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Cosmic Ray Physics with the LOFAR Radio Telescope

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Abstract. The LOFAR radio telescope is able to measure the radio emission from cosmic ray induced air showers with hundreds of individual antennas. This allows for precision testing of the emission mechanisms for the radio signal as well as determination of the depth of shower maximum $X_{\text{max}}$, the shower observable most sensitive to the mass of the primary cosmic ray, to better than 20 g cm$^{-2}$. With a densely instrumented circular area of roughly 320 m$^2$, LOFAR is targeting for cosmic ray astrophysics in the energy range $10^{16}$–$10^{18}$ eV. In this contribution we give an overview of the status, recent results, and future plans of cosmic ray detection with the LOFAR radio telescope.

1. Introduction
The detection of cosmic rays via the radio technique has matured from application in single engineering projects only to usage on large scales [1]. All major experiments in the field nowadays use this technique at least complementary with more traditional methods as surface detector arrays or fluorescence telescopes. The radio technique allows for precision measurements of the depth of shower maximum $X_{\text{max}}$ and the energy deposit in the atmosphere. Observation of cosmic rays with radio telescopes such as the Low Frequency Array (LOFAR) [2] and potentially also the future Square Kilometer Array (SKA) [3] provide observations of individual cosmic ray air showers with a high number of antennas, enabling testing details of the radio emission mechanism and shower development. High precision measurements of the cosmic ray mass composition in the energy range below the ankle may be important to understand the expected transition between galactic and extra-galactic cosmic rays [4].
LOFAR is the first digital radio telescope with more than 50 stations distributed throughout Europe. Twenty-four of these stations are located in a dense core in the Netherlands. Five of the core stations are located within a circle of 320 m radius, the so called ‘superterp’. Each core stations consists of 96 ‘low-band antennas’ (LBA) operating from 10–90 MHz and 768 high-band antennas (HBA) operating from 110–240 MHz. Both antennas are omnidirectional V-shaped dipoles, but HBA are analog beamformed for astronomical observations which diminish their usability for cosmic ray physics. In the following we will thus discuss LBA only.

2. Cosmic Ray Detection With LOFAR

Cosmic ray detection with LOFAR currently relies on detecting the particle cascade with an array of twenty scintillators, the LOfar Radboud air shower Array (LORA) [5]. These scintillators are arranged in groups of four around the stations on the superterp. If thirteen out of the twenty stations simultaneously detect particles, indicating a high energy shower, 2 ms out of 5 s of buffered antenna data are read out for further offline analysis.

The properties of the primary cosmic-rays are reconstructed by the comparison of the data with dedicated simulations using the CORSIKA [6] and CoREAS [7] software packages. This yields a higher resolution on $X_{\text{max}}$ then using parametrizations of the radio profile in ground plane [8] and simplifies the evaluation of the detection efficiency for the given shower parameters.

An example of a detected event and the reconstruction is shown in Figure 1. The left plot shows an example of a recorded event together with the best fitting simulated shower. The plot on the right the reduced chi-square as measure of the goodness of fit for all simulated showers. The $X_{\text{max}}$ of the individual shower is obtained from a fit of a parabola to the simulated values.

With this procedure, LOFAR measures the cosmic ray mass composition in the energy range $10^{17} - 10^{17.5}$ eV. The reconstruction achieves an energy resolution of 32 % and a statistical uncertainty of 16 g cm$^{-2}$ on $X_{\text{max}}$. The total systematic uncertainty on the energy calibration.
Figure 2. Variation of the refractive index along the shower profile for 100 different cosmic ray events observed with LOFAR.

is 27% and on the depth of shower maximum $+14_{-10} \, \text{g cm}^{-2}$. Improvements of the accuracy of the mass-composition data in the energy range covered by LOFAR may be vital to discriminate between models for the origin of galactic and extragalactic cosmic rays.

3. Improvement of Systematic Uncertainties

3.1. Atmospheric Corrections

The observed intensity distribution of the radio signal depends on the difference in propagation time of particles and radio waves, and therefore on the refractivity profile of the atmosphere at the time of the event. The refractivity of the atmosphere depends on the density and humidity and is thus expected to vary also on short time scales [9]. In Figure 2 the difference of the refractive index at the time of 100 individual cosmic ray events to the US standard atmosphere [10] is shown. At an altitude of 5-8 km where the shower maximum is located, and thus the bulk of radiation is emitted, the variation is of 3-5%. This corresponds to an uncertainty in the inferred $X_{\text{max}}$ of $3.5-11 \, \text{g cm}^{-2}$ [9].

So far in LOFAR and, to our knowledge, also in all other cosmic ray experiments, standardized average atmospheric models have been used for the interpretation of all showers. To account for the variation of the index of refraction, we started to use refractivity profiles obtained from atmospheric data of the Global Data Assimilation Project (GDAS) [11] in our simulations. For this, we contributed a modification to the CORSIKA simulation software to consistently use arbitrary atmospheric profiles in the simulation of the particle cascade and radio signals. The modification is included in CORSIKA version 7.6300 and following. For this purpose we fit the five layer atmospheric model to the available data for the location of the observatory and calculate the resulting index of refraction. The fit parameters describing the atmosphere layers, respectively the tabulated index of refraction as a function of height, is then fed into the particle and radio simulation. We developed a corresponding software gldastool that manages data download, fit, and steering file generation. This tool is also distributed alongside the CORSIKA source code [12].
Figure 3. Antenna calibration factor as function of the frequency for galaxy calibration and reference source. (left) Without detailed model of the LOFAR signal chain and (right) with detailed model of the LOFAR signal chain.

3.2. Antenna Calibration
To reconstruct amplitude and spectral shape of radio signals an accurate calibration of the receiving system is imperative. However, at meter wavelength achieving the accuracy in calibration necessary for cosmic ray physics with antenna systems is challenging. No anechoic chambers are easily accessible that can contain the antennas to be calibrated as well as the reference sources in the far field region. Therefore even acquiring reference sources for in-situ calibrations that are well defined in the desired frequency range is difficult. Alternatively to artificial reference sources, the ubiquitous galactic background can be used as reference. Compared to artificial sources the signal emitted by the galaxy is well understood in amplitude and shape. However, the galaxy is not a point source so that calibrations using the galaxy have to be based on a model for the directivity of the antenna.

So far we used a calibration obtained from an in-situ measurement with a reference source optimized for frequencies higher than our observation band. The calibration with a reference source is consistent with a calibration using the galaxy [13]. However, by modelling of the noise contributions of the individual components of the signal processing chain we reduced the uncertainty of the galaxy calibration to a value lower than the uncertainty in calibration using the reference sources. The calibration constants obtained with and without detailed modelling of the full signal chain methods are displayed in Figure 3. In particular in the frequency range between 60–80 MHz the uncertainty on the galaxy calibration is now smaller than the systematic uncertainty arising from two different calibrations of the reference source provided by the manufacturer. This reduces a frequency dependent bias of the measurement of the slope of the spectral shape of the signal as shown in 4. This also enables detailed analysis of the frequency spectrum of the observed events that may be used as an additional observable sensitive to $X_{\text{max}}$ [14].

4. Future Extensions
Several extensions are currently planned, respectively already under construction, that will increase the amount of data and extend the energy range for astrophysics analysis with LOFAR.

4.1. LORA Expansion
In April 2018 we installed infrastructure for twenty more particle detectors at five LOFAR stations close to the superterp. Installation of the detectors and electronics is expected to be finished
within 2018. These additional detectors will increase the effective area for cosmic ray detection by approximately 40% and enable the development of new trigger modes for specific classes of events. Of particular interest are showers whose Cherenkov cone is located outside the superterp. While the radio signal is greatly diminished in this geometry, it may be possible to retrieve more information on the longitudinal shower development, thus improving composition measurements and eventually constraining hadronic interaction models.

4.2. Advanced Trigger

The trigger rate for cosmic ray detection is limited to approximately one trigger per hour to not disturb astronomical observations of the LOFAR telescope. This is achieved by requiring a signal over threshold in 13 out of 20 LORA particle detectors. This yields virtually 100% detection efficiency for showers above an energy of 0.1 EeV, thereby defining the lower energy threshold for the data usable for composition studies. However, as a consequence of these trigger conditions most of the recorded showers are of lower energies and approximately 80% do not even contain an observable radio pulse.

Reduction of the energy threshold for bias-free composition measurements while keeping the trigger rate constant requires to focus on showers with a detectable radio signal only. This is possible with a hybrid trigger that requires a strong signal in the antennas in coincidence with a signal in the particle array. Such an hybrid trigger will be implemented using a monitoring channel implemented in the LOFAR system that records the voltage levels in the antennas and can be used to send information to the LORA system.

Still, the current setup in LOFAR and all other radio experiments outside Antarctica requires particle detectors to trigger on cosmic ray air showers. Triggering on radio data only would instead allow for a very cost-effective increase of the instrumented area. Therefore we are developing a self-trigger aiming for a high reduction of RFI [15].

4.3. LOFAR 2.0

In the current configuration, LOFAR observations cannot overlap and data of HBA and LBA cannot be recorded at the same time. As currently roughly 50% of the observations use HBA, and also data in-between observations cannot be processed, the available time for cosmic ray observations is limited. LOFAR 2.0 is a planned extension of the technical capabilities of LOFAR
allowing in particular for simultaneous observations with high-band and low-band antennas and also to perform multiple observations independently in parallel. This extension can thus significantly increase the available cosmic-ray data.

5. Conclusion
Precise measurements of the mass composition of cosmic rays are important to understand their origin and propagation. LOFAR continues to measure the cosmic ray mass composition with high precision in the expected transition region between cosmic rays of galactic and extragalactic origin. Several improvements of the analysis chain are being implemented that will allow for the reduction of the systematic uncertainties on composition and energy measurement. Additional upgrades are currently planned, respectively are already under construction, that will increase the duty cycle of LOFAR for cosmic ray measurements and reduce the energy threshold for mass composition analysis.

Acknowledgements
The LOFAR cosmic ray key science project acknowledges funding from an Advanced Grant of the European Research Council (FP/2007-2013) / ERC Grant Agreement n. 227610. The project has also received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 640130). We furthermore acknowledge financial support from FOM, (FOM-project 12PR3041-3) and NWO (Top Grant 614-001-454, and Spinoza Prize SPI 78-409). TW is supported by DFG grant WI 4946/1-1. 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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