrich, S. Valchierotti, J. van Buren, W. Walkowiak, A. Weindl, J. Wochele, J. Zabierowski, and S. Zagromski. KASCADE-Grande: a large acceptance, high-resolution cosmic-ray detector up to 10^{18}eV. *Nuclear Instruments and Methods in Physics Research A*, 518:207–209, 2004.

[54] S. Nehls and et al. Amplitude calibration of a digital radio antenna array for measuring cosmic ray air showers. *Nucl. Instr. Methods A*, submitted, 2008.

[55] A. Nigl and et al. (LOPES Collaboration). Direction identification in radio images of cosmic-ray air showers detected with LOPES and KASCADE. A&A, submitted, 2008.

[56] A. Nigl and et al. (LOPES Collaboration). Frequency spectra of cosmic ray air shower radio emission measured with LOPES. A&A, submitted, 2008.

[57] O. Ravel, R. Dallier, L. Denis, T. Gousset, F. Haddad, P. Lautridou, A. Lecacheux, E. Morteau, C. Rosolen, and C. Roy. Radio detection of cosmic ray air showers by the CODALEMA experiment. *Nuclear Instruments and Methods in Physics Research A*, 518:213–215, 2004.

[58] H. J. A. Rottgering, R. Braun, P. D. Barthel, M. P. van Haarlem, G. K. Miley, R. Morganti, I. Snellen, H. Falcke, A. G. de Bruyn, R. B. Stappers, W. H. W. M. Boland, H. R. Butcher, E. J. de Geus, L. Koopmans, R. Fender, J. Kuijpers, R. T. Schilizzi, C. Vogt, R. A. M. J. Wijers, M. Wise, W. N. Brouw, J. P. Hamaker, J. E. Noordam, T. Oosterloo, L. Bahren, M. A. Brentjens, S. J. Wijnholds, J. D. Bregman, W. A. van Cappellen, A. W. Gunst, G. W. Kant, J. Reitsma, K. van der Schaaf, and C. M. de Vos. LOFAR - Opening up a new window on the Universe. *ArXiv Astrophysics e-prints*, astro-ph/0610596, 2006.

[59] D. Saltzberg and P. Gorham, editors. *Radio Detection of High Energy Particles*, volume 579 of *American Institute of Physics Conference Series*, 2001.

[60] D. Saltzberg, P. Gorham, D. Walz, C. Field, R. Iverson, A. Odian, G. Resch, P. Schoessow, and D. Williams. Observation of the Askaryan Effect: Coherent Microwave Cherenkov Emission from Charge Asymmetry in High-Energy Particle Cascades. *Physical Review Letters*, 86:2802–2805, 2001.

[61] O. Scholten, J. Bacelar, R. Braun, A. G. de Bruyn, H. Falcke, B. Stappers, and R. G. Strom. Optimal radio window for the detection of Ultra-High Energy cosmic rays and neutrinos off the moon. *Astroparticle Physics*, 26:219–229, 2006.

[62] O. Scholten and et al. (NuMoon collaboration). First results on UHE Neutrinos from the NuMoon experiment. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0063], 2007.

[63] O. Scholten, K. Werner, and F. Rusydi. A Macroscopic Description of Coherent Geo-Magnetic Radiation from Cosmic Ray Air Showers. *ArXiv e-prints*, 709:0709.2872, 2007.

[64] G. Swarup, S. Ananthakrishnan, V. K. Kapahi, A. P. Rao, C. R. Subrahmanya, and V. K. Kulkarni. The Giant Metre-Wave Radio Telescope. *CURRENT SCIENCE V.60, NO.2/JAN25, P. 95, 1991*, 60:95, 1991.

[65] A. van den Berg, et al., and (Auger collaboration). Radio detection of high-energy cosmic rays at the Pierre Auger Observatory. In *30th ICRC, Merida, Mexico*, International Cosmic Ray Conference, page [0176], 2007.

[66] A. A. Watson. Highlights from the Pierre Auger Obseervatory - the birth of the hybrid era. *ArXiv e-prints*, 0801.2321, 2008.

[67] T. C. Weekes. Radio Pulses from Cosmic Ray Air Showers. In D. Saltzberg and P. Gorham, editors, *Radio Detection of High Energy Particles*, volume 579 of *American Institute of Physics Conference Series*, page 3, 2001.

[68] K. Werner and O. Scholten. Macroscopic Treatment of Radio Emission from Cosmic Ray Air Showers based on Shower Simulations. *ArXiv e-prints*, 712:0712.2517, 2007.

[69] E. Zas, F. Halzen, and T. Stanev. Electromagnetic pulses from high-energy showers: Implications for neutrino detection. *Phys. Rev. D*, 45:362–376, 1992.