An absolute calibration of the antennas at LOFAR

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Preface

In 1912, Victor Hess discovered the phenomenon of ‘cosmic rays’ by use of free balloon flights. This important discovery opened the door to numerous findings in both particle and nuclear physics, and ultimately led to a Nobel Prize in 1936. The cosmic rays that he described are now known to be particles originating in astrophysical sources, accelerated to such high energies that they can be detected away from its source. The most energetic cosmic rays are known to reach macroscopic energies of several $10^{20}$ eV - roughly the same energy a tennis ball has when moving at 80 km/h, and several decades in energy above anything particle physicists can produce with artificial accelerators.

When such highly energetic particles reach our atmosphere, they create a cascade of particles primarily through collisions with the nuclei of aerial molecules. Large detector arrays are built to detect and measure these cascades, called 'extensive air showers'. The detection of showers aids in our understanding of cosmic rays - because despite over a century in research, several questions still remain, regarding topics like their nature, origin, and acceleration mechanisms.

One specifically promising field to help answer these questions is the detection of cosmic rays in the radio regime. The LOw-Frequency ARray (LOFAR), located in the northern part of the Netherlands, is a leading experiment specialized in radio detection of cosmic rays. It is a distributed array, combining a large amount of antennas to detect radio waves in the 10 - 240 MHz frequency range. The data obtained at LOFAR help significantly in our understanding of cosmic rays.

However, in order to contribute, signal detection has to be understood in very great detail. The reconstructed electric field has to be highly accurate, and the response of the antenna has to be well-established. To obtain this, a calibration of the antennas has been performed. An earlier analysis has derived the directional antenna pattern [1], while this thesis focuses completely on the absolute calibration. Its main goal is to find an absolute scaling factor that translates the collected data to an incoming signal in known physical units.

This thesis is organized in the following way: after the preface, the next chapter contains an introduction to cosmic rays. The current status of research is described, as well as the most important challenges it faces. The instrumentation is illustrated in chapter 2; i.e. the radio telescope LOFAR, and any important antenna characteristics. The chapter will be concluded by proposing a flexible calibration method, applicable to different types of radio sources. In this thesis, two different calibrations are performed to achieve maximum accuracy. The first is by use of the Galactic background radiation. As this is the dominant source of noise in the collected cosmic ray events, significant amounts of data are available. The second calibration is by use of a stationary pre-calibrated reference antenna. Both techniques are expected to yield valuable information on the antenna response and the complete receiver system. In chapters 3 and 4, respectively, these calibrations will be discussed. After calculating calibration factors for specific ‘main’ antennas, both applications are extended to include all other antennas in the station (the reference antenna)
and several different stations and antenna sets (the Galactic emission). This is followed by a comparison of the two methods in chapter 5. Additionally, both are compared to air shower simulations provided by CoREAS, as well as to other experiments. In the last chapter, conclusions and a future outlook of the analysis as a whole will be provided.
Chapter 1

Phenomenology of Cosmic Rays and Extensive Air Showers

Even after over a hundred years of research in cosmic rays, several questions regarding this topic still remain unanswered. Examples of such questions regard their composition, and from what sources they originate. Radio detection of cosmic rays appears to be a promising tool to aid in such research. In this chapter, an overview of the status on research in cosmic rays will be described, as well as how cosmic rays can be detected in the radio frequencies, and how research in this field can aid in answering yet unanswered questions.

1.1 Cosmic rays

Cosmic rays are charged, highly energetic extraterrestrial particles, which are created in a wide range of sources. Over the full range of their spectrum, not only their energy - but also flux, composition, and sources change drastically. The rarest events contain energies far beyond what the most powerful artificial accelerator can currently accomplish. Such events carry information about the most extreme processes in the universe, and are therefore highly interesting for astrophysicists.

1.1.1 The energy spectrum

Cosmic ray energies range from $E = 10^8$ eV at the lower end of the spectrum, up to as much as $E = 10^{20}$ eV. This is depicted in figure 1.1, showing the differential flux of cosmic rays as a function of energy. The differential cosmic ray flux $\Phi(E)$ can be described by a power law:

$$\frac{d\Phi}{dE} \propto E^{-\gamma},$$  \hspace{1cm} (1.1)

with $\gamma$ varying slightly at several distinctive breaks in the spectrum. The first of such breaks is called the *knee*, at around $10^{15.5}$ eV. Here, the differential flux steepens, with index $\gamma$ changing from 2.7 to 3.1. For energies below this range, the particle flux is high enough to allow for observations via direct detection. Examples are high-altitude balloons and satellites, such as HET [3] and TRACER [4]. These experiments utilize a combination of detection methods, such as scintillators, Cherenkov (RICH) detectors and transition radiation detectors. Particles are then identified by determining their specific energy loss, as formulated by the Bethe Bloch formula.
However, the flux of particles drops by about a factor 1000 every decade in energy over the entire spectrum [5]. Around the knee, the flux is reduced to roughly 1 particle per square meter per year. With fluxes obtained at these energies and higher, measurements have to rely on air shower development, where the atmosphere is used as a calorimeter to develop a large detection area. Vast detectors are required to detect air showers induced by such energetic particles, such as the Pierre Auger observatory [6], LOFAR [7], HiRes [8], KASCADE [9], and KASCADE-Grande [10].

A second steepening occurs at $10^{17}$ eV, called the second knee. At the ankle, around $10^{18.5}$ eV, the spectrum flattens again to $\gamma = 2.7$. Above these energies, astrophysicists talk about so-called ultra-high-energy cosmic rays (UHECRs). Cosmic rays in this energy range happen as little as once per square kilometer per year, or for energies of $10^{20}$ eV even once per century [2]. At the end of the spectrum the flux quickly decreases, as the index changes to $\gamma = 4$ to $\gamma = 5$. The occurring changes in differential flux are thought to reflect the changing composition and sources of cosmic rays, and will be discussed in the next sections.

### 1.1.2 Composition

For the energy range that allows for direct measurement, the cosmic ray composition is well known. The flux at the lowest energies ($E \sim 10^8$ eV) is dominated by particles originating from
the Sun. For slightly higher energies, the distribution is in good agreement with the local Galactic abundance; making it highly likely that cosmic rays are regular matter, accelerated to extremely high energies. As such, they consist mainly of single protons and helium nuclei.

For indirect measurements with Earth-based detectors, identification of the type of the primary particle becomes more difficult. Rather than directly detecting the particle, the type and energy have to be statistically interpreted from a range of parameters. Experiments indicate that primary particles appear to be of mixed composition, with a trend towards lighter and heavier nuclei for energies above $10^{16.5}$ eV. For the highest attainable energies up to $10^{20}$ eV, the current knowledge is shown in figure 1.2. The figure shows the depth of the shower maximum (section 1.2.1) as predicted for proton and iron nuclei, and as actual measurements, as a function of energy. Since measurements are between the two predicted lines, this indicates that primary particles are either of mixed composition, or particles of intermediate mass.

The composition at highest energies could be explained by different effects. One option is that the maximum acceleration power of different sources has been reached, in which case a heavy composition is expected, as heavier elements attain stronger acceleration by the same sources (section 1.1.3). A different possibility would be a limited sky vision depth for the most energetic cosmic rays. For such particles, an interaction with the cosmic microwave background (CMB) is possible with a very large cross-section. This interaction, occurring via the Delta resonance, is called the GZK-effect

\begin{align}
    p + \gamma_{\text{CMB}} & \rightarrow \Delta^+ \rightarrow p' + \pi_0 \rightarrow p' + \gamma \gamma \hfill \quad (1.2) \\
    p + \gamma_{\text{CMB}} & \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu, \hfill \quad (1.3)
\end{align}

and strongly reduces the energy loss length of cosmic rays with an energy-threshold of $E_{\text{GZK}} = 6 \cdot 10^{19}$ eV. Both of these possible decay modes are expected to yield detectable residual particles,
Figure 1.3: Left: The Hillas plot gives an overview of sources potentially able to accelerate cosmic rays. As given by the Hillas condition (equation (1.5)), the maximum energy a cosmic ray can obtain is limited by the size and magnetic field strength in the source region. Lines are limits drawn for $10^{20}$ eV protons with $\beta = 1$ and $\beta = 1/300$. Possible accelerators have to touch or be above the diagonal [13]. Right: Energy loss length as a function of energy for cosmic rays. The large drop at $6 \cdot 10^{19}$ eV is the threshold for $p \rightarrow \gamma \gamma$ via the Delta resonance. One result hereof is a very limited sky vision depth at the highest energies. Figure taken from [14].

being either a highly energetic neutrino signal, or $\gamma$-rays. Not detecting either of these signals disfavors the GZK-effect [12]. At the moment, not enough data is available to reliably exclude or confirm either theory.

1.1.3 Propagation and sources

The search for cosmic rays is limited to finding sources that are large enough to accelerate particles to the detected energies. This is formulated in the Hillas condition, which tells us that the Larmor radius $R_L$ of a particle can not exceed the radius of the accelerator, lest it escapes and cannot gain further energy:

$$E \leq qBR,$$  \hspace{1cm} (1.4)

with size of source R and magnetic field of source B. Or, written in terms more directly related to cosmic rays,

$$E_{\text{max}} = 10^{18} \text{ eV} \left(\frac{Z\beta}{2}\right) \cdot \left(\frac{R}{\text{kpc}}\right) \cdot \left(\frac{B}{\mu G}\right),$$  \hspace{1cm} (1.5)

where $Z$ is the charge of the particle and $\beta$ the shock velocity as fraction of light speed. A so-called Hillas plot shows the acceleration limitations for different classes of objects, depicted in figure 1.3, which illustrates the size and the magnetic field of various astronomical objects. For the average magnetic field strength in our Galaxy of $B = 3 \mu G$ and a primary proton of several $10^{18}$ eV, the
Larmor radius becomes comparable to the thickness of the Galactic disk ($r_L \sim 0.3$ kpc), and even more for particles of higher charge $Z$. This forms therefore a plausible explanation for the cause of the ankle, which appears to be a complete transition from galactic to extra-galactic component; not only for lighter, but for all elements. For particles at the upper end of the spectrum, active galactic nuclei and gamma-ray bursts are assumed to be able to accelerate particles up to $10^{20}$ eV, motivated by the energy budget from the Hillas diagram. However, because of the low flux of particles this has not been confirmed yet. The long data collection time makes researching EHECRs extremely difficult.

The search for sources is hindered by the fact that cosmic rays are deflected by magnetic fields during their propagation. The magnitude of the deflection is a function of the charge of the primary particle, the magnetic field strength, and the path length of the cosmic ray. Iron nuclei therefore attain significantly more deflection than protons when traveling the same path. As both the galactic and intergalactic magnetic fields are not well known, it is difficult to correlate the arrival direction of cosmic rays directly to the direction of their sources [15]. So far, no strong correlations have been confirmed yet, but the arrival directions are not compatible with an isotropic distribution either [16], [17].
1.2 Extensive air showers

Upon reaching our atmosphere, cosmic rays induce extensive air showers. This happens for incoming particles of energies above $10^{14}$ eV, and creates signals visible with various detection techniques.

1.2.1 Development in the atmosphere

As an incoming particle hits our atmosphere with high enough energy, it collides with an aerial molecule. The collision creates a cascade of secondary particles. Secondary particles will either decay or collide as well, and thereby expand the so-called ‘shower’. This process continues until the energy of remaining particles is too low to produce additional particles.

The basics of this process are described in the Heitler model of extensive air showers [19] [20]. The Heitler model assumes an incoming electron or proton, with energy $E_0$, interacting after traveling a distance $\lambda_{int}$ in the atmosphere. During this interaction it creates 2 particles, both with half the initial energy, interacting after traveling distance $X_0$. The result after $n$ interactions is a shower with $2^n$ particles, each with energy $E(n) = E_0/2^n$. After a number of interactions, the remaining particles do not have sufficient energies to add to the shower, and the amount of particles decreases again as particles in the shower decay.

With this model, the depth of the maximum shower development in the atmosphere $X_{max}$ can be determined. For heavier primary particles with mass $A$, the Heitler model can easily be expanded by assuming a superposition of $A$ protons. The primary energy is then distributed over...
the different sub-showers as $E/A$. The depth of the shower maximum can then be expressed in relation with the mass of the primary particle as

$$X_{\text{max}} \sim \lambda_{\text{int}} + X_0 \ln \left( \frac{E}{A} \right)$$

(1.6)

While the model appears to be extremely simple, it correctly predicts both the proportional dependence of number of particles, and a logarithmic dependence of the shower maximum on the primary energy. Because of the still large momentum of secondary particles, all these particles travel at roughly the speed of light. The resulting shower front of the air shower is therefore a 'disk' of particles, roughly 1 to 3 meters thick in the center, with larger thickness further away the shower axis. Figure 1.4 illustrates the development of the air shower schematically. Typical diameters for showers are 20 meter for $10^{13}$ eV, and 7 kilometer for $10^{20}$ eV [21].

Particles created in extensive showers can be grouped into three different categories; electromagnetic, hadronic, and muonic shower components. These components are represented in figure 1.5. The hadronic component consists of mainly protons, neutrons and charged pions. Protons and neutrons are relatively stable and rarely decay, and for that reason are most likely to experience a second interaction. In comparison, charged pions decay mostly into electrons or muons, and their respective neutrinos, and are therefore largely responsible for the muonic component.

The electromagnetic component is caused mainly by two processes. The first of which is charged pions decaying to electrons, which create photons via Brehmsstrahlung. The second process is by neutral pions decaying to two photons. This decay happens near-instantly due to the extremely short lifetimes of the $\pi_0$. High energy photons then create new electron-positron pairs via pair-creation. The three different components make up roughly 90 %, 1 % and 10 % of particles in the shower at ground-level for respectively the electromagnetic, hadronic, and muonic component [1].

### 1.2.2 Radio emission of air showers

Already in the mid-1960s it was discovered that extensive air showers produce strongly pulsed radio emission at frequencies around 44 MHz [22]. However, at that time, a large number of conflicting theories revolved around the origin of radio emission. The technological advances of that time did not allow for sufficient data taking, and consequently made it impossible to reliably identify any emission mechanisms [23]. It is only at the beginning of this century that research into this field has picked up again. In part, this is made possible by the amount of computational power available. Since then, significant progress has been made in the understanding of radio emission mechanisms. It now appears that the measured radiation is a combination of two different components, both caused by varying charge densities in the air shower.

The main component is of geomagnetic origin, and results in a transverse charge imbalance. As the air shower propagates in our atmosphere and through the local geomagnetic field, the Lorentz force $\vec{F} \sim \vec{v} \times \vec{B}$ accelerates positive and negative charges in opposite directions. This continuous process can be interpreted as a transversal current moving at relativistic speed, perpendicular to the magnetic field. The strength of the current varies with the amount of charge present in the air shower, which builds up until the shower maximum, and decreases from there. Since the amount of charge also scales with the energy of the primary particle, it is believed that the strength of the radio emission scales the same way. In addition, the charge separation scales with the angle between the air shower and the geomagnetic field. This so-called geomagnetic effect has been first observed already in the 1960s, and is now confirmed by AERA[24], LOPES [25],
LOFAR [26] and Tunka-Rex [27]. The second component is the result of a longitudinal charge asymmetry. Relativistic particles in the shower contain enough energy to ionize air molecules, and therefore drag additional electrons along with the shower. Additionally, a large fraction of positrons recombines with electrons in the surrounding air. These two factors combined lead to a negative charge build-up in the shower front, which is also referred to as the Askaryan effect [28].

The resulting emission is generated in a broad frequency spectrum on a timescale of 10 to 100 nanoseconds, which propagates as a thick wavefront. When the size of the longitudinal extend of the shower front is smaller than the emitted wavelength, the radiation is produced coherently. This leads to broad-band pulses in the MHz frequency range, with an expected field strength per unit bandwidth of up to several $\mu$V m$^{-1}$ MHz$^{-1}$ in the 1 - 100 MHz range.

Additionally, Cherenkov ring structures are expected to appear in the radio emission of air showers for frequencies above $\sim 100$ MHz. The appearance of Cherenkov rings allows for geometrical measurements of $X_{\text{max}}$, although at the moment not with sufficient precision to add to the discussion. The method however looks promising when new extensions and data analysis routines have been developed. The first detailed measurements of such Cherenkov ring structures are described in [29].

The combined radio emission can be detected with dual polarized radio antennas, and analyzed to determine parameters such as the energy and arrival direction of the cosmic ray. The energy is proportional to the amount of radiation detected, whereas the direction is based on arrival times in the different antennas. An important parameter in this process is the shape of the wavefront of the air shower, as different shapes result in different coincidental arrival times throughout the station. It is recently shown by LOFAR that the shape of the wavefront is best parametrized as a hyperboloid, which is curved near the shower axis and nearly conical further out [30]. Such a shape fits significantly better than previously proposed purely spherical or conical shapes. Use of the hyperbolic wavefront is assumed to improve angular resolution from $\sim 1^\circ$ to $\sim 0.1^\circ$.

In addition, a new, fast and analytic parameterization for the development radio pulse power has been developed. The parameterization yields shower position, energy, and an estimation of shower maximum with sufficient accuracy for the analysis of large data-sets. The application of such a parameterization to Monte-Carlo simulations, which have a calculation time of several days per shower, promises significant savings in computer time, as it will reduce the number of simulations needed by a factor of two to four [31].

When the characteristic pulse from cosmic rays is detected by the antennas, the signal is disturbed by several sources of noise. The most important contributions are formed by Galactic and intrinsic noise, as well as man-made radio frequency interference (RFI).

Radio detection yields a number of significant benefits. As radio emission is not absorbed in the atmosphere or by water vapor in clouds, observing conditions do not yield any constraints on the detection time. Unlike optical telescopes, which have a need for clear, moonless nights and can therefore operate only 10% of the time, the duty cycle of radio-based antennas is near 100%. Additionally, radio detectors are sensitive to the height of the shower maximum. With this feature, radio detection adds greatly to the discussion of the composition of cosmic rays, and is therefore a valuable addition to cosmic ray detection techniques.
Chapter 2

Instrumentation

The different components of radio emission in air showers imply a largely asymmetrical radio-pattern. For that reason, measurements require dense sampling of the electric field over a sufficiently large area [32]. An instrument designed to do this is the LOw Frequency ARray (LOFAR). Since its first moment of data collection in 2012, it has already significantly contributed to conclusively confirm predictions for radio emission in air showers - something which was previously not possible due to a lack of high-quality data. In this chapter a detailed overview of the LOFAR antenna array is presented. The used antennas are discussed in detail, as well as several parameters that are fundamental in understanding the emission patterns detected by LOFAR. The chapter is concluded with a proposed method to fully calibrate radio antennas, applicable to LOFAR LBAs.

2.1 The LOw Frequency ARray - LOFAR

This section contains an overview of the LOFAR radio telescope. A general overview is given, as well as the different utilized antennas are discussed.

2.1.1 The radio telescope

LOFAR is a distributed radio telescope designed to observe radio frequencies ranging from 10 to 240 MHz. With its large instantaneous field of view and electronical-, rather than mechanical pointing, the project is particularly well designed to carry out cosmic-ray detection. The array is fully operational since June 12th, 2012, and consists of over 25,000 radio antennas grouped into stations. These stations are placed throughout Europe, with a dense distribution in the northern part of the Netherlands. At the center of the Dutch array, a roughly 2 km wide core hosts 24 core stations. Additional 16 Dutch remote stations are placed in a logarithmic spiral distribution, with a radius of 90 km - deviations exist due to the availability of land and fiber infrastructure. International stations are placed in Germany, Denmark, France and the UK, resulting in a maximum baseline of 1292 km.

Both core and remote stations comprise 96 LBAs and 48 HBAs, while international stations consist of 96 LBAs and 96 HBAs. All Dutch LBA arrays are further divided into an inner- and outer circle. Within the the center of the core stations itself, 6 core stations are closely packed together on the Superterp - an area roughly 320 m in diameter. A schematic view of the superterp is depicted in figure 2.1 (left). The dense antenna-population that the superterp provides makes
it ideal for cosmic-ray observations. Each single station performs the same basic functions as the dishes of a conventional interferometric radio telescope. Stations can also be combined for imaging purposes, or used for array beams to produce high-resolution time series, with the purpose of solar-, pulsar-, and other studies. Because of the high bandwidth-intensity of these electronical telescopes, all stations are also equipped with significant computing resources.

### 2.1.2 Low-Band Antennas

The lowest frequencies to which the LOFAR experiment is sensitive are detected by use of Low-Band antennas (LBAs). Their frequency bandwidth ranges from the ionospheric cutoff at 10 MHz up to 90 MHz. However, because of strong radio interference at the upper and lower limit (e.g. interference with the radio FM band), the LBA frequency range is operationally limited to 30 - 80 MHz [33]. The design was optimized to have a sky-noise dominated antenna with all-sky sensitivity. For over 70% of the total bandwidth, this goal has been achieved [7].

The LBA consists of two crossed dipoles, pointing in the NW-SE and NE-SW directions, which are defined as dipole X and dipole Y, respectively. Because of its pyramid-like structure the antenna is sensitive to all three orthogonal linear polarizations. Each polarization is detected using two copper wires, both with a length of 1.38 meter, which are connected at the top of the antenna to the low-noise amplifier (LNA). At the lower end they are connected to either a polyester string on the one side, or a synthetic spring at the other side. When taking into account all electronics, the antenna has a resonance frequency of 58 MHz. A PVC pipe functions to keep the antenna standing upright, and contains two coaxial cables providing power and carrying the signal for the
two respective polarizations. The entire construction rests on a metal mesh groundframe on top of a foil sheet to reduce vegetation growth. Figure 2.1 (right) depicts a photograph of an LBA. Figure 2.2 shows an example trace detected in a single dipole as a function of time.

While its design is extremely simple, the combining of signals within a station results in a powerful detection method for lower frequencies. In particular, the omni-directional response allows for full-sky observations with a duty cycle close to 100%, and results in all-sky maps on a nanosecond timescale.

2.1.3 High-Band Antennas

The high end of LOFARs operational bandwidth, from 110 MHz to 240 MHz, is covered by High-Band Antennas. Because sky-noise is less prominent in this region, it does not dominate the signal at the accepted bandwidth as with LBAs. Consequently, a different 'butterfly'-like design was required to reduce the relative contribution of electronics noise.

Every HBA sub-array consists of 24 antenna tiles spaced 15 cm apart, each of which contains 16 butterfly antennas grouped together. Each sub-array can be analyzed for its individual signal, or both sub-arrays can be used to form a station. Contrary to the LBA, HBAs can only use beamforming in a pre-set direction, and are sensitive within \( \sim 20^\circ \) of the beamtile. For that reason, they detect cosmic rays only when cosmic-ray direction and beam-direction coincide - resulting in a much smaller effective detection area. As with the LBA, coaxial cables transport the signal to an electronic readout system. While the HBAs form an integral part of the LOFAR experiment, they are not used in this thesis, and will therefore not be further discussed.
2.1.4 The LOFAR Radboud Air Shower Array

The superterp stations are, in addition to the regular antennas, further supplemented with five clusters of four particle detectors each; the LOfar Radboud air shower Array (LORA). This array is composed of 20 detectors, each with 2 scintillators, spaced 50 to 100 meters apart. The aim of LORA is to aid in confirming the detection of cosmic rays, and is able to measure air showers from $10^{16} \text{ eV}$ to $10^{18} \text{ eV}$. The particle detectors combined provide several basic parameters - such as energy, direction, position, and time of arrival - of the incoming air shower. When 13 of all 20 detectors register a signal of more than $4\sigma$ above the noise-level, a read-out trigger is sent to RAM buffers on transient buffer boards (TBBs). The trigger-level can be adjusted as desired, but the current setting of 13 out of 20 detectors is selected as optimal. A more detailed description of LORA can be found in [34, 35].

2.2 Measurements with the LBA

After detection in the LBA, several steps have to be taken in order to analyze the different traces obtained. The data have to be saved, and cleaned from residual noise and malfunctioning antennas.

2.2.1 Electronics

Signals from the LBAs are continuously forwarded to the electronics cabinet, where they are amplified, filtered, and digitized by a 12 bit A/D converter. Because of the 200 MHz sampling frequency of the converter, time resolution is as good as 5 nanoseconds. However, upsampling can increase the resolution to 1 nanosecond [29]. The electronics cabinets are located at the edge of each station, and shielded against varying weather conditions. Transient buffer boards (TBBs) with RAM buffers continuously store the most recent 1.3 seconds of raw data. When these are triggered - either by LORA or manually - 2.1 ms of current data are frozen and stored on disk for further analysis. This is then labelled as an \textit{event}. The read-out is limited by the fact that only half the number antennas in the station can be read out at any time due to bandwidth limitations. For all data used in the analysis this is split up in samples per antenna set (i.e. inner and outer antennas), both consisting of 48 dual-polarized antennas. This means that a single sample contains all 48 traces from X-dipoles, as well as 48 traces from Y-dipoles.

2.2.2 Data processing for calibration

All data in the TBBs are recorded in the time domain. For the calibration of the LBA, it is important to determine frequency dependent characteristics between an incoming electromagnetic wave and the registered measurement. This is done by translating traces to the frequency domain by use of a Fourier transform. The Fourier transform decomposes a signal as a function of time into the frequencies that it contains [36]. According to Parseval’s theorem it is unitary, which means that the power in the frequency-domain is conserved with respect to the power in the time-domain [37]. For discrete signals, the Fourier transform becomes

$$
\sum_{n=0}^{N-1} |x[n]|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X[k]|^2, 
$$

(2.1)
Figure 2.3: Left: Median averaged spectrum of all LBA dipoles in an arbitrary station. Clearly visible is the resonance peak at 58 MHz, as well as heavy RFI below 30 MHz (in part due to ionospheric reflection of sub-horizon RFI) and above 80 MHz (due to the FM band). Right: Average spectrum cleaned of flagged channels, and clipped to 30 - 80 MHz.

where $X[k]$ is the discrete Fourier transform of $x[n]$, both of which are of length $N$. The factor $\frac{1}{N}$ normalizes the Fourier transform to the number of used bins.

The framework used for the analysis is PyCRTools [38], consisting of fast low-level C++ routines which are embedded in Python for high flexibility. It utilizes a specific implementation of FFTW [39], called the Fast Fourier Transform (FFT). This FFT is faster than other Fourier transforms for large $N$, as is often the case in radio detection. The Fast Fourier Transform of a trace signal, which is expressed in Analog-Digital Converter Units (ADU’s), is denoted as $F(\nu)$. The amplitude of $F(\nu)$ is proportional to the incoming electric field $\vec{E}(\nu)$, so that the physically measured uncalibrated power $P_m(\nu)$ is equal to the square of $F(\nu)$

$$P_m(\nu) = |F(\nu)|^2,$$

To achieve a desired frequency resolution, block sizes (frequency channel sizes) can be arbitrarily chosen within the full data length. A better signal-to-noise ratio is obtained by averaging the power spectrum over several blocks of data. Strong RFI transmitters can be isolated by looking at the phase difference between individual antennas. This method is described in [33]. Additionally, one of two filter settings can be applied: either a bandpass ranging from 10 to 80 MHz is applied, or one ranging from 30 to 80 MHz. The latter of these is used mostly in all cosmic-ray data, as well as for all analyses in this thesis, thereby already flagging the bandwidths with highest RFI. This can be seen in figure 2.3, which shows the measured spectrum as a function of frequency both before and after flagging and clipping (sub-figures left and right, respectively). To account for antennas with invalid signals, e.g. due to hardware malfunctioning, so-called bad antennas are identified. This is done by integrating the spectral power

$$P = \int_{30MHz}^{80MHz} |x(w)|^2dw$$

and requiring it to be within one half to two times the median power of all antennas in a station.
2.3 Antenna modelling and characteristics

To give an accurate description of the antenna and its received signal, it is necessary to explore the model used for the LBAs, and define different emission regions common in antenna theory. Both parameters are required in performing an absolute system calibration, and will be described in this section. The section will conclude by defining a flexible method that allows for independent calibration of the LBAs, applicable to various types of radio sources.

2.3.1 Vector Effective Length

The Vector Effective Length (VEL) is a fundamental parameter in the description of an antenna. It fully describes the antenna’s response to an incoming pulse - generally including all signal amplification, dispersion effects and reflections. For the directional accuracy of the VEL, a measurement campaign has already been performed. Simulations appear to be a good match to measurements for most directions [1]. However, the modelled VEL does not take the full end-to-end setup into consideration - rather, anything after the LNA is left out. For that reason the absolute response of the model is unknown at this point, and it is the main goal of this thesis to establish this. The VEL $\vec{H}(\nu, \theta, \phi)$ depends on both frequency and direction, and maps the electric field $\vec{E}(\nu, \theta, \phi)$ to the response voltage $V(\nu, \theta, \phi)$

$$V(\nu, \theta, \phi) = \vec{H}(\nu, \theta, \phi) \cdot \vec{E}(\nu, \theta, \phi).$$

(2.4)

Here $\theta$ and $\phi$ describe the azimuth and zenith direction in a spherical coordinate system with the antenna at its origin. This geometry can be seen in figure 2.4. In the most general case $\vec{H}(\nu, \theta, \phi)$
Figure 2.5: Example response of the Vector Effective Length of the LBA, in the form of output voltage $\Delta V$. Left: response as a function of frequency to an incoming wave polarized in the $\vec{e}_\theta$ direction (circles), and a wave polarized in the $\vec{e}_\phi$ direction (triangles), with arrival direction $\theta = 45^\circ$ and $\phi = 65^\circ$. Right: $|J_{X\theta}|$ component at 60 MHz as a function of direction for a wave only polarized in the $\vec{e}_\theta$ direction ($E_\theta = 1$).

is a complex quantity of the form

$$\vec{H}(\nu, \theta, \phi) = |\vec{H}(\nu, \theta, \phi)| \cdot e^{i\psi}, \quad (2.5)$$

with $\psi$ the phase shift of the signal as it passes through the antenna and electronics. Incoming electromagnetic waves are polarized, and their respective polarization can be split up into two independent directions

$$\vec{E} = E_\theta \vec{e}_\theta + E_\phi \vec{e}_\phi. \quad (2.6)$$

The two orthogonal directions can also be described as the sine and cosine of a parameter $\omega$

$$\vec{E} = \begin{pmatrix} E_\theta \\ E_\phi \end{pmatrix} = \begin{pmatrix} \sin(\omega) \\ \cos(\omega) \end{pmatrix}. \quad (2.7)$$

For single frequencies the VEL is called the Jones matrix $J(\theta, \phi)$, and its mapping can be represented in response to the two different dipoles of the LBA. The dipoles, pointing in directions NW-SE and NE-SW, are defined as dipole X and dipole Y, respectively. The mapping of the Jones matrix is then

$$(V_X \ V_Y) = \begin{pmatrix} J_{X\theta} & J_{X\phi} \\ J_{Y\theta} & J_{Y\phi} \end{pmatrix} \cdot \begin{pmatrix} E_\theta \\ E_\phi \end{pmatrix}. \quad (2.8)$$

Here components $J_{X\theta}$ and $J_{X\phi}$ are responses in the X-dipole to waves polarized in directions $\vec{e}_\theta$ and $\vec{e}_\phi$, respectively, and similarly $J_{Y\theta}$ and $J_{Y\phi}$ responses in dipole Y. Because signals in the X- and Y-dipoles are independent of one another, this can be split into two independent equations

$$V_X = (J_{X\theta} \ J_{X\phi}) \cdot \begin{pmatrix} E_\theta \\ E_\phi \end{pmatrix} = J_{X\theta} E_\theta + J_{X\phi} E_\phi, \quad (2.9)$$

$$V_Y = (J_{Y\theta} \ J_{Y\phi}) \cdot \begin{pmatrix} E_\theta \\ E_\phi \end{pmatrix} = J_{Y\theta} E_\theta + J_{Y\phi} E_\phi. \quad (2.10)$$
Figure 2.6: Illustration of perceived field regions with respect to an arbitrary transmitting antenna. In the far-field region, the waves radiated in a given direction from distinct parts of the antenna are approximately parallel. Figure taken from [41].

The Jones matrix is modelled in the LOFAR software with electromagnetic simulation software WIPL-D [40] and a customised software model of the measured gain of the electronics [33]. It predicts the response to an incoming wave with an electric field strength of 1 V/m, and is computed with steps of 1 MHz in frequency, 5° in $\theta$ and 10° in $\phi$. The components at intermediate values are obtained via trilinear interpolation when needed. Example responses as a function of frequency and direction can be found in figure 2.5. Since both LBA dipoles are independent, it is possible to look only at the contribution to either one. This simplifies the use of the antenna model $\vec{H}(\nu, \theta, \phi)$ - which is normally a 2x2 matrix - to either $\vec{H}_X$ or $\vec{H}_Y$, with

\[
\vec{H}_X(\nu, \theta, \phi) = \begin{pmatrix} J_{X\theta} & J_{X\phi} \end{pmatrix}
\]

(2.11)

\[
\vec{H}_Y(\nu, \theta, \phi) = \begin{pmatrix} J_{Y\theta} & J_{Y\phi} \end{pmatrix}
\]

(2.12)

2.3.2 Radiation pattern

The characteristics of electromagnetic fields change depending on the distance from the antenna. The field is typically divided in a near-field region and a far-field region, with a transition region in between. The different regions can be characterised by the Poynting vector $S$

\[
S = \frac{1}{\mu_0} \vec{E} \times \vec{B},
\]

(2.13)

and are a result of the sensitivity to different multipoles at certain distances. Definitions on where both regions begin and end vary significantly. Some literature suggests that the outer boundary of the near-field is defined where $r < \lambda$ [42], while others suggest that $r < 2D^2/\lambda$ [43] or variations of those [44]. The most agreed upon definition is that the near field - also called inductive region is less than one wavelength ($\lambda$) from the antenna. In the inductive region, the energy density
In general Applied to LBA

<table>
<thead>
<tr>
<th></th>
<th>In general</th>
<th>Applied to LBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$R &gt; \frac{2D^2}{\lambda}$</td>
<td>$R &gt; 0.8$ m</td>
</tr>
<tr>
<td>2</td>
<td>$R &gt;&gt; D$</td>
<td>$R &gt;&gt; 2$ m</td>
</tr>
<tr>
<td>3</td>
<td>$R &gt;&gt; \lambda$</td>
<td>$R &gt;&gt; 10$ m</td>
</tr>
</tbody>
</table>

Table 2.1: Three necessary far-field conditions, both theoretical and applied to the LBA bandwidth. $D$ is the maximum linear dimension of the antenna, $\lambda$ the emitted wavelength, and $R$ the distance to the antenna.

\[ S_{\text{inductive}} \propto r^{-4}. \]  

(2.14)

The far field, where emitted waves behave as plane waves, is usually considered to start where the three conditions in table 2.1 are satisfied \[42\], even though a significant amount of articles only require the first condition of table 2.1. The first two conditions ensure that the fields radiated in a given direction from distinct parts of the antenna are approximately parallel. The third ensures that any near-field effects are gone, and the resulting energy density $S_{\text{far}}$ drops with

\[ S_{\text{far}} \propto r^{-2}. \]  

(2.15)

For a calibration measurement with any reference antenna, it is important that the emitted wave sufficiently approximates the behaviour of a plane wave. The reason for this is that plane waves behave in a well-described way, and can therefore be modelled into the VEL. Waves that cannot be approximated by a plane wave will yield different response voltages.

Table 2.1 suggests the reference antenna needs to be at least (or even much further than) 10 meters away from the receiver in order to satisfy all three far-field conditions. For similar distances and a maximum wavelength of 10 m, other experiments report variations of at most $\pm 0.5$ dB in power when compared to measurements performed at much larger distances \[45\].

### 2.3.3 Calibration method

For the calibration of the LBA, it is important to determine frequency dependent characteristics between signal and measurement. In general, two different methods exist to achieve this.

One method would be to theoretically predict the antenna characteristics, and calibrate the electronic chain in the laboratory. This has been performed earlier for LOPES10, but has only limited applicability \[46\]. Specifically, it is most useful for relative comparisons, and the obtained calibration values are relatively difficult to confirm as no source of known strength is used.

The other method would be to calibrate the full electronics chain, end-to-end, via an external source of known field strength. The advantage here is that one calibrates the full setup, including both antennas and electronics. Therefore, this method faces no issues such as impedance matching, and does not rely on the modelling of hardware characteristics. Consequently, the result is a clear conversion from input to output - or vice versa - to accurately establish parameters of measured air showers. For this thesis, the end-to-end calibration method has been chosen as most viable.
Signal and measurements in the LBA are best described in the form of an expected and measured power. The measured power is calculated by taking the Fourier transform of traces in the LBA, as described in chapter 2.2.2, while the expected (signal) power is calculated from a known source.

To compare signals coming from different directions, it is useful to include the antenna model $\vec{H}(\nu)$, which is known up to a frequency-dependent calibration constant. For an incoming electric field of known field strength $\vec{E}(\nu)$, the resulting expected voltage $V_e(\nu)$ and power $P_e(\nu)$ are

$$V_e(\nu) = \vec{E}(\nu) \cdot \vec{H}(\nu)$$  \hspace{1cm} (2.16)

$$P_e(\nu) = \frac{V_e(\nu)^2}{Z_0},$$  \hspace{1cm} (2.17)

where $Z_0 \sim 120\pi$ is the vacuum impedance. As the antenna system is not calibrated yet, the measured and expected power still vary up to a frequency-dependent factor $X(\nu)$. This calibration factor $X(\nu)$ measures how the incoming electric field translates to Analog-Digital converter units (ADU’s) in the receiver. With this definition, $X(\nu)$ can be expressed as

$$X(\nu)^2 = \frac{P_e(\nu)}{P_m(\nu)} = \frac{V_e(\nu)^2}{Z_0 \cdot |F(\nu)|^2}.$$  \hspace{1cm} (2.18)

To include all unknown frequency-dependencies, this can be compared per single MHz frequency-bin (i.e. the power at [30, 31, ... , 78, 79, 80] MHz). A reason for this discrete binning is that the reference antenna source utilized yields power in single MHz frequency bins (chapter 4). Additionally, the bins are chosen so that they are small enough not to overlook systematic trends in the power spectrum, and large enough to use the least amount of data bandwidth. The calibration factor at a specific frequency $\nu_0$ is then

$$X(\nu_0)^2 = \frac{\int_{\nu_0-0.5MHz}^{\nu_0+0.5MHz} P_e(\nu) d\nu}{\sum_{i=\nu_0-0.5MHz}^{\nu_0+0.5MHz} |F(\nu)|^2}.$$  \hspace{1cm} (2.20)

The advantage of such a method is that the full equipment and electronic setup is included in the calibration. It is a direct translation from detected signal to incoming field strength, without the need to simulate impedance losses and mismatches in the various electronic circuits as is done in other experiments [46].

This thesis will apply the proposed method to two independent sources of radio emission: a reference antenna, and the Galactic background radiation emission. Both setups will be discussed in more detail in the next chapters. In addition, the calibrated values are cross-referenced with simulations of extensive air showers, as well as with other experiments. These cross-references will be described in chapter 5.
Chapter 3

Calibration using the Galactic background radiation

The LBA receiver, including LNA, is built in such a way that Galactic noise dominates over internal noise from electronics [7]. In combination with the location of LOFAR – an area with relatively small amounts of RFI – the situation is ideal to perform a full-spectrum calibration with the Galactic background radiation. In this chapter, several different Galactic emission models are described. One of these – called LFmap – is chosen and applied to perform such a calibration. This is applied to different stations and antenna sets, so that systematic and statistical variations can be determined.

3.1 Simulations of Galactic radio background

The Galactic background radiation forms a diffuse source of emission, ranging from tens to several hundreds of MHz over both the northern and southern sky. Several maps have been published at specific frequencies within this range, such as the 45 MHz map by Alvarez [47], and the 408 MHz map by Haslam [48]. However, only very few possibilities exist to electronically construct a sky map at other desired frequencies. In this section possible models will be described, as well as how relevant predictions can be made using Galactic radiation models.

3.1.1 Evaluation of different models

At the moment of writing this thesis, two electronic models are known that interpolate to a desired frequency; one is called LFmap [49], and the other Galactic Sky Model (GSM) [50]. Both predict the sky temperature by interpolation of established reference maps, where the exact method depends on the model. The models can be evaluated on a relative, as well as on an absolute accuracy. The relative accuracy contains two elements: first, neither LFmap, nor GSM, exactly reconstruct the reference maps up to each data point, but merely fit to each of them. An important measure for the accuracy of both models is therefore how well they describe the reference maps used. Second, the absolute uncertainty describes how well measurements – that is, the data in the reference maps – describe the true sky temperature. Both measures of uncertainty are discussed in this section.
Figure 3.1: Map of the Galactic radio emission, generated by LFmap at 60MHz. The upper region is visible from the location of LOFAR at 17:20 h LST. The black line corresponds to our horizon, and the dashed region is not visible at this specific time.

Relative uncertainties of the used models

LFmap is a program (in C) that calculates the sky temperature at any desired frequency within this range. The program works in the following way:

For low frequencies, the sky temperature $T(\nu)$ can be described by a power law

$$T(\nu) \propto \nu^{-\beta}, \quad [T] = \text{W m}^{-2} \text{ Hz}^{-1}. \quad (3.1)$$

The spectral index $\beta$ depends on frequency and observed direction (large in regions of low $T(\nu)$ and vice versa). This is generally interpreted as $T(\nu)$ consisting of three contributions. The first is an anisotropic component with a relatively flat spectrum, caused mainly by synchrotron radiation from charged particles gyrating in the Galactic magnetic field. The second is an isotropic component with a steep spectrum. This can be attributed to the integrated emission of unspecified extragalactic sources, as well as an isotropic Galactic emission component. Third, the cosmic microwave background (CMB) at 2.73 K is isotropic, with a flat spectrum. The sky temperature $T(\alpha, \delta, \nu)$ at any coordinate and frequency can then be described as

$$T(\alpha, \delta, \nu) = T_{\text{CMB}} + T_{\text{Iso}}(\nu) + T_{\text{Gal}}(\alpha, \delta, \nu). \quad (3.2)$$

LFmap calculates both $T_{\text{Iso}}(\nu)$ and $T_{\text{Gal}}(\alpha, \delta, \nu)$ by interpolating these values from several established maps widely used in astrophysics. One example of these is the 408 MHz map by Haslam, and for frequency ranges relevant for this thesis, the 22 MHz [51] and 45 MHz [52, 53] maps are used as additional reference points. The 22 MHz map however is incomplete for declinations $> 75^\circ$ and $<-27^\circ$ and around strong discrete sources, so that averaged values from surrounding regions
are interpolated for these regions. As part of these regions contain bright sources, small deviations from true values can have a significant effect on calculations of the antenna temperature.

An example of LFmap output can be seen in figure 3.1, showing the sky temperature as a function of equatorial coordinates (right ascension and declination). Note that the visible region of the Galaxy (and therefore the power received at the Earth’s surface) varies as a function of local sidereal time (LST). This is a time scale based on the Earth’s rotation relative to the vernal equinox, which is useful when pointing to fixed regions in space from Earth-based telescopes. A full LST cycle is equal to about 23 hours and 56 minutes 'local time'.

The Galactic Sky Model calculates an all-sky temperature at any desired frequency in the 10 MHz to 100 GHz frequency range, by interpolation of the 11 most accurate data sets (at 10, 22, 45 & 408 MHz and 1.42, 2.326, 23, 33, 41, 61, 94 GHz). The predicted sky maps have an angular resolution of 5.1°, and are almost as good as information theory allows to be the best possible case. The model is reported to be accurate between 1% and 10% on a relative scale (i.e. not accounting for errors in reference maps).

Other examples of simpler models include a Thompson model \( T_{\text{thompson}} = 60 \pm 20 \left( \frac{\lambda}{m} \right)^{2.55} \), which describes the average sky temperature as a function of wavelength [54], or parameterized spectral models. The latter is developed with six bright radio sources visible in the northern sky in the 30 - 300 MHz frequency range, with relative uncertainties of less than 5% for three out of six sources [55]. However, as part of the complete calibration study already contains the use of a point-source with known emitted field strength (chapter 4), the choice in source models has been restricted to diffuse all-sky radiation with angular dependencies, such as LFmap and GSM.

Figure 3.2 illustrates the relative difference between LFmap and GSM as a function of frequency. Differences are less than 5% over the full frequency bandwidth. As differences between models are small enough, the final choice of model has fallen on LFmap because of its flexibility and easy-to-use software. The documentation of LFmap does not describe how well the model agrees with used reference maps, while GSM reports relative uncertainties of up to 10%. Therefore, as a conservative estimate, the relative uncertainty on LFmap is taken to include the difference between GSM and LFmap, as well as the relative uncertainty on GSM, corresponding to 5% and 10%, respectively.

### Absolute uncertainties of the reference maps

Even though differences between various maps are small, this is no guarantee that they closely resemble the true sky temperature. Both GSM and LFmap interpolate to various reference maps in different ways, but neither account for errors and uncertainties on the used reference points. In the paper describing GSM, the authors do make a prediction of absolute errors\(^1\) for the different reference maps. In the range relevant to this analysis, uncertainties are mostly around the 10% level, ranging up to 20% for some partial maps [50].

Additionally, the 45 MHz map [47], which is well within the used frequency range, is reported to have an absolute accuracy of better than 15%. The map is constructed using two independent surveys – one observing the northern hemisphere [53], while the other survey observed the southern hemisphere [52]. The combined map describes over 95% of the complete sky, and uncertainties are determined by comparing overlapping sky regions. Finally, a different paper describes an analysis

---

\(^1\)Absolute errors refer to how well measurements describe the true sky temperature. As this is still expressed in percentages, one could argue to call this relative errors. However, for this thesis, this relative error refers to differences between the used models and reference maps, as mentioned in section 3.1.1.
of the spectrum of Cas A in absolute units, with a reported accuracy of 2% for the 0.3 - 30 GHz range, which increases to 5% for frequencies below 300 MHz [56]. In the paper, the spectrum is consequently used to be compared with different secondary calibrators. Differences with a 408 MHz map by Wyllie [57] are less than 3%. The discrepancy increases slightly for lower frequencies, to a maximum of 13% at 38 MHz.

The various surveys that are described here clearly indicate a consistent absolute accuracy around the 10% range for the 10 - 100 MHz frequency range. Some partial maps have uncertainties as high as 20%, but this is only rarely and mostly for small regions. A conservative estimate is therefore taken to be the maximum uncertainty found in the literature. For the purposes of this analysis, this is deemed to be sufficiently accurate, and the value of 20% is adopted as absolute scaling uncertainty for all frequencies.

### 3.1.2 Predictions using a Galactic emission model

The output of LFmap can be translated to a spectral radiance per solid angle \( B \) as a function of equatorial coordinates. For low frequencies (below 10\(^3\) MHz), the Rayleigh-Jeans law approximates the spectral radiance at a given temperature

\[
B(\alpha, \delta, \nu) = \frac{2k_B}{c^2} \nu^2 T(\alpha, \delta, \nu), \quad [B] = \text{W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1},
\]

with \( k_B \) the Boltzmann constant, and \( c \) the speed of light. The received spectral power density \( S_\nu \) at some frequency \( \nu \) is then the integral over the visible half-sphere sky

\[
S_\nu = \int_{\Omega} B(\alpha, \delta, \nu) \, d\Omega = \frac{2k_B}{c^2} \nu^2 \int_{\Omega} T(\alpha, \delta, \nu) \, d\Omega.
\]

The LOFAR Superterp is located at latitude 52.92° and longitude 6.87°. Using this location in combination with the Local Sidereal Time, it is possible to convert equatorial coordinates \((\alpha, \delta)\)
Figure 3.3: Simulated received power as a function of Local Sidereal Time, for dipoles X and Y. Also plotted is the simulated power without antenna model, scaled to match dipoles X and Y.

to the antenna-based coordinates \((\theta, \phi)\), so that

\[
S_\nu(t) = \frac{2k_B}{c^2} \nu^2 \int_0^{2\pi} \int_0^\pi T(\theta, \phi, \nu, t) \sin(\theta) \cos(\theta) \, d\theta \, d\phi,
\]

(3.5)

where the factor \(\sin(\theta)\) follows from the integral over a sphere, and \(\cos(\theta)\) is the projection of incoming radiation onto the Earth’s surface. The total power density at some time is then

\[
S_{total} = \int_\nu S_\nu \, d\nu, \quad [S_{total}] = \text{W m}^{-2} \text{ Hz}^{-1}.
\]

(3.6)

The LBA does not map power density directly to received power, as it is not equally sensitive to every direction. To account for this sensitivity, the antenna model needs to be included. This leads to

\[
P_\nu = S_\nu \cdot A_e, \quad [P] = \text{W Hz}^{-1}
\]

(3.7)

\[
= \int T(\nu, \theta, \phi) |H(\nu, \theta, \phi)|^2 \, d\Omega
\]

(3.8)

\[
= \frac{2k_B}{c^2} \nu^2 \int T(\nu, \theta, \phi) |H(\nu, \theta, \phi)|^2 \, d\Omega, \quad \text{so that}
\]

(3.9)

\[
P_{total} = \int_{30 \, \text{MHz}}^{80 \, \text{MHz}} P_\nu \, d\nu
\]

(3.10)

\[
= \frac{2k_B}{c^2} \nu^2 \int_{30 \, \text{MHz}}^{80 \, \text{MHz}} T(\nu, \theta, \phi) |H(\nu, \theta, \phi)|^2 \, d\Omega \, d\nu.
\]

(3.11)

The frequency-integrated received power is now in Watts. Since we are interested in how the time-averaged response of antennas, it is important to simulate numerous cycles of Local Sidereal
<table>
<thead>
<tr>
<th>Station</th>
<th>Antenna set</th>
<th># total events</th>
<th># events after filter</th>
<th># antennas (X/Y)</th>
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<tr>
<td>CS002</td>
<td>LBA INNER</td>
<td>654</td>
<td>638</td>
<td>86 (43/43)</td>
</tr>
<tr>
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<td>LBA OUTER</td>
<td>3444</td>
<td>3310</td>
<td>90 (45/45)</td>
</tr>
<tr>
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<td>LBA INNER</td>
<td>649</td>
<td>631</td>
<td>90 (45/45)</td>
</tr>
<tr>
<td>CS003</td>
<td>LBA OUTER</td>
<td>3548</td>
<td>3425</td>
<td>94 (47/47)</td>
</tr>
<tr>
<td>CS004</td>
<td>LBA INNER</td>
<td>536</td>
<td>518</td>
<td>88 (44/44)</td>
</tr>
<tr>
<td>CS004</td>
<td>LBA OUTER</td>
<td>3084</td>
<td>2958</td>
<td>88 (44/44)</td>
</tr>
</tbody>
</table>

Table 3.1: Number of events before and after filtering, as well as the number of antennas with non-zero response in at least 95% of events. Station locations are depicted in figure 2.1 (left).

Time. The result is an incoming electric field without preferred polarization direction. To find the value of $|H_x(\nu, \theta, \phi)|^2$ we can then look how the antenna model responds to an electric field that solely consists of unpolarized waves:

$$< V^2_X > = < (J_{X\theta}E_\theta + J_{X\phi}E_\phi)^2 > \quad (3.12)$$
$$= < (J_{X\theta}E_\theta)^2 + (J_{X\phi}E_\phi)^2 + 2 \cdot J_{X\theta}J_{X\phi}E_\theta E_\phi > \quad (3.13)$$
$$= < (J_{X\theta} \sin(\omega))^2 + (J_{X\phi} \cos(\omega))^2 + 2 \cdot J_{X\theta}J_{X\phi} \sin(\omega) \cos(\omega) > \quad (3.14)$$
$$= \frac{1}{2\pi} \int_0^{2\pi} |J_{X\theta}|^2 \sin(\omega)^2 d\omega + \frac{1}{2\pi} \int_0^{2\pi} |J_{X\phi}|^2 \cos(\omega)^2 d\omega$$
$$\quad + \frac{1}{2\pi} \int_0^{2\pi} 2 \cdot J_{X\theta}J_{X\phi} \sin(\omega) \cos(\omega) d\omega \quad (3.15)$$
$$= \frac{1}{2} |J_{X\theta}|^2 + \frac{1}{2} |J_{X\phi}|^2 + 0 \quad (3.16)$$
$$= \frac{1}{2} (|J_{X\theta}|^2 + |J_{X\phi}|^2). \quad (3.17)$$

It is clear that for unpolarized waves the cross-term drops, and we are only left with the squared components of the Jones matrix, as well as a factor $1/2$. After inserting equation (3.17) into equation (3.11), the received power in a dipole (now arbitrarily chosen to be dipole X) becomes

$$P_X = \frac{k_B}{c^2} \int_{30 \, MHz}^{80 \, MHz} \nu^2 \int_{\Omega} T(\nu, \theta, \phi) (|J_{X\theta}|^2 + |J_{X\phi}|^2) \, d\Omega \, d\nu, \quad (3.18)$$

with $d\Omega = \sin(\theta) \, \cos(\theta) \, d\theta \, d\phi$.

The resulting expected power as a function of time is shown in figure 3.3. We observe that the visibility of the Galaxy is mapped differently onto the recorded power by both dipoles. Also, the progression of noise power over time differs significantly between simulations with and without antenna model; the detected Galactic minima and maxima are both magnified in amplitude as well as shifted in time.
Figure 3.4: Integrated median uncalibrated power, as a function of local sidereal time, in dipole X (left) and dipole Y (right) (dipoles 83 and 82 respectively of CS002 LBA OUTER). Also shown is simulated received power in both dipoles (solid red lines). Uncertainties on the data include systematic and statistical uncertainties, where each data point contains 34 data points on average.

3.2 Observations of the Galactic radio background

As discussed in chapter 2, LBAs are read out after a trigger from LORA when a cosmic ray was detected – which is then labeled as an event. In such an event, the pulse duration from the cosmic ray is much shorter than the total data length, which is therefore mostly noise-dominated. This allows us to use air shower data for a calibration based on the Galactic background radiation.

For this analysis, events detected by the outer antennas of station CS002 are used. In cases where other stations (stations CS003 and CS004) are used, this is specifically mentioned. Only events where all 96 dipoles are read out are included in the analysis. Events with zero response in traces of all dipoles (i.e. no signal in the entire station) are filtered out. All dipoles with a non-zero response in at least 95% of events are used, which excludes about 10 dipoles per station and/or antenna set (table 3.1).

Block sizes of \( N_t = 65400 \) time-bins are used, corresponding to \( N_\nu = \frac{N_t}{2} + 1 = 32701 \) frequency-bins, and each event has up to 16 blocks. An averaged spectrum is calculated by averaging over all blocks of an event. The frequency-resolution in the full 1 - 100 MHz interval is determined by the number of bins \( N_\nu = 32701 \) as 100 MHz / \( N \sim 3 \) kHz, which is then clipped to an interval of 30 - 80 MHz. This bandpass filter is applied with edges smoothed in a Gaussian-like fashion to reduce sharp cut-off affects, affecting 5 bins at both ends of the spectrum after integrating in bins of 1 MHz (i.e. [28, 29, 30, 31, 32] MHz, with similar result centered around 80 MHz). Frequency-channels contaminated by RFI are set to zero, as described in section 2.2.2. The number of events before and after filtering, and the number of antennas after filtering are listed in table 3.1.

The system noise temperature \( T_{\text{sys}}(\nu,t) \) is defined as the sum of the receiver noise temperature \( T_{\text{rec}}(\nu,t) \) and the electronics noise temperature \( T_{\text{elec}}(\nu) \)

\[
T_{\text{sys}}(\nu,t) = T_{\text{rec}}(\nu,t) + T_{\text{elec}}(\nu),
\]

where, in the absence of RFI, the receiver noise temperature only contains Galactic radiation,
Figure 3.5: Left: Reduced χ-square values for all 5 sub-bands. For clarity, the dashed lines indicate minima, which vary from χ² = 0.15 at 30 - 40 MHz up to χ² = 2.62 at 60 - 70 MHz. Right: Electronics noise correction in µV/MHz. Uncertainties are the noise correction at the point where χ = χ² min + 1, for each of the different sub-bands.

so that \( T_{\text{rec}}(\nu, t) = T_{\text{sky}}(\nu, t) \) \([58]\). Measurements on the subject of electronics noise in the LBA have so far been sparse, and the only data available are represented in figure 3.7, which shows the fraction of sky noise over total noise as a function of frequency. It is clear from the figure that the antenna is sky-noise dominated below \( \sim 65 \) MHz, but only by a small margin. Above 65 MHz it is electronic noise that dominates. No uncertainties on the depicted values are available. However, as is clear from the figure, electronics noise forms a non-negligible part of the detected signal, and it is therefore essential to investigate the uncertainties into more detail.

In order to do this, the received power for both simulations and data have been plotted as a function of time. Values have been expressed in decibel (dB) to reveal the relative variations more clearly, using the conversion

\[
G_{\text{dB}} = 10 \cdot \log_{10} \left( \frac{P(t)}{P_0} \right),
\]

with \( P(t) \) the frequency-integrated power at time \( t \), and \( P_0 \) the power at 00:00 h LST. Results are shown in figure 3.4, using CS002 LBA OUTER. The figure shows that significantly larger variations in power occur for simulations, reaching a minimum of -1.5 dB from \( P_0 \) around 10:00 h LST.

Since the data has been cleaned from radio interference, it consists solely of noise originating from the Galaxy, as well as a residual electronics signal. It is therefore possible to determine the amount of electronics noise in the signal, by adding an absolute offset (i.e. a value constant with respect to time) to the simulated voltage. This offset replicates the effect electronics noise has in the data. The offset that results in the most overlap between simulated and measured power – when expressed in dB, so that only relative variations are shown – is the most probable electronics offset in the trace. As the electronics noise is a frequency-dependent factor, this noise-floor analysis has been split up into different 5 different sub-bands of 10 MHz each, ranging \([30 - 39, 40 - 49, \ldots, 70 - 79]\) MHz. The integrated uncalibrated power and simulated power are depicted in figure 3.6 for
each of these sub-bands, similar to figure 3.4. The large error bars in the 30 - 40 MHz sub-band are caused by large variations at the very lowest limit of the frequency spectrum (below 34 MHz). As noted in chapter 2, two different bandpass filters exist that can be chosen before observations, ranging either 10 - 80 MHz, or 30 - 80 MHz. All analyses have been performed in the 30 - 80 MHz frequency range. However, the narrower 30 - 80 MHz bandpass results in a noticeable power cut-off around 30 MHz when compared to the wider bandpass [58]. Events with either setting are included in the analysis, yielding a larger spread in power at the lowest frequencies.

In each band, the corrected power at a certain time has been determined as

\[
P_{\text{sim}}(t) = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} \frac{(V(\nu, t)_{\text{sim}} + a)^2}{Z_0} \, d\nu, \quad (3.21)
\]

\[
P_{\text{data}}(t) = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} |\mathcal{F}(\nu, t)|^2 \, d\nu, \quad (3.22)
\]

with \(\nu_{\text{max}}\) and \(\nu_{\text{min}}\) the upper and lower limits of each frequency sub-band, and \(a\) the voltage offset. The measured power has been binned in time-intervals of 15 minutes, and required to be within one half and two times the median power in that time-bin.

A reduced \(\chi^2\)-square fit has been performed to determine the optimal voltage offset (value of \(a\)) per separate band. The 15-minute bins result in 97 data points, and consequently 96 degrees of freedom. Each data point contains on average 34 events, where variations exist due to statistical fluctuations. The results are shown on the left side of figure 3.5, showing reduced \(\chi^2\)-square values for different noise corrections in each sub-band. The final voltage offset band is the noise correction value where \(\chi^2 = \chi^2_{\text{min}}\), the minimum value. The low value for \(\chi^2\) in the 30 - 40 MHz sub-band (where \(\chi^2 = 0.15\)) is caused by the large uncertainties in this frequency range due to varying bandpass filter settings.

Uncertainties on the voltage offset correspond to noise corrections at the point where \(\chi^2 = \chi^2_{\text{min}} + 1\). Final voltages offsets including uncertainties are depicted in figure 3.5 on the right. A sharp minimum in \(\chi^2\) results in much smaller uncertainties on the final correction value, as is the case for the 40 - 50 MHz sub-band. In contrast, the 60 - 70 MHz sub-band has an offset with substantially larger uncertainties, as a result of the broader minimum in \(\chi^2\). Different stations than the currently used station CS002 yield almost identical results. Only outer antenna sets have been used to ensure at least several data points exists in each bin. It is however important to note that a \(\chi^2\)-fit relies on a Gaussian distribution of data points within each bin. For the average of 34 events per bin, this might not entirely be the case. Additionally, the different uncertainties are not uncorrelated. Gain-fluctuations e.g. due to rain in one event will possibly have residual effects in events detected at a slightly later time. However, these effects are expected to be small enough to allow for the use of a \(\chi^2\)-fit. Figure 3.8 shows corrected powers as a function of frequency for each frequency band, similar to figure 3.6.

Using the obtained results, it is possible to establish new values for the ratio of \(T_{\text{sky}}\) over \(T_{\text{sys}}\). The contribution of sky noise in each sub-band \(T_{\nu, \text{sky}}\) has been determined as the mean simulated voltage in the frequency band, divided by the average contribution of the antenna model in this frequency range. Simulated voltages have been taken at 00:00 h LST, where the received Galactic radiation is evenly located between the Galactic minimum and maximum, and dipole X and Y.
Figure 3.6: Median uncalibrated power, integrated in various frequency sub-bands, as a function of local sidereal time, in dipoles X and Y. Also shown is the simulated received power in both dipoles (solid red lines) in the same frequency range. Uncertainties and dipoles are used in the same way as figure 3.4.
Figure 3.7: Left: Contribution of sky temperature to the total system temperature, for LBA INNER (circles) and LBA OUTER (squares). Fractions are mean values. Figure taken from [7]. Right: Calculated values for the contribution of sky temperature to the total system temperature, using CS002 LBA OUTER. Values and uncertainties follow from equation (3.27).

receive the same simulated signal, so that

$$V_{\nu, mean} = \frac{1}{N} \sum_{i = \nu_{\text{min}}}^{\nu_{\text{max}}} V(i),$$  \hspace{1cm} (3.23)$$

$$J_{\nu, mean} = \frac{1}{N} \sum_{i = \nu_{\text{min}}}^{\nu_{\text{max}}} \int_{\Omega} \sqrt{|J_{X, \theta, \nu}|^2 + |J_{X, \phi, \nu}|^2} \, d\Omega, \text{ and}$$

$$T_{\nu, sky} = \frac{V_{\nu, mean}}{J_{\nu, mean}}.$$ \hspace{1cm} (3.24)

Note that the choice for dipole X in $J_{\nu, mean}$ is arbitrary as no radiation model is implemented here, so that

$$\int_{\Omega} \sqrt{|J_{X, \theta, \nu}|^2 + |J_{X, \phi, \nu}|^2} \, d\Omega = \int_{\Omega} \sqrt{|J_{Y, \theta, \nu}|^2 + |J_{Y, \phi, \nu}|^2} \, d\Omega$$ \hspace{1cm} (3.26)

for all frequencies. The resulting $T_{\nu,sky}$ is then a close approximation of the Galactic power received in the frequency band before antenna response. The absolute electronics noise correction in each band has been corrected by the average contribution of the antenna model in the full 30 - 80 MHz frequency range for normalization, so that the ratio of $T_{sky}$ over $T_{sys}$ becomes

$$\frac{T_{sky}}{T_{sys}} = \frac{T_{\nu, sky}}{\left(\frac{V_{\nu, noise}^2}{J_{30 - 80, mean}}\right) + T_{\nu, sky}}.$$ \hspace{1cm} (3.27)

For the majority of frequency range, the new $T_{sky}/T_{sys}$ are roughly equal to the previous results in figure 3.7. The lower frequency range has a sky-noise contribution of roughly 65% in both figures. However, where previous results claim this same constant contribution up to 60 MHz, new values
Figure 3.8: Median measured uncalibrated power, integrated in various frequency sub-bands as indicated, as a function of local sidereal time, in dipoles X and Y. Also shown is the corrected simulated received power in both dipoles (solid red lines) in the same frequency range. Uncertainties and dipoles are used in the same way as figure 3.4.
Figure 3.9: Integrated measured median uncalibrated power, as a function of local sidereal time, in dipole X (left) and dipole Y (right) (Dipoles 83 and 82 respectively of CS002 LBA OUTER). Also shown is the simulated received power in both dipoles (solid red lines), corrected for electronics noise offsets as depicted in figure 3.5.

are significantly lower in the 50 - 60 MHz range. At higher frequencies, the fraction of sky-noise in the full signal remains relatively constant.

Figure 3.9 shows the resulting variation in decibel after correction for electronics noise as a function of local sidereal time. It is clear that simulations and data have significantly more overlap after corrections. Still, a time-dependent discrepancy still exists for both dipoles, which is most pronounced in dipole X between 10:00 h LST and 20:00 h LST. In the following analyses an electronics noise offset has been applied to simulations. In order to negate the effect of discontinuous large bumps at multiples of 10 MHz, the noise offsets per sub-band have been smoothed over 4 bins around each 10 MHz multiple.

### 3.3 Results of the calibration

The received power for a single event as well as simulations at 02:00 h LST as a function of frequency is shown in figure 3.10 (left). Both show similar behavior over the full frequency range, spanning a little less than two decades in power overall. The resonance frequency however is slightly shifted, appearing at 60 MHz for simulations, while data peaks at 58 - 59 MHz. Also, simulations appear to be more symmetric around the resonance frequency, resulting in a slightly higher power at 80 MHz than at 30 MHz. A slight flattening of the simulated spectrum appears around 70 MHz. Even after smoothing, small bumps due to electronics noise correction can still be discerned where jumps in noise correction are largest, i.e. around 50 MHz and 70 MHz.

The measurements show a different pattern, with a much flatter spectrum below the resonance frequency and a much steeper fall-off at higher frequencies. It is reported that cables running from the LBA towards the TBBs yield a signal-attenuation that increases with frequency. However, corrections with coaxial cable measurements result only in a very slightly decreased slope, and are therefore insufficient by far to explain the steep fall-off at the end of the spectrum. Also, several
discontinuities are observed around 35, 50 and 63 MHz. The slight increase in power at 63 MHz is a known issue for the LBA. However, attempts by others to reconstruct the same behaviour in the antenna model have not succeeded so far.

The dips around 35 and 50 MHz could possibly be explained by signal propagation through the LNA receiver, which is known to receive signals in different frequency sub-bands. Slight deformations are therefore possible. Additionally, signal reflection on different antennas are a possibility. It is also expected that water on the antenna, e.g. due to rain or snow, results in a complete shifting of the gain towards lower frequencies. As the dipoles dry up again, the gain-curve is expected to slowly drift back towards its original position. Since the used data contains over 3000 event collected in several years of data, any type of weather possible is represented in the data. For that reason, any shifts in the gain-curve could be averaged out.

The calibration factor can now be calculated as a function of frequency. Calibration factors are corrected for local sidereal time in the following way: the simulated power in a certain dipole – which is normally simulated at intervals of 30 minutes in LST – is taken to be the closest to the actual event timestamp. Then, the total simulated power is scaled to an interpolated value, following the curves of dipole X and Y in figure 3.3. Interpolated powers are no more than 4 minutes away from the actual event timestamp. When using all events from CS002 LBA OUTER, this results in the graph shown in figure 3.10 (right) where the calibration factor is plotted as a function of frequency.

The mean calibration factor shows a clear slope as a function of frequency. This slope steeply increases at the upper edge of the frequency spectrum, due to the flattening of the simulated spectrum, which is not observed in the measurements. Also, the uncertainty on $X(\nu)$ grows slightly with increasing frequency. The curving behaviour of $X(\nu)$ between 50 and 75 MHz appears to be a residual effect of electronics noise corrections to the simulated spectra.
Figure 3.11: Relative deviations from the mean calibration factors for dipoles X/Y in LBA INNER (left) and LBA OUTER (right) as a function of frequency. Values are taken to be variations from the mean calibration factor of each particular sample, where a sample corresponds to all events of a single station, with one particular antenna set.

Figure 3.11 depicts relative deviations from the mean calibration factor for different samples. The figure shows that separating samples per used dipole yields very small fluctuations. Deviations range up to a maximum difference with the mean value of 2.9%, and both antenna sets show the strongest X-Y separation in station CS004, with the smallest separation in CS003. Both sets show relatively stable deviations from the mean for frequencies below 60 MHz, with more turbulent behaviour at higher frequencies. Outer antennas show less variation over most of the bandwidth. This could be a result of less statistical fluctuations, as significantly more data are available for the outer antennas. Also, cross-talk is expected among the inner antennas as their separation distance is smaller than the detected wavelengths. This effect is expected to be less pronounced in the outer antenna set. Dipoles Y have systematically lower calibration factors than dipoles X. A possible reason is how the strongest contribution of radiation – the Galactic center – moves through the field of view of LOFAR. The two dipoles measure the Galactic center with varying intensities at most time. A slight error either in the used radiation model or in the description of the antenna model could account for small differences, possibly explaining the difference seen in this figure.

When varying stations and antenna sets, variations are shown in figure 3.12. Deviations are less than 4% for all samples. All stations show quite consistent behaviour for most of the frequency range, with relatively larger variations for station CS003 around the resonance frequency. Inner antennas reveal higher calibration values than the outer antennas for low and high frequencies. Around 50 - 70 MHz, however, the differences converge to zero, and no clear differences are apparent in this region.
Figure 3.12: Relative deviation from the mean calibration factor for different stations and antenna sets as a function of frequency. The mean calibration value is taken to be the mean over all samples combined. Deviations are less than 4% over the full bandwidth for all stations.

3.4 Intermediate conclusions and uncertainties

The method applied in this chapter provides a calibration of the LOFAR low-band antennas with models of the Galactic radio emission. After interpretation of both the expected and received signals – which required an additional analysis of intrinsic noise levels in the dipoles – the method is applied on a single antenna level to reliably calibrate the complete array. Additionally, differences between antennas and various stations are determined. For future work, it would also be relatively straightforward to implement the analysis at completely different radio experiments, such as AERA and Tunka-Rex.

For the LBAs, the calibration factor appears to show a slope as a function of frequency. This slope ranges from almost non-existent at 30 MHz, to significantly larger at the upper end of the spectrum. Slight discrepancies between measured and expected spectra result in a curving behaviour between 50 and 75 MHz. Comparing the analysis for different stations and antenna sets yields only small fluctuations. Variations deviate 4% from the mean over all stations at most, and are significantly less around the resonance frequency – which contributes the majority of the received power. One drawback of the analysis is that in using this calibration method, the angular dependence can not be distinguished. The reason for this is that the setup integrates signals over the full sky (corresponding to half of a sphere). Therefore, if the response at one angle is underestimated, it could be corrected for at other, possibly overestimated angles. The method is also sensitive to several uncertainties, such as the Galactic emission model, statistical variations, and the amount of electronics noise in the LNA.

The use of a Galactic emission model introduces two different sources of uncertainties. The first is a relative measure of how well the model is compatible with measurements. In this thesis, this is referred to as a relative uncertainty. For GSM, the relative uncertainty is reported to range from 1 - 10% in sky temperature. Additionally, differences between LFmap and GSM are also taken into account, and are 5% at most. The second source of uncertainty, here referred to as an absolute scaling, corresponds to how closely the measurements – that is, the reference
<table>
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<th>Value [%]</th>
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</tr>
<tr>
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</tr>
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<tr>
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<tr>
<td>Electronics noise</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td>38</td>
</tr>
</tbody>
</table>

Table 3.2: Contributions to uncertainties on $X(\nu)$ in the calibration using the Galactic background radiation. Note that values are expressed in amplitude rather than power. As described in section 3.4, the relative uncertainty refers to how well models describe measurements, while the absolute uncertainty illustrates how well measurements describe the true sky-temperature.

maps that GSM and LFmap interpolate to – describe the true sky-temperature. Indications from several surveys show that this is mostly around the 10% range, ranging up to a maximum of 20% for some frequencies and regions. Therefore, as a conservative estimate, the value of 20% is adopted as absolute uncertainty. Note that these uncertainties are expressed in power, while the calibration factor $X(\nu)$ scales with the amplitude (i.e. the square root of the power). Modelled sky-temperatures fluctuating between these uncertainties yield a maximum uncertainty on $X(\nu)$ of 5%, 9% and 2%, respectively, for relative scaling, absolute scaling, and differences between the two models.

Statistical fluctuations contain a variety of aspects. Per data sample, they contain all used dipoles (up to a maximum of 96). In addition, every sample contains data from events detected over the course of several years. Within this timeframe, several environmental factors have fluctuated heavily. Grass between antennas varies between freshly mown and relatively long. Temperatures in the Netherlands fluctuate mostly from just below zero up to 25°. In addition, the antennas may be partially covered by a layer of snow, although this happens only rarely. Droplets of water – as a result of rain or fog – are expected to have a noticeable effect on the resonance frequency. The deviation on the measured statistical fluctuations ranges up to a maximum of 5% over the full frequency range. Calculating $X(\nu)$ for all events in any single antenna results in fluctuations of the same order, so that can be concluded that this is completely dominated by environmental circumstances. An analysis of the electronics noise in the antenna resulted in several frequency-dependent sub-bands with different noise-contributions. Optimal electronics noise values are determined by a $\chi^2$ fit, which are comparable to results from earlier measurements with slight differences of the entire frequency range. Calculations of $X(\nu)$ with $T_{\text{sys}} \pm$ one standard deviation result in uncertainties of 37% at most, although this is generally more centered around 25%.

An overview of all different contributing uncertainties can be found in table 3.2. Using conservative estimates, the total uncertainties in amplitude sum up to

$$\frac{\sigma X(\nu)}{X(\nu)} = \pm 5\% \text{ (statistical)} \pm 38\% \text{ (systematic).}$$  (3.28)
Chapter 4

Calibration using a reference antenna

A method is proposed to calibrate the LBA receiver system in the last section of chapter 2.3. This has been carried out by use of the galactic radio emission in the previous chapter. The same calibration technique can be carried out using a stationary reference antenna with a known field strength. Such an application will be less sensitive to the mentioned uncertainties, and is therefore an important independent study. In-field calibrations have been performed at the LOFAR superterp near Exloo during a 2-day campaign in May 2014. This chapter describes in detail the measurement campaign performed, and discusses the results that are found.

Figure 4.1: Experimental set-up for the calibration campaign. Left: crane with the wooden construction and the LBA underneath. Right: Dipole source VSQ 1000 with DGPS, as it is suspended by the crane and held in place by two strings.
4.1 Method

To effectively calculate the sensitivity of the LBA, a transmitting dipole antenna (type VSQ 1000) is placed at a distance of $r = 12.65 \pm 0.25$ m above the antenna (the ‘main’ antenna). This is held in position by a movable crane with a wooden extension of 5.3 meter. The extension is used to avoid reflection of the signal on metal parts of the crane, which would otherwise cause interference. Along with the radio source, the crane also holds a differential GPS system to accurately determine the position of the source. Figure 4.1 shows the experimental set-up for the calibration campaign. The source is aligned by use of strings, which are secured to the ground. During this campaign, measurements have been performed on antenna 36 (LBA INNER) and 63 (LBA OUTER) of station CS001. The emitted frequency-comb signal is strong enough to be detected by all antennas in the station, but not in other stations, as the nearest station is over 100 meters away. The setup is similar to a calibration campaign earlier performed at LOPES, also using exactly the same reference antenna [59].

4.1.1 The reference antenna

The radio source used for the direct calibration is a commercial product: company Schaffner, Augsburg – type VSQ 1000. The VSQ 1000 consists of two parts: a signal generator RSG 1000, and the biconical antenna DPA 4000, as depicted in figure 4.2, left.

The RSG 1000 is a signal comb-generator, generating continuous signal peaks at multiples of 1 MHz, in the 1 MHz to 1 GHz range. Over the entire used frequency range from 30 to 80 MHz, it has a mean power of 1 $\mu$W, and is battery-operated - making it easy to use for measurements in-field. The DPA 4000 biconical antenna is linearly polarized, with near-constant directivity close...
to the main lobe. This means that small misalignments with the receiving antenna result in small losses only. The VSQ 1000 setup is certified for the 30 MHz to 1 GHz frequency range, and is therefore suitable for the LOFAR calibration. The datasheet provided by the manufacturer reports that the VSQ emits signals with an effective amplitude ranging from 5.37 µV/m at 30 MHz to 120.2 µV/m at 80 MHz at a distance of 10 meter\(^1\). A certificate provided by the manufacturer also puts the systematic uncertainty of the emitted field to 2.5 dB (corresponding to \(\sim 33\%\) in amplitude). Additionally, the signal generator has an uncertainty on the stability better than 0.5 dB (6% in amplitude) in the temperature range from 10\(^{\circ}\) to 30\(^{\circ}\). Data-sheets containing the expected emitted spectrum for the entire frequency range can be found in figure 4.3. An example of a typical VSQ-generated spectrum detected by the LBA can be seen in figure 4.2 (right) which shows the received spectrum as a function of frequency. The single MHz peaks, which are up to a factor \(10^{5.5}\) higher than noiselevels, can clearly be distinguished. Some RFI-lines are still visible, but are also several orders of magnitude lower than the signal.

\(^1\)These values are a factor \(\sim 2\) different from what is used in [59]. The reference antenna has since been recalibrated by the manufacturer in a situation more closely resembling the measurement campaign, and the new values have thus been used in this thesis.
4.1.2 Data set

Data samples have been taken in various setups, such as varying altitude and orientation of the transmission antenna. For each sample, a trigger was sent manually to the TBBs, causing them to read out 2000 pages, which corresponds to 10 ms of data. A blocksize of $N_\nu = 32701$ bins is used, corresponding to a frequency-resolution of $\sim 3$ kHz in the full 1 - 100 MHz interval. The edges of the spectra are again smoothed in a Gaussian-like fashion at 30 MHz on the lower end of the spectrum and at 80 MHz at the upper end. These edges spread over 5 bins at each side, following the same procedure as with the calibration using galactic emission. Each signal peak has spread over up to 3 bins at this frequency resolution, corresponding to a width of less than 9 kHz. The total power is obtained by integrating over these bins. The noise baseline is at least three orders of magnitude lower than the signal, and contributes less than 1% to the total power.

4.2 Pre-analysis cross-checks

In order to reliably calibrate the end-to-end system, it is important to make sure the data are well-understood. Different cross-checks have been performed to check the stability of the data, and to see whether the emitted field is understood correctly.

4.2.1 Signal detection in the station

It is insightful to check how the signal emitted by the reference antenna is received over the entire station. This could identify malfunctioning- or only partially working antennas, as well as unexpected behaviour in the reference antenna. Figure 4.4 shows the integrated received uncalibrated power in each antenna, as a function of distance. The figure shows that for both days the power falls off in a well-behaved way and in very similar fashion, thereby not marking any malfunctioning
antennas. Since day 1 corresponds to the outer antennas, which are placed further apart, distances are greater than the second day.

However, the received uncalibrated power is consistently almost 35% lower on the first day when compared to the power received during the second day. The reduced power does appear to affect all antennas during day 1. This suggests that some unexpected effect is disrupting the data acquisition in station CS001. All measurements are taken at the same maximum altitude the setup allows, which is a distance of $12.65 \pm 0.25$ m. Figure 4.5 shows the (uncalibrated) power received by the main antenna, as a function of distance between the reference- and LOFAR antenna for both days. The figure illustrates that the altitude has not accidently been different than recorded, since it follows a reasonably good $r^{-2}$ fit. It is therefore plausible that the reduced power can be contributed to malfunctioning of the reference antenna. This seems extra likely because of a small technical error in the set-up of day 1, that was detected after the campaign. The same was not observed in the set-up of day 2. Unlike for day 1, the measurements of day 2 are therefore expected to be well-behaved and in line with the calibrated effective amplitude of the reference antenna as described in section 4.1.1.

4.2.2 Field region measurements

As discussed in chapter 2.3.2, it is unclear which field region is dominating at the LBA - and consequently, how the received uncalibrated power varies with distance. Depending on the dominating field region, this power should drop as $P \propto 1/r^2$ for the far field, and as $P \propto 1/r^4$ for the inductive field.

In an attempt to identify the leading field region, measurements are performed with the trans-
mission antenna at different heights above the LBA. The received uncalibrated power has been integrated over the full bandwidth (30 - 80 MHz). In addition, a separate integration over low frequencies (35 - 40 MHz) and high frequencies (70 - 75 MHz) has been carried out. This separation is then used to distinguish whether possibly a far-field approximation is valid only for the high-frequency interval (corresponding to short wavelengths), while this is not necessarily the case for the low-frequency interval (longer wavelengths).

Results can be found in figure 4.5, which shows the received uncalibrated power \( P_m \) with respect to distance \( r \) between VSQ and antenna. It is clear from the figure that a far-field approximation is a significantly better fit, for all frequency ranges. However, it cannot be excluded completely that the field at the LBA is a mixture of far- and inductive field to some degree. The figure also shows that at a distance of 12.65 meters, where most of the measurements have taken place, no signal saturation takes place.

### 4.2.3 Polarization sensitivity

The dual-polarized configuration of the LBA allows for a good cross-check of the polarization sensitivity. The received power should change with \( \cos^2 d\Phi \), with \( d\Phi \) defined as the angle between the axis of the VSQ and the LOFAR antenna. Figure 4.6 (left) depicts the integrated received uncalibrated power as a function of angle between the reference antenna and the LOFAR antenna, for campaign day 2. Both dipoles appear to follow the expected curve, although the Y-dipole receives almost 30% less power than dipole X. A possible influence might be signal reflections on either the metal crane, or other nearby antennas. Additionally, cross-talk is expected. This can be interpreted from figure 4.6 (right) which shows the position of antennas within a station, and as a
comparison one wavelength for electromagnetic waves with a frequency of 30 MHz, as well as for 80 MHz. For inner antennas, where the distance between the antennas is smaller than the detected wavelengths, cross-talk is therefore expected. Distances between outer antennas are mostly larger than one wavelength for all frequencies. Dipole Y of antenna 63 directly faces the nearest antenna at less than a meter distance. It is therefore possible the dipole experiences cross-talk to some amount. In addition, bad alignment might contribute to a small extent. A large contribution is unlikely, as that would result in a detectable signal in dipole X as well, and is therefore less likely. Finally, the manufacturer of the antennas claims that differences in power are at most 10% from the mean for different dipoles. For that reason, the reduced power detected in dipole Y could also simply be unlucky.

4.2.4 Conclusions for consistency checks

Most of the data samples taken during the campaign appear to be very consistent in their results. Wind and other non-systematical external effects appear to have a small influence only, as different data samples taken with the same setup yield very similar results. A far-field approximation appears to be valid for all frequencies within 30 - 80 MHz, and rotational effects are mostly consistent with expectations. However, signals detected during the first day are significantly lower compared to day 2 throughout the entire station. The lower measured power led to the exclusion of day 1 in the rest of the analysis entirely, as we feel the inconsistencies are too large to yield a reliable calibration of the receiving antenna.

Data for the second day show a slightly lower received power in dipole Y than expected. No official journal tracking the functioning of antennas exists, so there is no way to directly confirm the status of the antenna during the campaign. Manually investigating data recorded in the events surrounding the campaign for LBA INNER reveals no abnormalities. However, only events roughly three weeks earlier and later are recorded, and it is possible that any defects have occurred and been fixed in the meantime. Because of this, it is likely that the most reliable data contain samples from the second day taken at maximum altitude, using only the signals detected in dipole X. All further analyses are done using these results. In cases where other dipoles are included, this is specifically mentioned.

4.3 Results using single antenna measurements

If there are no disrupting effects - such as signal influences because of the metal crane or reflection on nearby antennas - the expected power in a dipole is calculated via equation (2.17) as

$$P_e(\nu) = \frac{|\vec{E}(\nu) \cdot \vec{H}(\nu)|^2}{Z_0}. \quad (4.1)$$

with $\vec{E}(\nu)$ the effective amplitude of the electric field. The amplitude of $\vec{E}(\nu)$ is corrected for the height of the transmission antenna above the LBA, since the manufacturer reports values at 10 meter, while the transmission antenna was positioned 12.65 meter above the LBA. Additionally, within an experimental uncertainty of a few degrees, the transmission antenna was aligned with the receiving dipole. Because of the linear polarization of the source antenna, $\vec{E}(\nu)$ is reduced to

$$\vec{E}(\nu) = \begin{pmatrix} E_\theta \\ E_\phi \end{pmatrix} = E_{eff}(\nu) \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix}. \quad (4.2)$$
with $E_{\text{eff}}(\nu)$ the effective amplitude of the electric field as provided by the manufacturer (depicted in figure 4.3, as a function of frequency). As a result of the linear polarization, only the $J_{X\theta, \nu}$ component contributes at each specific frequency (equation (2.11)). Inserting this into equation (2.19), $X(\nu)$ is obtained – which is now directly the translation from the expected power $P_e(\nu)$ to the power $P_m$ that is measured in the dipole

$$X(\nu)^2 \equiv \frac{P_e(\nu)}{P_m(\nu)} \quad (4.3)$$

$$= \frac{1}{Z_0} \frac{|\vec{E}(\nu) \cdot \vec{H}(\nu)|^2}{|\mathcal{F}(\nu)|^2} \quad (4.4)$$

$$= \frac{1}{Z_0} \frac{|E_{\text{eff}}(\nu) \cdot J_{X\theta, \nu}|^2}{|\mathcal{F}(\nu)|^2}. \quad (4.5)$$

The results are shown in figure 4.7. The left figure shows both the simulated and the (uncalibrated) measured power spectrum, as a function of frequency. The right figure depicts the resulting calibration factor $X(\nu)$, also as a function of frequency. Only data from day 2 are used, at maximum altitude and aligned with dipole $X$. Both simulated and measured power spectra show a very similar pattern, with a small number of subtle differences. The simulated spectrum has distinctive peak when compared to measurements, suggesting that the actual antenna response is flatter than the modelled VEL. This was earlier established in [1]. Similar to the calibration efforts with Galactic emission, bumps appear at 52 and 64 MHz. Possible causes are signal propagation through the LNA receiver, and reflections on different antennas and the crane. This would be most strongly detected around the resonance frequency, where the signal is strongest and small fluctuations are more pronounced.

At the upper frequency-limit of the spectrum, the measured power spectrum drops significantly,
Figure 4.8: Left: Emission of an ideal dipole, drawn in black in the center of the figure. The radiated field strength drops to zero for small angles between the polarization axis and the emission direction. Right: Integrated power received in all dipoles X (circles) and dipoles Y (triangles) for $d\Phi = 0$. Powers are corrected for losses due to a lower VEL amplitude at different angles, and due to polarization mismatches. Colored markers are measurements, open markers are simulations. The solid $r^{-2}$ line is fitted to data in dipole X. Simulations are scaled to match the power in dipole 72, and all exactly follow the $r^{-2}$ line.

while the simulated spectrum appears to flatten. This is also apparent in the calibration curve, which increases steeply by a factor $\sim 2.5$ in the upper 5 MHz. The peak around the resonance frequency is clearly visible for $X(\nu)$, due to the mismatching of the modelled VEL and the real antenna model. Since weather conditions shift the entire gain-curve (chapter 3), it is difficult to correctly implement this in the antenna model.

4.4 Results using full station measurements

By expanding the calibration method to all 96 antennas in the station, it is possible to get a sense of directional differences, as well as further reduce statistical fluctuations. The documentation of the VSQ 1000 only gives calibrated values for the front lobe. The same method used for a single antenna can easily be expanded to a include the full station. For a single dipole, the calibration factor can still be expressed as equation (2.19), where the expected power requires a new expression for the electric field $\vec{E}(\nu)$ and the VEL $\vec{H}(\nu, \theta, \phi)$.

In order to estimate the received electric field at antennas at varying angles, a simple dipole model has been used where the simulated electric field $E(\nu)$ is determined by

$$\vec{E}(\nu, \theta') = \frac{E_0(\nu) \cdot \sin(\theta')}{\vec{r}},$$

(4.6)

with $\vec{r}$ the distance from the antenna, and $\theta'$ the angle between the reference antenna and the
receiving antenna. Figure 4.8, left, illustrates the emission pattern of an ideal dipole, as a function of angle \( \theta' \). A far-field approximation has been assumed in the entire station, which is evident from the fact that the simulated electric field falls off with \( \vec{E}(\nu, \theta') \propto r^{-1} \), so that the corresponding power decreases as \( P(\nu, \theta') \propto r^{-2} \).

In finding the correct amplitude of the VEL for an incoming signal at antennas not located directly below the source antenna, polarization effects need to be taken into account. A signal arriving under angle \( \theta' \) will experience a polarization

\[
\vec{E}(\nu) = \begin{pmatrix} E_{\theta} \\ E_{\phi} \end{pmatrix} = \begin{pmatrix} \sin(\theta') \\ \cos(\theta') \end{pmatrix}.
\] (4.7)

The expected power for a specific frequency \( P_{e, \nu} \) at a dipole is then

\[
P_{e, \nu} = \left( \frac{E_0(\nu) \cdot \sin(\theta')}{r} \right)^2 \cdot \left[ \sin(\theta') \cdot J_{X\theta, \nu} + \cos(\theta') \cdot J_{X\phi, \nu} \right]^2
\] (4.8)

with

\[
P_e = \int P_{e, \nu} \, d\nu.
\] (4.9)

Expected and received measured power for all dipoles in LBA INNER station CS001 – corresponding to campaign day 2 – are depicted in figure 4.8, right, as a function of the distance to the reference antenna. Both expected and measured powers are corrected for losses due to a lower VEL amplitude for antennas not directly below the reference antenna, as well as for polarization mismatches. For dipoles oriented perpendicular to the reference antenna (corresponding to a strong polarization mismatch, so that almost no power is received even for very strong signals), this correction could over-compensate. Noise in the trace becomes exaggerated, which could explain the upward trend in power with increasing distance for dipoles Y. This same over-compensation is not expected for dipoles X at large zenith angles (resulting in a low VEL amplitude), as the received signal in these dipoles is still orders of magnitude larger when compared to noise levels. Except for a significant dip in measured power in the dipole X closest to the main antenna, data and simulations for X-dipoles match closely. Most yield a simulated power very closely resembling the measured power after scaling, with only small variations in the entire antenna set. However, it is clear that as a function of distance, the measured power drops less fast than the expected \( P(r) \propto r^{-2} \).

Figure 4.9 shows the frequency-averaged calibration values for the different dipoles as a function of distance, with various measurement setups. The frequency bandwidths are clipped to 30 - 70 MHz to exclude the steep increase in \( X(\nu) \) at the highest frequencies. The situation illustrated in the top left subfigure is deemed to be the most reliable and best-executed measurement set-up, and is the setup used for all single antenna measurements in previous sections of this chapter. Even though uncertainties are substantial, the figure shows a clear decrease in calibration factor \( X(\nu) \) with increasing distance. The same conclusion can be drawn for the other figures, albeit with a significantly larger scattering. This is most strongly pronounced for both X and Y dipoles with an angle between the reference antenna and the LOFAR antenna of \( d\Phi = 135^\circ \). Possibly this could be caused by a relatively bad alignment, meaning that the source in fact was rotated slightly askew from the recorded value. This appears to be consistent with figure 4.6, where rotation \( d\Phi = 135^\circ \) is the only sample for which dipole X is removed somewhat from the expected curve. For the decrease in \( X(\nu) \) with increasing distance, possible explanations could be:
Figure 4.9: Mean calibration factor for the full station, dipoles X (left) and dipoles Y (right), for varying values of the angle between the reference antenna and the receiving antenna $\Phi$. Distance $r$ is the distance from the source to the receiving antenna. Error bars are the standard deviation from the mean calibration value per antenna, clipped to a 30 - 70 MHz frequency bandwidth. The red band corresponds to the mean value $\pm$ one standard deviation for Galaxy, CS002 LBA OUTER, also clipped to 30 - 70 MHz.
1. The modelled VEL of the reference antenna is incorrect. The power transmitted by the source drops as \( r^{-\alpha} \), with \( \alpha < 2 \), as is visible from figure 4.8, right, or the assumption of a simple dipole is too far simplified.

2. The modelled VEL of the receiving antenna is incorrect. The zenith-dependence of the modelled VEL is overestimated, so that the real VEL is more flat with respect to the zenith angle.

Unfortunately, with the used measurement setup, it is not possible to untangle these two possible effects. Since the source antenna is only calibrated in the forward direction, no uncertainties for different zenithal inclinations are available. However, a study of the relative sensitivity of the VEL has shown that the angular dependence of the antenna gain pattern is very well understood [1]. It is therefore most likely that the dipole simulations oversimplify the VEL of the source, and are not a good fit to the actually emitted field strength at various distances. To test whether this is the case, an improved model – obtained with an antenna simulation program Nec2 [60] – has been tested as well. The model includes more of the geometric model of the reference source, and should therefore yield more accurate results. These results are nearly identical as when using a simple dipole model, and do not change the observed trend. It is clear from this analysis that the correct modelling of an antennas response is difficult to perform. Various effects, such as the geometric model and internal resistances, make this an expert task, and any antenna simulations should therefore not be trusted without extensive testing beforehand.

A different setup, where the source antenna would be directed towards a receiving LBA under some inclination \( \theta \neq 0 \), would be able to exclude either of the possible effects. A different possibility would be to focus LBAs on an astrophysical point-source through spectral imaging\(^3\), and follow the object over longer periods of time as it moves through the field of view of LOFAR. The power obtained from the source at different angles yields information on how well the modelled VEL relatively agrees with the real antenna model. This method however is not applicable for an absolute calibration, as for most astrophysical point-sources the emission is not known with enough precision to be used in such a campaign.

### 4.5 Intermediate conclusions and uncertainties

The application of the calibration method with a linearly polarized reference source yields a number of significant benefits over a calibration with the Galactic background emission. It is less sensitive to uncertainties on intrinsic electronics noise, and requires less extensive knowledge of the antenna VEL as the signal only arrives from one direction. However, experimental errors can very easily be introduced with the used setup, such as bad alignment of the reference antenna, or even wrongly recorded transmission height or receiving antennas.

For single antenna measurements, a calibration factor \( X(\nu) \) is obtained. This factor is relatively flat over most of the frequency range of 30 - 80 MHz, with only small deformations. Additionally, \( X(\nu) \) reveals a steep increase in slope at the upper end of the spectrum as a result of a drop in the observed frequency spectrum. This same behaviour is not observed in simulations. By assuming a simple dipole model for the transmission antenna the same method can be applied to the entire inner set of antennas in CS001. Resulting calibration factors decrease with distance

\(^3\)A form of spectroscopy in which a complete spectrum is collected at every point in an image plane.
<table>
<thead>
<tr>
<th></th>
<th>Value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical</td>
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<td></td>
<td>Total 1</td>
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<tr>
<td></td>
<td>Alignment reference antenna and receiving dipole 5</td>
</tr>
<tr>
<td></td>
<td>Reference source emission 33</td>
</tr>
<tr>
<td>systematic</td>
<td>Reference source temperature stability 6</td>
</tr>
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<td></td>
<td>Environmental (excluding reference source effects) 5</td>
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<td></td>
<td>Far-field approximation 6</td>
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<td></td>
<td>Signal reflections 5</td>
</tr>
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<td>Total 35</td>
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Table 4.1: Contributions to uncertainties on $X(\nu)$ for the calibration with a reference source. Note that values are expressed in amplitude rather than power.

to the source, which is most likely caused by the oversimplification of the emission model of the reference antenna.

When comparing the integrated power between different measurement samples, it appears that statistical fluctuations are of the order of less than 1%. The expected signal is dominated by large systematic uncertainties on the emitted power of 33%. Stability due to temperature introduces another systematic uncertainty of 6%, although with a stable temperature around 10°C during those days\(^4\), this expected to fluctuate only marginally.

In addition to the uncertainties provided by the source antenna itself, the alignment between the source and the LBA provides an unknown factor. The GPS yields an uncertainty on the position of the source antenna of 0.25 meter. However, as the source has a near-constant gain close to its main lobe, small positional offsets result only in small losses. The same conclusion can be drawn for rotational offsets as a result of the $\cos(d\Phi)$ dependence, which are estimated to be less than 5°. Uncertainties as a result of misalignment contribute up to 5%.

In addition to the experimental setup, the local environmental conditions also influence the measurements. The entirety of local conditions such as vegetation growth, air humidity and drops of water on the antenna influence reflection and propagation of the emitted signal. Following the calibration using the galactic emission, environmental effects are determined to contribute 5% at most.

Measurements of the applicability of a far-field approximation reveal a good fit of $P \propto r^{-2}$ to data. This is the case for distances ranging from 5 to 13 meter above the LBA, for all frequencies on both days. However, most literature suggests a far-field approximation would only be valid for distances of $\lambda$ – corresponding to 10 meters for the LBA – at the very least. A conservative estimate therefore assumes an uncertainty equal to the value of 0.5 dB (~ 6%) found in other experiments at a significantly larger distance [45].

Less quantifiable factors include signal reflections on different antennas, and reflections on the metal crane. Signal reflections can occur when the distance between antennas is smaller than the wavelength of the signal, since reflections can interfere destructively with the original signal. This is reported to yield small spectrum deformations around the resonance frequency in other papers [1]. The same might be true for the metal crane. A wooden beam extension of roughly 5 meters

\(^4\)Temperature data available via the Royal Netherlands Meteorological Institute [61]
has been used to prevent reflections on the crane, but it is impossible to completely exclude minor influences. For further applications it might be advisable to use a larger crane, which could be positioned further away. However, as the LOFAR field is wet and almost swamp-like, the crane during this campaign had to be as light as possible, or it would sink in the ground. Still, no clear deformations are apparent when comparing dipoles X and Y, except for a reduced integrated power. Such systematic contributions, collectively summarized as contributions originating from the measurement set-up, are therefore expected to yield uncertainties of no more than 5%.

An overview of all different contributing uncertainties can be found in table 3.2. Using conservative estimates, total uncertainties sum up to

$$\frac{\sigma_{X(\nu)}}{X(\nu)} = \pm 5\% \text{ (statistical)} \pm 35\% \text{ (systematic)}. \quad (4.10)$$

These values are almost completely dominated by the large systematic uncertainty on the emission pattern of the pre-calibrated source. Other contributions are mainly effects due to the used measurement setup, although none are as significant as the emitted power. Different measurement samples are very stable, and fluctuate only very little.
In chapters 3 and 4, a frequency-dependent calibration factor $X(\nu)$ has been determined by use of two different sources; a reference antenna, and the radio emission from the Galaxy. In this chapter the two methods will be compared, and two additional cross-references will be discussed. The first of these is a direct comparison with measurements performed at other arrays. The second is a comparison with air shower simulations provided by CoREAS.

### 5.1 Comparing the applied calibration methods

The calibration method proposed in chapter 2 has been applied using a reference antenna, as well as the diffuse radio emission originating from the Galaxy. The advantage of two independent methods is that both have different uncertainties. The calibration with a linearly polarized reference source is for example less sensitive to uncertainties on intrinsic electronics noise. However, experimental errors can very easily be introduced with the used setup, such as signal reflections and bad alignment of the source antenna.

When comparing calibration factors obtained by the two methods, both exhibit a very similar behaviour. Results can be found in figure 5.1, which shows the calibration factors obtained, as a function of frequency. The two curves yield near-identical results below 60 MHz, with a slight deviation above this frequency. The calibration using the Galactic emission is higher by a factor $\sim 1.5$ for 60 - 75 MHz, still overlapping within one-sigma. As is established in [1], the real antenna model is more flat than the modelled VEL, with a slightly shifted resonance frequency. This effect causes the peak for the calibration with a reference antenna around 59 MHz. However, rain and snow cause the gain-curve of the antenna to shift in frequency. Therefore with the calibration using the Galactic background radiation, where events have been gathered over 4 years time during all types of weather, this peak is ’smeared out’ over a larger frequency range. For that reason, the peak is not visibly present. The calibration using a reference source, where data have been gathered over two days only, does not reveal this smearing effect. Additionally, both methods reveal a small slope over the full frequency range, while this significantly increases at the upper frequency range for the reference source. The two methods also reveal several bumps at different frequencies, caused by either signal propagation in the different sub-bands of the LNA (40 MHz), corrections on electronics noise (50 - 70 MHz), or a mismatch between VEL and data originating from a still unknown cause (63 MHz). Signal reflections and some measure of cross-talk is expected between closely spaced antennas, possibly explaining any remaining discrepancies.
Figure 5.1: Calibration factors as a function of frequency, for both calibration methods (red dashed and blue solid lines respectively). Both contain a darker band with statistical fluctuations, and a lighter band with statistical and systematic uncertainties combined.

5.2 Comparison to other measurements

Other calibration campaigns have been performed at both LOPES and Tunka, very similar to the calibration using a reference antenna that is performed in this thesis [59], [62]. Both use the exact same source antenna VSQ 1000, and place this above the receiving antenna by use of a crane. The methods are however slightly different. For LOPES and Tunka hardware-, cable- and ADC-responses are simulated, and compared to measured values. For LOFAR, all this is intrinsically included in the calibration values. Still, a comparison between the three experiments can be made. Traces obtained with the VSQ 1000 are normalized to a source at 10 meter distance, and then calibrated. The resulting calibrated traces are depicted in figure 5.2, as a function of time.

As the calibration is designed to calibrate the detected pulses to values reported by the manufacturer of the VSQ 1000, the pulses are required to be (approximately) the same. Small differences occur due to different hardware responses. For example, group delays remain uncalibrated across the different experiments. Also, LOPES originally has a sampling rate of 80 MHz. The trace is artificially upsampled to match Tunka-Rex and LOFAR. Additionally, uncertainties in the measurement setup - e.g. slightly different altitudes, signal reflections, misalignments - can cause small fluctuations. The figure shows that all three experiments are nearly identically calibrated. In all three of these calibration, the dominating source of uncertainty is the emission of the reference antenna. Since the same reference antenna is used for all three calibration efforts, this contribution cancels out, and only relatively small uncertainties remain. These are depicted in the figure as the grey box in the lower left corner. The expectation is that with the three traces closely calibrated, the determination of the energy content in the radio frequency domain of air showers becomes very well-comparable between these different experiments. The aim is therefore that in the future, as a result of these calibrations, detections of cosmic rays made by LOFAR, LOPES and Tunka will be consistent with one another to great precision. These efforts are currently still
Figure 5.2: Calibrated traces obtained with the VSQ 1000 for LOFAR, LOPES and Tunka, as well as corresponding Hilbert envelopes. Data obtained from [63]. Traces are Fourier transforms of frequency spectra clipped to 43 - 73 MHz. The grey block in the lower left corner represent the systematic uncertainties on the peak amplitude that remain between the three different experiments, as determined from the LOFAR calibration campaign.

5.3 Comparison to CoREAS predictions

In order to interpret measurements obtained from cosmic-ray detections, measured events are compared with Monte Carlo simulations. Such simulations follow the trajectories of particles in a shower, and calculate their emission on a single particle level. Different models exist, and all show consistent predictions of the signal distribution.

The model most widely used at LOFAR is called CoREAS, which is a program in C++ that provides a way of calculating the electromagnetic radiation associated with arbitrarily moving particles [32]. CoREAS simulates air showers for selected high-quality events (i.e. no disturbing effects, and enough good stations contained by the shower). Basic parameters describing the event (both the energy and the arrival direction reconstructed from the actual measurements) are used as input parameters for the simulation, thereby ‘mimicking’ the real air shower as closely as possible.

The development of the simulated air shower in the atmosphere is predicted per individual particle using Monte Carlo techniques, up to the three-dimensional electric field expected. Such air shower simulations help in better understanding different relevant physical parameters of the air shower, as well as in the development of more accurate particle interaction models. Using CoREAS, it is possible to perform a similar calibration effort to what has been carried out in the previous chapters.
5.3.1 Predictions from CoREAS

Every time a high-quality event is selected to be reconstructed by simulations with CoREAS, 40 identical events are simulated, with varying primary particles\(^1\) to prevent a bias in this regard. Fluctuations between these 40 simulations\(^2\) regarding parameters such as the depth of the shower maximum \(X_{\text{max}}\), and the shower core, reflect the natural possible spread for each shower.

For each simulation, a two-dimensional radiation map as well as a one-dimensional particle density function are fitted to the data simultaneously, by minimizing

\[
\chi^2 = \sum_{\text{antennas}} \left( \frac{E_{\text{ant}} - f_p^2 E_{\text{sim}}(\vec{x}_{\text{ant}} - \vec{x}_0)}{\sigma_{\text{ant}}} \right)^2 + \sum_{\text{particle detectors}} \left( \frac{d_{\text{det}} - f_p d_{\text{sim}}(\vec{x}_{\text{det}} - \vec{x}_0)}{\sigma_{\text{det}}} \right)^2,
\]

where \(E_{\text{ant}}\) is the measured energy integrated in each antenna at location \(\vec{x}_{\text{ant}}\), with noise level \(\sigma_{\text{ant}}\) and \(E_{\text{sim}}\) the simulated energy. Similarly, \(d_{\text{det}}\) is the deposited energy measured by a LORA detector at location \(\vec{x}_{\text{det}}\), with noise level \(\sigma_{\text{det}}\), and \(d_{\text{sim}}\) is the simulated deposited energy. The scaling parameter \(f_p\) is needed to correct the energy scale, and mostly correlates to the sensitivity of the LORA detectors, rather than the antennas. The parameter \(f_p^2\) corresponds to the calibration of the radio power, as it is detected by the antennas, and is the parameter of interest for this analysis.

The energy in each antenna, both for simulations \((E_{\text{sim}})\) and for measurements \((E_{\text{ant}})\), is calculated as follows. The calculation is performed in the time-domain, rather than as a function

---

\(^1\)The 40 events contain 25 proton and 15 iron showers

\(^2\)Not every simulated shower with the same energy, composition and direction gives the exact same resulting electric field, since the development of each predicted shower is based on Monte Carlo simulations, i.e. based on chance.
of frequency. The reason for this is that pulses induced by cosmic rays are too short to perform a reliable Fourier transform with the sampling rate used at LOFAR. The roughly 11 time-bins that contain a pulse would result in 7 frequency-bins\(^3\) in the 1 - 100 MHz range, which is deemed insufficient for a reliable comparison. Therefore, a comparison with CoREAS is performed by obtaining the total energy \(E\) per individual antenna in the time-domain as

\[
E = \sum_i |F_{i,\text{signal}}(t)|^2 - |F_{\text{noise}}(t)|^2
\]

(5.2)

where \(F_{i,\text{signal}}\) is the number of ADC counts in each bin of a single trace, for a total of 11 bins around the pulse peak. The noise value in each bin \(F_{\text{noise}}(t)\) is averaged over several bins around the peak window. With this, the total energy of the pulse in each single antenna is determined.

Note that the method of minimizing equation (5.1) here described results in one best-fitting value for each of the free parameters \(\vec{x}_0\), \(f_r^2\), and \(f_d\) per simulated event, and not per antenna within each event. Such a best-fitting set is obtained for each of the 40 events, and the event with the lowest \(\chi^2\) is taken as the ‘optimal’ simulation for an air shower, and used in this analysis. An example of the optimal simulation for one single air shower is depicted in figure 5.3, which shows the total energy in each antenna, as a function of distance to the shower axis. The red circles correspond to the measured energy in each antenna. The blue squares correspond to the simulated energies for the simulation that yielded the fit with the lowest \(\chi^2\).

The parameter of interest for this analysis is the best-fitting value of the radio power \(f_r^2\), as it corresponds to how closely the simulated radio power matches the measurements. This ‘scaling factor’ in the time-domain \(f_r^2\) can be calculated for each air shower. The same method is also

\(^3\)As described in chapter 3.2, the number of frequency-bins \(N_\nu\) is obtained from the number of time-bins \(N_t\) as \(N_\nu = N_t^2 + 1\).
applied in [64], and results can be found in figure 5.4 (left), which shows the distribution of the resulting scaling factors, each obtained from a single air shower. The median value for $f_r^2$ along with the corresponding standard deviation are obtained via a Gaussian fit. All 205 air showers used in this analysis are filtered from RFI. Note that the method by which $f_r^2$ is obtained varies significantly from the calibration methods used in chapters 3 and 4 of this thesis, meaning that values of parameters $f_r^2$ and $X(\nu)$ can not be compared directly. It is also important to note that $X(\nu)$ allows for a discussion of frequency-dependent characteristics, such as a mismatch in resonance frequency between modelled and real VEL. The value of $f_r^2$ on the other hand is only a scalar value, and therefore yields significantly less additional information.

It should be noted that CoREAS also includes several systematic uncertainties. First, simulations constructed by CoREAS are based on the reconstructed energy of the originally measured cosmic ray. The energy resolution of the method is estimated to be $\sim 50\%$. The calculated scaling factor $f_r^2$ is proportional to the measured power, which again scales quadratically with the energy of the cosmic ray. Therefore, any resulting scaling factors rely heavily on the energy scaling of the measurements. Additionally, the simulated power depends on any uncertainties in the emission-modelling from CoREAS. Any errors in either the used hadronic interaction model, or in the emission predicted from these particles, can have a significant effect. For example, the use of ZHAires - a model operating in a way similar to CoREAS, with slightly different parameters - results in a median scaling parameter roughly 30\% lower when compared to CoREAS [65]. However, this is only a rough estimate. The reason for this is that the ZHAires sample currently contains only 10 air showers. Which such low statistics, it is challenging to draw clear conclusions. The sample is considered too small to actually fit a distribution to, so that it cannot be included in this analysis.

5.3.2 Application to the galaxy and the reference antenna

The same method as used in the previous subsection can be applied to the calibration with a reference antenna, as well to the calibration using the galaxy. A similar 'scaling factor' in the time-domain $S$ can be defined as

$$ S = E_m/E_e $$

$$ [S] = \sum_i |F_i|^2 J, $$

(5.3)

with $E_m$ and $E_e$ the measured energy and the simulated energy, respectively. This factor $S$ is directly comparable to the scaling factor $f_r^2$ determined for CoREAS.

For the calibration using the Galactic radio emission, the data set consists solely of cosmic-ray events. These are dominated by electronics noise and Galactic emission, since the pulse duration from a cosmic ray is much shorter than the total trace length. A measured energy $E_m$ can therefore be obtained by integration over each trace. The expected energy $E_e$ is calculated by integrating the simulated spectral power over the 30 - 80 MHz frequency range. As noted in chapter 2.2.2, the power in a trace is conserved, whether it is expressed in the frequency- or in the time-domain. Calculating $E_e$ in the frequency-domain should therefore yield the exact same results as compared to the time-domain. Values for scaling factor $S$ with the Galactic application are depicted in figure 5.4 (right). Each event corresponds to the calculation of $S$ using a single cosmic-ray measurement, with $E_e$ and $E_m$ calculated as described above. A clear separation between dipoles X and Y exists for most of the outer antennas in CS002, although the difference is small. When
Figure 5.5: Scaling factor $S$ as defined in equation 5.3 for CoREAS, the Galactic emission and the reference source. Depicted values and uncertainties are median value and standard deviation. For the Galactic emission and the reference source, the dark red band contains statistical fluctuations when including the entire station. The lighter red band includes systematic uncertainties, as defined in the previous chapters, combined with statistical uncertainties.

compared to CoREAS in the left figure, both peaks show significantly less spread ($\sim 6\%$, versus $\sim 60\%$ for CoREAS). The absolute scale difference will be discussed in the final paragraphs of this section. For the calibration using the reference antenna, the total energy received in an antenna is calculated similarly to the method used for CoREAS. Clear signal pulses are visible in the trace. The measured energy $E_m$ is obtained by integration over these pulses. As discussed in chapter 4, the pulses are at least three orders of magnitude larger in power than the noise levels, and contribute less than 1% to the total energy in the trace. $E_e$ is obtained in the frequency-domain, similar to the method using Galactic emission.

A more direct comparison for all three different methods (Galactic emission, reference antenna, CoREAS) is shown in figure 5.5. For each method, the blue dot with uncertainty bars contains fluctuations per event, which is considerably larger for CoREAS than for the other two methods. The dark red bands, containing statistical fluctuations, signifies the standard deviation on the distribution of mean scaling factors for different antennas (i.e. variations per antenna, within each event). The lighter red band includes systematic uncertainties (i.e. variations per method), which are defined in tables 3.2 and 4.1 for the Galactic emission, and the reference antenna, respectively. For CoREAS, these are discussed in section 5.3.1. Both methods, using Galactic emission as well as the reference source, result in very similar values for $S$. Analogous to figure 5.1, which shows the originally determined calibration factors $X(\nu)$ as a function of frequency, both methods are dominated by systematic uncertainties. Statistical variations contribute significantly more for the Galactic emission method. The two methods are clearly compatible with CoREAS on a one-sigma level. However, the large systematic uncertainties make it difficult to draw conclusions about the correctness of the model of radio emission in air showers.
Conclusions and outlook

The LOw-Frequency ARray (LOFAR), located in the northern part of the Netherlands, is a distributed array, capable to measure radio emission induced by air showers. It does this by combining a large amount of antennas to detect radio waves mainly in the 30 - 80 MHz frequency range. With their duty-cycle near 100% and omni-directional sensitivity, the low-band antennas form an ideal tool to study the physics of emission mechanisms in air showers. However, the precise reconstruction of the corresponding electric fields requires a very exact knowledge of the antenna response. An absolute calibration of the antenna response has been performed in this thesis to achieve this.

The implemented calibration is a complete end-to-end calibration. The advantage of such a method is that it includes the full electronics chain, LNA and cables in the calculations. For that reason, this method faces no issues such as impedance matching. The result is therefore a direct conversion from input to output - or vice versa. The logical alternative method, where part of the electronics chain is modelled, requires extensive measurements of each individual component of the electronics chain, and is therefore significantly more invasive. The used method additionally allows for a discussion of frequency-dependent characteristics of the antenna, as well as possible mismatches between modelled and real antenna response.

While the proposed method is relatively straightforward in theory, the actual calibration of antennas in the sub-100 MHz frequency range is challenging. Man-made RFI, such as the radio FM frequency band, poses a strong source of signal disturbances in this range. Even for relatively remote regions, signals 'bounce' on the ionosphere, so that even sub-horizon RFI sources are detected for frequencies below 30 MHz. In part due to the easy propagation of sub-horizon radio signals, only few antenna systems exist in this range, with even less published maps. These effects make it difficult to perform the calibration of antennas in this frequency range.

Still, a full calibration has been performed with two different types of radio sources. The first of these is Galactic emission - a large, diffuse all-sky source of radio waves. With this method, the collected data are compared to a full-sky integrated simulated power at each frequency. Existing sky maps in this frequency bandwidth have uncertainties of 20% with respect to measurements. Differences between models range less than 5%. Additionally, electronics noise forms an non-negligible factor in measured signals. To evaluate the amount of the eletronics signal in the LBAs, the variation in power has been calculated for different frequency sub-bands of 10 MHz. In each band, different voltage offsets has been applied to simulations, replicating the effect electronic noise has in the data. The offset that introduces the most overlap between simulation and measurements - up to an absolute scaling factor - is the most probable voltage offset in that specific sub-band. With these results, an improved ratio of $T_{\text{sky}}/T_{\text{sys}}$ has been determined. The values resemble results from an earlier analysis, albeit with a significantly lower noise contribution in the 50 - 60 MHz range. Additionally, the new results include an analysis of uncertainties - something that
was missing the other analyses.

Using these results, a calibration factor using the Galactic emission has been established on a single-antenna level, and compared station-wide. The curve shows a slightly increasing slope towards higher frequencies, with uncertainties ranging ± 5% statistical and ± 38% systematic. Different dipoles, antenna sets and stations yield differences of less than 4% from the mean, and are fairly stable with respect to frequency over most of the bandwidth.

The second type of source used is a pre-calibrated linearly polarized reference antenna. This emission source is physically attached above the LBA, and held in place by a crane during a two-day campaign in May 2014. The generated comb-like signal is detected by the LOFAR low-band antennas at least three order of magnitude above noise levels. Both inner and outer antennas have been measured during this campaign. However, cross-checks of their performance indicate that the outer antennas behave in a somewhat unexpected way. Registered powers are consequently 35% lower when compared to inner antennas, most likely due to a technical error in the set-up. The measurements regarding outer antennas (corresponding to day 1 of the measurement campaign) are therefore discarded. For the second day, one of both inner antenna polarizations shows slightly reduced power as well. Possible explanations would be antenna cross-talk, signal reflections and slight manufacturing differences. For these combined reasons, measurements of the source signal detected in inner antennas, with dipoles oriented in the NW-SE direction are deemed the most reliable, and are used as signal in the rest of the analysis.

The resulting calibration factor obtained via a reference source reveals a similar behaviour as the calibration factor obtained using the Galactic emission. Differences are a bump around the resonance frequency, and a strongly enhanced slope above 74 MHz. The largest contribution to the uncertainties follows from the source emission, accounting for 33%, followed by a (conservative) estimate of the validity of a far-field approximation at distances ≤ λ of 6%. Overlap is within one-sigma over the entire frequency range. Uncertainties are dictated by systematics for all frequencies, while statistical variations are significantly smaller. Expanding the emission pattern of the source antenna to include the full station results in a frequency-averaged calibration factor, that slightly decreases with distance. The most probable explanation is that the simple dipole approximation used for the transmitting antenna oversimplifies the real situation. The use of a different source that is not only calibrated in the forward direction would be more suitable to perform such a task.

A similar calibration effort, using the reference antenna, has been performed at other experiments. Calibrations of radio antennas at LOPES, Tunka, and LOFAR result in almost identically calibrated traces. The expectation is that, after the application of the obtained calibration curves, detections of cosmic rays made by LOFAR, LOPES and Tunka will be consistent with one another to great precision. In the future, this allows for a one-on-one comparison of measured cosmic ray events between the different experiments. These efforts are currently still ongoing.

As a last analysis, by use of a slightly different method, it becomes possible to compare both calibrations to air shower simulations. Using integrated powers in the time-domain, one can define a scaling factor $S$ as the ratio of measured over expected power. Resulting values for $S$ are nearly identical for the methods using the Galactic emission and the reference antenna, and are compatible with CoREAS on a one-sigma level. Still, large systematic uncertainties make it challenging to draw any conclusions on the correctness of the used model for radio emission in air showers. Uncertainties originate mainly from the absolute energy scaling from LORA for CoREAS, from electronics noise for the calibration with the Galactic emission, and from source emission for the calibration with a reference antenna. Therefore, the method would strongly benefit from a better understanding of these parameters. While it is difficult to increase the energy resolution,
the use of variations on CoREAS and ZHAires, with different hadronic interaction models and radio emission patterns, should give a better grasp of their influence. Additionally, more investigation in the internal antenna characteristics should reduce systematic uncertainties for the calibration using the Galactic emission. The use of a more narrowly calibrated source would reduce systematic uncertainties for the reference antenna, but to obtain such a precisely calibrated reference antenna is technically not feasible. Still, even then, the method is decidedly more prone to experimental error. The attained data sample is small, spanning only two consecutive days with one inner and one outer antenna. The swamp-like grounds of LOFAR do not allow for the use of a large crane, possibly introducing signal reflections on the metal frame. For these reasons, a campaign with a larger crane, spread out over different antennas and longer periods of time - as performed at LOPES [46] - would greatly improve the reliability of the data sample. However, the logistics of such a campaign at the LOFAR site are nearly impossible. It therefore seems that a calibration via the Galactic emission is easier to perform. As the systematics of such a calibration are still dominated by electronics noise, dedicated antenna measurements should be able to strongly reduce this effect. In future work, uncertainties could therefore be limited to what is provided by Galactic radiation models.
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