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Measuring the cosmic ray mass composition with LOFAR

S. Buitink[*1], **A. Corstanje**[2], **J.E. Enriquez**[2], **H. Falcke**[2,3,4], **J.R. Hörandel**[2,3], **T. Huege**[5], **A. Nelles**[2,6], **J.P. Rachen**[2], **L. Rossetto**[2], **P. Schellart**[2], **O. Scholten**[7,8], **S. ter Veen**[2,4], **S. Thoudam**[2], **T.N.G. Trinh**[7]

1 *Astrophysical Institute, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium*
2 *Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
3 *NIKHEF, Science Park Amsterdam, 1098 XG Amsterdam, The Netherlands*
4 *Netherlands Institute of Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands*
5 *IKP, Karlsruhe Institute of Technology (KIT), Postfach 3640, 76021 Karlsruhe, Germany*
6 *Now at: Department of Physics and Astronomy, University of California Irvine, Irvine, CA 92697-4575, USA*
7 *KVI-CART, University Groningen, P.O. Box 72, 9700 AB Groningen, The Netherlands*
8 *Interuniversity Institute for High-Energy, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium*
E-mail: Stijn.Buitink@vub.ac.be

The LOFAR radio telescope measures the radio emission from air showers with unprecedented precision. In the dense core individual air showers are detected by hundreds of dipole antennas. The complicated radio pattern on the ground is accurately reproduced by modern radio simulation codes and contains information about the longitudinal shower development. With a hybrid reconstruction technique, we measure the depth of the shower maximum with an accuracy of less than 20 g/cm^2. We will present the latest LOFAR results of cosmic-ray mass analysis in the energy regime of 10^{17} eV to 10^{18} eV. This range is of particular interest as it may harbor the transition from a Galactic to an extragalactic origin of cosmic rays.

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[*] Speaker.

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1. Radio measurements of Xmax with LOFAR

Radio detection of air showers [1, 2] offers a new way to measure the atmospheric depth of the shower maximum, $X_{\max}$, a mass-sensitive parameter [3]. The radio emission is generated by the motion of electrons and positrons in the geomagnetic field [4, 5, 6], and the accumulation of a negative charge excess in the shower front [7, 8]. The radio intensity pattern observed on the ground depends crucially on the shower development. At LOPES, it was shown that the rate with which the pulse amplitude decreases with distance to the shower axis provides a measurement of the geometrical distance to the shower maximum [9]. However, the intensity profile is in fact not rotationally symmetrical and a better $X_{\max}$ resolution can be obtained by fitting two-dimensional profiles to the measured power, provided that the radio footprint is sampled densely enough [3]. The extremely large antenna densities of phased arrays, like LOFAR [10] and the future SKA [11], are therefore excellent sites for cosmic-ray mass measurements.

We have developed a reconstruction technique for LOFAR that yields a resolution on $X_{\max}$ of ~ 20 g/cm^2 [3], i.e. the same resolution of fluorescence detection at the Pierre Auger Observatory [12] and the Telescope Array [13]. At LOFAR, individual air showers are detected by hundreds of antennas simultaneously. The data is fitted to two-dimensional profiles of the radio intensity produced with CORSIKA [14] and the CoREAS radio plug-in [15]. For each detected shower, a dedicated set of simulations is produced of 50 proton showers and 25 iron showers. When all simulations are fitted to the data, the quality-of-fit as a function of simulated $X_{\max}$ is a curve with a sharp minimum at the reconstructed $X_{\max}$ value. The technique is described in Buitink et al. (2014) [3] and elsewhere in these proceedings [16]. Here, we describe the procedure of event selection for a mass composition study in the energy range 10^{17}-$10^{17.5}$ eV.

2. Event selection

Air shower observations at LOFAR always run in the background during astronomical observations. However, not all antennas can take data simultaneously. Which antennas are active depends on the settings of the main observation. In particular this means that a large part of the cosmic-ray data is taken with high band antennas (HBAs; 110-190 MHz). In this frequency range, the radio intensity pattern on the ground has the shape of a ring, due to Cherenkov-like propagation effects in the atmosphere. It has been shown that these patterns can be successfully fitted to simulations, and they can possibly be used for $X_{\max}$ measurements [17]. However, a problem arises due to the nature of the HBAs. One HBA tile is essentially a phased array of 16 small antennas, forming a beam in the direction of the astronomical source that is being observed. In general, the direction of the beam will not coincide with the arrival direction of the air shower. Therefore, the pulses are distorted, which makes the relative calibration between HBA stations extremely unstable.

For this analysis we use only low band antenna (LBA; 30-80 MHz) data. This is one of the reasons why LOFAR does not reach the near 100% duty cycle, that the technique of radio detection in principle has. Other reasons are dead time between observation runs and during maintenance of either the LOFAR antennas or the LORA particle detector array, that is used for triggering.

The radio emission mechanism can be influenced by atmospheric electric fields during thunderstorms, when strong fields exist over a large range [18]. These events are removed from the analysis in two ways. First, whenever lightning strikes have been reported by the Dutch Meteorological Institute near LOFAR, showers within a two hour window are removed from the sample. However, it is possible that strong fields are present even in the absence of lightning strikes. Fortunately, the polarisation of the radio pulse is very sensitive to the nature of the emission process. It can for example be used to measure the relative contributions of geomagnetic and charge excess radiation [19, 20]. Likewise, it can indicate an additional contribution due to electric fields. When the measured polarisation angles are significantly distorted, the shower is also removed from the sample. Note however, that these *thunderstorm events* are very interesting in their own right, as they can be used to infer characteristics of the electric fields in thunderstorms [21].

Air shower observations are triggered by the LOFAR Radboud Array (LORA) [22], a particle array that comprises twenty scintillator detectors. When sixteen detectors have a signal above threshold the buffers at all active antennas are read out and stored for offline analysis [23]. LOFAR antennas are arranged in dense groups of antennas, or *stations*. In the present analysis, we select all showers that were detected in at least four stations, in order to sample a large part of the radio footprint. Because in each station there are 48 antennas actively taking data, all showers are detected by at least 196 antennas.

This selection criterium and the trigger conditions introduce a mass bias. The size of the radio footprint becomes larger for showers that are further away, i.e. have a smaller $X_{\max}$. This increases the chance that a signal is detected by four antenna stations, which causes a bias towards heavy primary cosmic rays. On the other hand, deep showers have a larger particle density at ground level ($\approx$ sea level), and have a larger chance to produce a trigger. This means that there is a bias towards light primaries, especially for low energies and high zenith angles.

A common way to correct such biases is to investigate the parameter space in which a (near) 100% efficiency is reached. Typically this leads to cuts on energy, core position, and zenith angle. For LOFAR this approach is very impractical. Firstly, the strength of the radio signal depends on the angle of the shower axis with the geomagnetic field, which is a function of both zenith and azimuth angle. Secondly, the antenna array is highly irregular, so for each position there is a unique combination of energy and sky coverage for which full efficiency is reached. Constructing cuts that are not overly conservative requires an unfeasible amount of simulation.

Instead, we take the inverse approach and check if 100% efficiency is reached *given* the energy, core position, and arrival direction of each observed air shower. This can be easily done, because a dedicated set of CORSIKA simulations is generated for each shower anyway, since it is needed for the reconstruction.

For each observed shower we generate 50 proton and 25 iron showers, using CORSIKA 7.400, with hadronic interaction models FLUKA 2011.2b [24] and QGSJETII.04 [25]. Thinning is applied at a level of 10^{-6} with optimised weight limitation [26]. The response of the LORA detectors is simulated with GEANT4 [27].

We require that *all* simulated showers in the set pass the LORA trigger condition, and produce a detectable radio signal in at least four antenna stations.

3. Energy reconstruction

Below 10^{17} eV many showers are discarded due to the anti-bias cut, mainly because of the

LORA trigger. Above that energy, only $\sim 5\%$ of the showers are discarded. In this analysis, we limit ourselves to showers with an energy exceeding 10^{17} eV.

The energy reconstruction is based on the particle data from the LORA detectors. In the event reconstruction the radio and particle data are fitted simultaneously to the data, by minimizing:

$$\chi^2 = \sum_{\text{antennas}} \left(\frac{P_{\text{ant}} - f_r^2 P_{\text{sim}}(x_{\text{ant}} - x_0, y_{\text{ant}} - y_0)}{\sigma_{\text{ant}}} \right)^2 + \sum_{\substack{\text{particle}\\ \text{detectors}}} \left(\frac{d_{\text{det}} - f_p d_{\text{sim}}(x_{\text{det}} - x_0, y_{\text{det}} - y_0)}{\sigma_{\text{det}}} \right)^2, \tag{3.1}$$

where P_{ant} is the measured power integrated over a 55 ns window at an antenna at location $(x_{\text{ant}}, y_{\text{ant}})$ with noise level σ_{ant}, P_{sim} is the simulated power, d_{det} is the deposited energy as measured by a LORA detector at location $(x_{\text{det}}, y_{\text{det}})$ with noise σ_{det}, and d_{sim} is the simulated deposited energy. The fit contains four free parameters, two of which describe the location of the shower axis (x_0, y_0). A scaling parameter f_p for the particle lateral distribution function is needed to correct the energy scale, while a scaling parameter for the radio power f_r^2 is needed because the antennas do not yet have an absolute calibration. When f_p deviates from unity, the reconstructed energy is different than the simulated energy. When the deviation is large, a new set of simulation is produced at the reconstructed energy. The procedure is repeated until the energy is consistent within uncertainties.

The left panel in Fig. 1 shows the distribution of $\log_{10}(f_r/f_p)$ for 118 observed showers. The values are arbitrary because the lack of absolute calibration in this analysis. The distribution can be used to derive the energy resolution by fitting a Gaussian, yielding 32%.

The energy cut at 10^{17} eV potentially introduces a new bias in composition. This is often the case for reconstructions based on only particle data, because X_{max} is unknown. In our hybrid fit of radio and particle data, we essentially fit X_{max} and energy simultaneously, and therefore this method is much less prone to such a bias.

The right panel of Fig. 1 shows a Monte Carlo study on systematic offsets in the energy reconstruction of proton and iron showers. For both types of showers a distribution is plotted of the ration between the real and reconstructed energy. The energy offset between proton and iron is of the order of $\sim 1\%$, much less than the energy resolution. Hence, the energy cut does not introduce a bias.

4. Quality cut

Events on the border of the array are harder to reconstruct. For detector arrays with a regular grid it is easy to define the border and to implement a quality cut by requiring that the core is contained. However, for LOFAR it is not possible to make a clear definition of *containment*, because of the irregular placement of the antenna stations. A truly contained event would have antennas in each direction from the core, or *full azimuthal coverage*. Typically, radio reconstructions are of high quality even for fractional azimuthal coverage. This is a direct consequence of the asymmetry in the intensity profile and the two-dimensional fitting approach. However, when the azimuthal coverage becomes to small the quality degrades. In particular, the core position and X_{max} become degenerate.

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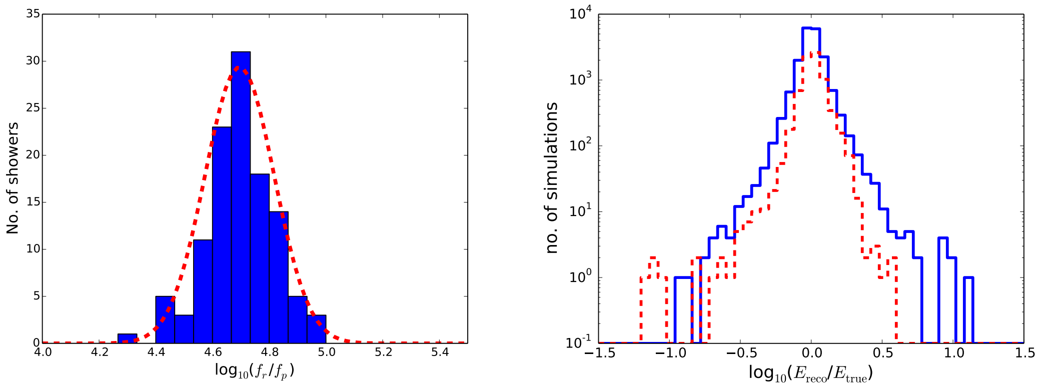

Figure 1: Left: The distribution of f_r/f_p for a set of 118 showers. It is fitted with a Gaussian with $\sigma = 0.12$, corresponding to a 32% energy resolution. Right: Monte Carlo study of the ratio between true and reconstructed energy for proton and iron showers. The two types of showers have a systematic offset of the order of $\sim 1\%$.

We use the dedicated sets of simulations to assess the reconstruction quality. One simulated shower is isolated and used to produce a 'fake' data set by adding noise at the same level of the observed shower. This fake data set is then reconstructed using the 74 remaining showers. The reconstructed core position, energy and $X_{\rm max}$ can now be compared to the real values. This procedure is repeated three times (with different random noise) for all showers, yielding a total of 225 reconstructions, from which the uncertainty on the core position, energy, and $X_{\rm max}$ are determined.

These uncertainties are highly correlated as can be seen in Fig. 2. When the core uncertainty is smaller than 5 m, the energy uncertainty is below 30%, and the resolution on $X_{\rm max}$ is below $\sim$20 g/cm^2 for all but a few showers. Because of the correlation, there is only need for a single cut on core position.

Showers with a core uncertainty exceeding 5 m are excluded from the sample. This cut is based entirely on the set of simulations and not on the data itself. It therefore does not introduce a new bias on composition.

5. Conclusion

We have described a procedure to obtain a bias-free sample of high quality air shower measurements with LOFAR. Between June 2011 and January 2015 there have been approximately 150 days of effective uptime. The total event sample after all cuts described above counts 118. Although the number of showers is low, the high precision on $X_{\rm max}$ per shower still allows competitive mass measurements in the $10^{17} - 10^{17.5}$ eV energy range. This range is of particular interest as it may harbor the transition from a Galactic to an extragalactic origin of cosmic rays.

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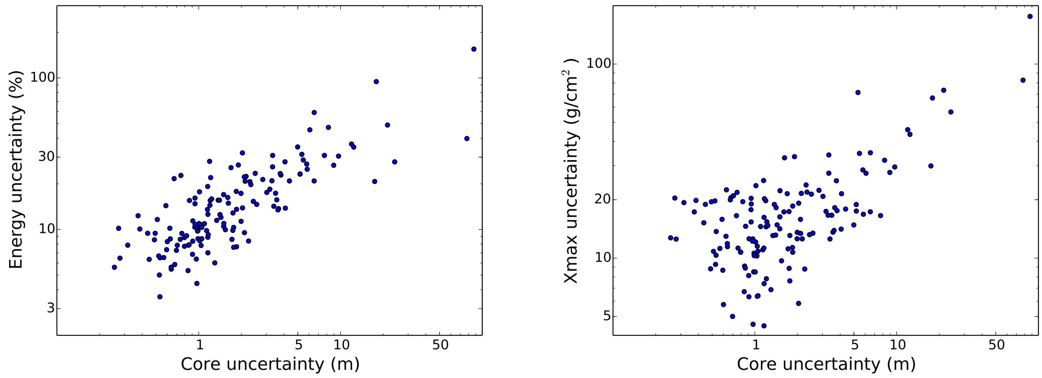

Figure 2: Correlation between uncertainties on core position, energy and $X_{\max}$. The uncertainties are calculated using the dedicated simulation sets. The sets used were generated for 290 observed showers with an energy above 10^{17} eV.

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LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope foundation under a joint scientific policy.

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