PROCEEDINGS OF SCIENCE

Cosmic rays with LOFAR 2.0 - what's next?

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The LOFAR radio telescope has been used to measure radio emission from cosmic-ray air showers in the $10^{16.5}-10^{18}$ eV range for over a decade. LOFAR is currently undergoing an upgrade (LOFAR 2.0) which will enable continuous observation and a tenfold increase in data rate, as well as a wider measurement bandwidth. We have recently doubled the size of the particle detector triggering array located at LOFAR to maximize the benefits of this upgrade. We are also developing new analysis techniques and data pipelines in order to best utilize the new influx of data and increase the energy range in which we measure. In this contribution, we present our plans for the LOFAR 2.0 cosmic-ray observation program.

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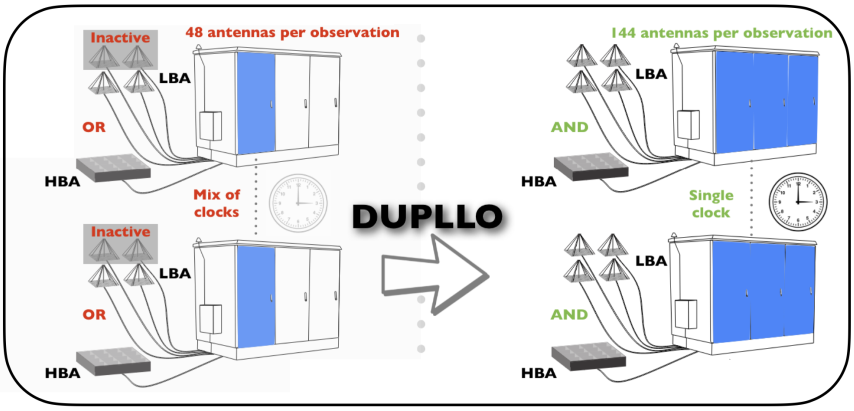


Figure 1: Schematic of the LOFAR 2.0 upgrades, taken from the LOFAR 2.0 white paper [9]. Most important for cosmic-ray observations is the option to observe with unbeamformed HBA antennas and to have multiple antenna sets available for each observation.

1. Introduction

LOFAR (Low Frequency Array) is currently the world's largest radio telescope, with antenna stations distributed across northern Europe and a dense core of 24 stations in the Netherlands [1]. Each station consists of two sets of 48 dual-polarized Low Band Antennas (LBAs) operating in the 30 – 80 MHz band and High Band Antennas (HBAs), operating between 120 – 240 MHz. Although LOFAR serves primarily as a telescope for radio astronomy, it is also an ideal instrument for measuring the radio emission generated in cosmic-ray air showers, which is predominantly generated by the geomagnetically induced, time-varying transverse current that develops as the shower propagates through the atmosphere [2]. The dense antenna spacing in LOFAR's core makes it unique among radio detection experiments, and the detailed LOFAR measurements helped established the technique of detecting air showers via radio emission [3–7]. LOFAR detects cosmic rays in the $10^{16.5}$ – 10^{18} eV energy range, which is scientifically interesting because it is the region where the origin of cosmic rays is expected to shift from galactic to extragalactic sources.

The LOFAR telescope is currently undergoing a significant upgrade, "LOFAR 2.0". Although designed primarily for astronomical observations, the upgrade will also be highly beneficial for cosmic-ray measurements. Changes to the hardware and software will allow for continuous observations and provide a tenfold increase in data rate, as well as a wider frequency bandwidth in which to measure. To maximize the benefits of this upgrade, we have recently doubled the size of the particle detector triggering array located at LOFAR [8]. We are also developing new analysis techniques and data pipelines in order to best utilize the new influx of data and increase the energy range in which we measure. In this contribution, we present our plans for the LOFAR 2.0 cosmic-ray observation program.

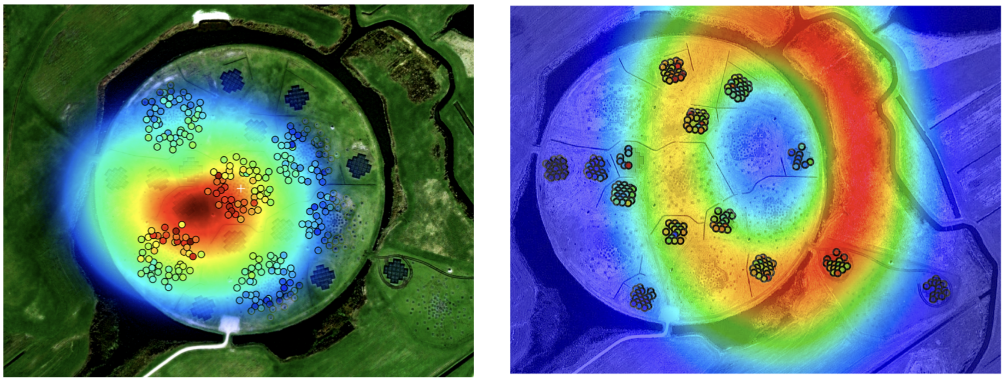


Figure 2: Simulated radio footprints from cosmic-ray air showers in the LBA band (30 – 80 MHz, left), and LBA band (120 – 240 MHz, right). The locations of each antenna set are also shown.

2. LOFAR 2.0

To give context to the importance of LOFAR 2.0 upgrades, we briefly discuss the curent cosmic-ray observation strategy. Cosmic-ray detection at LOFAR happens in the background of regular, scheduled observations. Antennas continuously buffer radio data, and when a cosmic-ray is detected (triggered by an in-situ particle detector "LORA"), the buffers are frozen and data read out. As long as data readout is rare (about one event per hour) this process happens without interrupting ongoing observations. Because cosmic-ray observations run in parallel with ongoing astronomical observations, we don't control which antenna set is used (LBA or HBA). In this section, we describe how the LOFAR 2.0 upgrades impact cosmic-ray observations. Figure 1 shows the most important upgrades for our science.

Observations with HBAs: Cosmic rays contain a wealth of information in the frequency range above 100 MHz, however, until now we have primarily observed in the LBA (30 – 80 MHz) range at LOFAR. This was due to the fact that all accessible HBA data were beamformed on the sky in the direction of the ongoing observation. (This is not the case for the LBAs, which are buffered at the raw voltage level.) This meant that it was rare to find a cosmic-ray in an advantageous place in the beam. With LOFAR 2.0, we have the option to observe with unbeamformed HBA antennas, giving us access to the 120 – 240 MHz band during each observation. Simulations of the radio footprint observed with LBAs and HBAs is shown in figure 2.

Simultaneous observation with LBAs and HBAs: In standard LOFAR observations, a single antenna set (LBA or HBA) is used, determined by the science requirements of the ongoing observation. HBA observations were the most common in recent years. Due to the fact that HBA data was generally not usable for us, we suffered a lot of downtime during these observations. In LOFAR 2.0, it will be possible to simultaneously measure with LBAs and HBAs, increasing both our bandwidth and uptime considerably. Furthermore, this will provide us with a known observing time, which will make it possible to determine the observed cosmic-ray flux.

Network speed: We currently tune our cosmic-ray trigger so that we record data from an event about once per hour. This data rate is limited so that we do not strain the LOFAR network by downloading large amounts of data during ongoing observations. We expect that improvements to the network will allow for more event readout, allowing us to trigger more frequently.

These improvements together will increase the number of usable events we observe by about a factor of ten, and give us more information (bandwidth and fluence) per event. This in turn increases the energy range in which we can measure, and gives us a high quality event catalogue we can use for different analyses.

3. Preparation for LOFAR 2.0

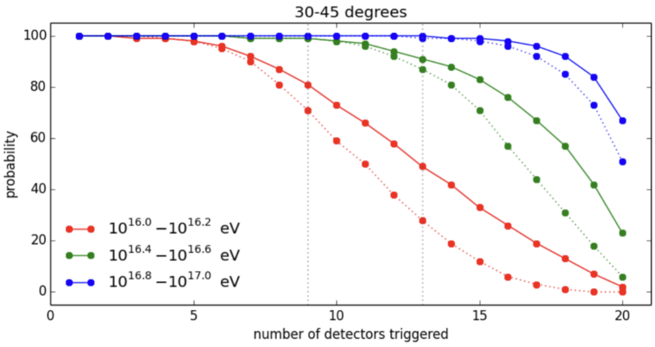
While the observatory has been implementing LOFAR 2.0, the cosmic-ray group has been making improvements to multiple areas of its observation program to make the most of the LOFAR 2.0 upgrades.

3.1 Triggering strategies

As noted above, we currently form a trigger for radio-data readout based on a coincident signal in multiple detectors of a particle detector array. We set our trigger requirements (minimum number of particle detectors with a signal) such that we don't overwhelm the system reading out data. This provides a consistent and noise-free cosmic-ray trigger. However, there are biases introduced with this strategy, primarily due to different primaries which produce different particle footprints on the ground. Light primaries interact deeper in the atmosphere, yielding more secondaries at ground level and therefore increasing the chance that they produce a trigger. In practice, this reduces our ability to use low-energy events in analyses, as these events are most affected by biases. This bias could be reduced by relaxing the trigger requirement, but then our event rate would grow too large for the system to handle. Our main goal in developing new trigger strategies is to reduce these biases while maintaining a suitable event rate, thereby increasing our energy range and overall number of usable events.

Expanded triggering array: In 2019, we doubled the size of the triggering particle detector array at LOFAR (see figure 3, right) [8]. This improvement offers more flexibility in triggering, allows us to trigger on higher quality events, and expands our energy range. With a larger footprint, the expanded array offers the chance to trigger on higher energy events. Having more particle detectors in the array also reduces triggering biases in particle type, allowing us to utilise events at lower energies in our analyses. This is due to the fact that both heavy and light primaries produce triggers more consistently.

Hybrid trigger: We have also been pursuing a hybrid trigger approach. To reiterate, much of the bias introduced in triggering comes from the fact that we require a minimum number of detectors to record an event, and this number is kept relatively high to throttle the trigger rate. This can be seen in the left panel of figure 3, which shows the probability of forming a trigger as a function of different number of detectors required to see a signal. It is clear that lighter primaries are more likely to trigger, and that this effect increases at lower energies. With a hybrid trigger, we would require a smaller number of particle detectors to record an event, but also monitor the radio data



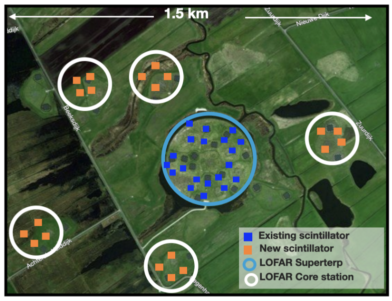


Figure 3: Left: Probability of triggering on a proton (solid line) or iron (dashed line) initiated cosmic ray, as a function of minimum number of detectors required for a trigger. This plot indicates that a bias is introduce, especially for lower energy events. This can be mitigated by reducing the number of detectors required for a trigger. Right: Map of the expansion of the triggering array [8].

stream in real time to identify a radio signal. This strategy would greatly reduce trigger biases, while still keeping the trigger rate manageable, as only higher energy showers would contain a visible radio signal required for a trigger. Being in an inhabited area, we aim to use an FIR filter to remove RFI lines from the real-time stream of radio data to make the approach feasible. This strategy has been simulated using raw LOFAR data and we intend to implement it in LOFAR 2.0.

3.2 Software development

We have migrated to using the NuRadioReco software framework for the LOFAR cosmic-ray data analysis pipeline [10]. This modular software is widely used in the field, and contains state-of-the-art radio analysis tools. This move will allow us to more easily maintain our pipelines and check our analysis techniques for consistency with other experiments. As an example, an ongoing analysis uses the NuRadioReco module for reconstructing air shower development using interferometric techniques [11, 12]. Integrating the LOFAR detector into this software make analyses like this far easier.

3.3 Flexible simulations

Typical LOFAR analyses are primarily based on Monte Carlo simulations using CORSIKA and CoREAS [13, 14]. These simulations capture the natural shower-to-shower fluctuations that occur in nature, and the radio footprint produced by CoREAS has been shown to reproduce data extremely well. As we collect more data, the time required to run simulations needed for analyses grows dramatically. For this reason, we have investigated new techniques to speed up simulations and to make them more flexible to study particular features of the shower footprint.

High-order interpolation: We have developed a robust pulse interpolator, which makes simulating antennas at specific positions possible without re-running entire air showers. This method uses a CoREAS simulation with observers in the standard "star shaped pattern," with radial arms of antennas evenly spaced in the $\vec{v}\times\vec{B}$, $\vec{v}\times\vec{v}\times\vec{B}$ plane. The pulses are interpolated using a higher-order algorithm which interpolates the amplitude and phase spectra of signals in the frequency domain using a Fourier method. This allows the user to determine the signal at an arbitrary position [15]. This method keeps the detail and event-by-event fluctuations in the radio signal, while making the simulations essential reusable for different core positions and detector layouts.

Template Synthesis Method: Another approach to addressing the simulation challenge is the Template Synthesis Method [16]. This method allows the user to "synthesize" radio emission from an air shower with an arbitrary longitudinal profile from the full Monte Carlo simulation of another shower with the same geometry (zenith and azimuth angles). The method uses semi-analytical relations which depend on X_{max} and the desired antenna position, and which are derived by slicing the atmosphere into layers of constant atmospheric depth and analyzing the contribution to the total signal in an antenna from each slice. For more details about the method, see the 2024 ARENA contribution [17].

MGMR3D: MGMR3D is a fast, semi-analytic code that calculates the complete radio footprint (intensity, polarization, and pulse shapes) using the 3-dimensional structure of an extensive air shower [18]. It can be used to investigate the sensitivity of the radio footprint to shower parameters, like shower width and X_{max}. These parameters can also be fit using a chi-square optimization with measured radio data. To demonstrate the effectiveness of this technique, selected LOFAR data have been reconstructed with MGMR3D, obtaining a resolution of 22 g/cm^2 on X_{max} and an energy resolution of 19% [19]. Although this method does not reach the same resolution on X_{max} and energy as the CoREAS method, it provides a fast and efficient tool to reconstruct air-shower parameters. It can also be combined with Monte Carlo simulations as a preliminary estimate to help reduce the required simulation time. As an example, this method has been used to reconstruct electric field structures in the atmosphere during thunderstorm conditions [20]. Without a quick method to simulate the unique radio footprint, this would be impossible.

4. Conclusion

The planned upgrades to LOFAR will prove highly beneficial for cosmic-ray studies. The increased measurement bandwidth, continuous measurements, and new triggering strategies will increase the number of usable events ten fold and offer more information per measurement. These improvements will allow for better reconstruction of the air shower development, which in turn allows for better cosmic-ray event reconstruction and sheds light on high-energy particle interactions. The upgrade is expected to happen over the next few years. In the fall of 2024, current LOFAR operations will be halted so that new electronics can be installed. At this point, we will begin commissioning the un-beamformed HBAs and continue commissioning the expansion of the particle detector array. By summer 2025, we expect to have a finalized data set from the current LOFAR system, collected over a decade of observations. Until then, we will continue to improve our calibration and analysis techniques. We expect to have the cosmic-ray observation mode implemented in LOFAR 2.0 by late 2025, and see our first events simultanesouly with LBA and HBA antennas.

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