Investigating Ionospheric Calibration for LOFAR 2.0 with Simulated Observations

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Abstract

The Low-Frequency Array (LOFAR) will receive a number of upgrades leading to the development version LO-FAR 2.0. These upgrades include a distributed clock signal and improved station hardware, which will allow simultaneous observations with all low- and high-band antennas of the instrument. We present the LOFAR simulation tool (LoSiTo), a software to simulate LOFAR and LOFAR 2.0 observations. The code features realistic models for the first and second order ionospheric corruptions as well as instrumental systematic effects and thermal noise. The ionosphere is represented as a thin layer of frozen turbulence. We employ this code to simulate a full 8 h simultaneous low- and high-band observation with the LOFAR 2.0 instrument. The simulated data is calibrated to examine novel approaches for direction-dependent ionospheric calibration in LOFAR 2.0.

1 Introduction

The Low-Frequency Array (LOFAR) is a radio interferometer working in the regime of low and ultra-low frequencies between 10 MHz and 240 MHz [1]. In this frequency range, the direction-dependent ionospheric corruption poses a challenge for high-fidelity radio-interferometric imaging. In the past decade, the development of a new generation of direction-dependent calibration strategies was initiated [2, 3, 4, 5]. Nevertheless, excellent image fidelity is still hard to achieve with LOFAR for complex fields (e.g. towards the Galactic plane), during exceptionally active ionospheric conditions, and for the lowest part of the frequency band (≤ 40 MHz).

This motivates the LOFAR 2.0 upgrade, which is going to increase system performance, especially for the low-band antenna (LBA) part of the array. The upgrade will allow for simultaneous observations with the low-band and high-band antennas (HBA), and thus enable novel calibration algorithms which combine information of both antenna systems. To make efficient use of the upgraded hardware, it is important to examine new calibration strategies for LO-FAR 2.0 prior to the deployment of the upgraded hardware. We present the *LOFAR Simulation Tool* (LoSiTo) and a simulated full 8 h simultaneous calibrator and target field observation with the upgraded LOFAR 2.0 system. We cal-

ibrate the simulated data with the aim of investigating novel approaches to improve the direction-dependent calibration of the LBA.

2 LOFAR and Future Upgrades

LOFAR is an array composed of 24 core stations (CS) and 16 remote stations (RS) located in the Netherlands as well as 15 more international stations in eight European countries. Each station hosts a field of dipoles operating as phased array, two drastically different dipole designs are employed: the LBA are sensitive in the frequency range from 10 to 90 MHz. The upper part of the frequency bandwidth of LOFAR is covered by the HBA, which are sensitive from 110 to 240 MHz. Each Dutch station is equipped with 96 LBA dipoles and 48 HBA tiles. Due to a limitations in the station hardware, operation of the current LO-FAR system is restricted to either all 48 HBA tiles or 48 out of the 96 LBA dipoles [1]. Therefore, the instrument is not utilized to its full potential. Currently, the clock signals for all remote and international stations are provided by GPS-synchronized rubidium clocks. These clocks show the presence of $\mathcal{O}(10 \text{ ns} \text{ h}^{-1})$ clock drift which causes nonnegligible phase errors in the data [5, 6].

The LOFAR 2.0 upgrade is designed to overcome these limitations and consists of multiple projects. Here, we focus on the changes introduced by the Digital Upgrade for Premier LOFAR Low-band Observing (DUPLLO), its main focus lies on improving the performance of the LBA system. Among the key components of DUPLLO is the deployment of improved station electronics. The number of receiver units per station will be tripled, which will allow simultaneous observations with all 96 LBA dipoles as well as all 48 HBA tiles. Consequences will be an increase of sensitivity and field of view in LBA observations and the possibility of innovative calibration algorithms which exploit the simultaneous observation to derive more accurate ionospheric calibration solutions. Another improvement introduced by DUPLLO will be a new clock system. The signal of a single clock will distributed to all Dutch stations, strongly reducing clock-related phase errors.

3 Model Corruptions

To accurately simulate LOFAR observations, realistic models for the corrupting effects present in the observations are required. In this section, we give an overview on the models we implemented in LoSiTo. The code and documentation are available online¹.

3.1 Ionosphere Model

The ionized plasma of the upper atmosphere interferes with radioastronomic observations in a variety of ways. The dominant ionospheric effect is a dispersive delay which expresses as a scalar phase error $\Delta \phi$ with a characteristic frequency dependence of $\propto v^{-1}$ [7]:

$$\Delta \phi = -84.48 \left[\frac{\mathrm{d}TEC}{\mathrm{1\,TECU}} \right] \left[\frac{100\,\mathrm{MHz}}{\mathrm{v}} \right] \mathrm{rad.} \qquad (1)$$

This phase error depends on the line of sight integrated electron density N_e , which is referred to as the total electron content (*TEC*):

$$TEC = \int N_e \mathrm{d}l. \tag{2}$$

The second ionospheric effect that is non-negligible at the frequency range of LOFAR is Faraday rotation. It is of second order in v^{-1} and hence, especially problematic at the lowest frequencies. It expresses as rotation angle β in the plane of linear polarization. The line-of-sight contribution to the Faraday rotation depends on the magnetic field \vec{B} and the free electron density and can be summarized into the *rotation measure (RM)*:

$$RM = \frac{e^3}{8\pi^2 \varepsilon_0 m_e^2 c^3} \int N_e(l) \|\vec{B}\| \cos(\theta) \,\mathrm{d}l. \tag{3}$$

Here, *e* is the electron charge, m_e the electron mass, *c* the speed of light in vacuum, ε_0 the vacuum permittivity and θ the angle between the magnetic field vector and the line-of-sight. The corresponding rotation angle β is given by:

$$\beta = RM \cdot \left(\frac{c}{v}\right)^2. \tag{4}$$

We employ the thin-layer approximation for our ionospheric model. In this approximation, the ionosphere is represented as two-dimensional spherical shell at a height of h_{ion} around the Earth. This approximation is motivated by the vertical structure of the ionosphere, where the majority of the free electrons are constrained within the ionospheric F-layer. Contracting the three-dimensional structure onto a two-dimensional sphere drastically reduces the complexity of the model while maintaining many of the important characteristics, such as spatial coherency and to some accuracy, the elevation dependence of the projected electron content [8]. In the thin-layer approximation, the ionosphere is parametrized by a two-dimensional distribution of the



Figure 1. Snapshot of a simulated turbulent *TEC*-screen. Each circle marks one pierce-point, circles of the same color belong to the same station. We display only points belonging to *CS001*, the most distant CS (*CS501*) as well as the three outermost stations (*RS210, RS310, RS509*).

vertical total electron content (*vTEC*). This distribution is referred to as a *TEC-screen*.

A substantial fraction of ionospheric inhomogeneity can be attributed to turbulent phenomena [9, 10]. Ionospheric turbulence can be approximately described by a process where energy is injected into a system with high Reynolds number at large spacial scales and iteratively distributed to smaller scales [11]. This self-similarity leads to a refractive-index power spectrum $\Phi(k)$ that follows a power-law in spacial frequency k. In the Kolmogorov case, the spectral index β takes a value of $\beta = 11/3$ [12, 13]. Taking the finite outer scale L_0 of the turbulence into consideration yields the von Kármán-spectrum [14]:

$$\Phi(k) \propto \left(k^2 + L_0^{-2}\right)^{-\beta}.$$
 (5)

Previous studies with LOFAR confirmed the power-law shape, but found a slightly steeper spectrum of $\beta = 3.89 \pm 0.01$ compared to the pure Kolmogorov case [6, 7]. We adopt this empirically derived value for our ionospheric model.

To generate a turbulent *TEC*-screen in LoSiTo, we employ the algorithm described in Buscher [15]. This algorithm makes use of the frozen turbulence approximation, the change of the turbulent structure is assumed to be negligible with respect to the bulk velocity of the ionosphere. We scale the *dTEC* sampled from the *TEC*-screen such that the maximum range is 0.25 TECU (1 TECU = 10×10^{16} m⁻²). We add a homogeneous component of the *TEC* at 7.0 TECU. The daily ionospheric variation is included using a simple sinusoidal pattern: The total electron content peaks at

¹https://github.com/darafferty/losito



Figure 2. The top panels show simulated dTEC for three stations as a function of time. The bottom panels show simulated *RM* for the same stations. For each station, we show the values towards the phase center (orange) and towards directions 1.8° (blue) respectively 4.5° (green) separated from the phase center. The values of each direction are referenced with respect to the same direction in *CS001LBA*.

3 p.m. and drops to a level of 10% at 3 a.m. We place our model-ionosphere at a height of $h_{ion} = 250$ km, around the typical location of the peak electron density at the latitude of LOFAR as modelled by the international reference ionosphere [16]. The ionospheric grid is simulated at an angular resolution of 1" (≈ 72 m) and moves eastwards at a velocity of 20 m s^{-1} . One snapshot of such a *TEC*-screen is displayed in Figure 1.

To derive the Faraday rotation towards a direction \hat{d} from the ionospheric model, we apply the thin-layer approximation to Equation 3:

$$RM = 2.62 \times 10^{-13} \,\mathrm{T}^{-1} TEC \hat{d} \cdot \vec{B} \big|_{\text{pierce-point}}.$$
 (6)

As model for the magnetic flux density \vec{B} , we use the implementation of the *World Magnetic Model* [17] in the RMExtract library [18]. The simulated d*TEC* and d*RM*-values for three stations and directions are displayed in Figure 2. As expected from Equation 6, the d*TEC* and d*RM* values are highly correlated.

3.2 Instrumental Systematic Effects

In addition to the ionospheric corruption, we include all dominant instrumental-based systematic effects isolated in de Gasperin et al. [6] in our simulation. The direction and frequency-dependence of the instrument response are described by the primary beam respectively the bandpass. To model the primary beam, we rely on the results of electromagnetic simulations of the dipoles implemented in the LOFARBeam² library. To include the bandpass which was determined in an empirical study in van Haarlem et al. [1].

LOFAR observations show the presence of station-based timing delays. These manifest as phase errors, a delay of

 Δt between two stations causes a phase-offset $\Delta \Phi$ which is proportional to the frequency *v*:

$$\Delta \phi = 2\pi v \Delta t. \tag{7}$$

Station-based delays present in LOFAR can be split into two categories, time-variable delays of the station clock signal and constant misalignments between the X and Ypolarization data streams attributed to improper calibration of the station-level electronics. We model the former effect as a superposition of a constant offset and a sinusoidal variation, assuming an expectation value of the clock error in LOFAR 2.0 of $\mathcal{O}(100 \text{ ps})$ depending on the station type and based on the design requirements of the system. To model the polarization misalignment, we sample a Gaussian distribution of 1 ns width for each station.

In addition to the instrumental and ionospheric effects, radio-interferometric observations are affected by the presence of thermal noise. The level and spectral properties of the noise for the current development version of LOFAR were determined in and empiric study in [1]. We employ these results in our simulation and rescale them to account for the increase in low-band dipoles in LOFAR 2.0.

4 Simulated observation

We simulate a full 8 h LOFAR 2.0 observation of a calibrator source and a target field simultaneously using the Dutch LBA and HBA stations. The sky model for our simulation is extracted form a real LOFAR LBA observation. The visibility data of this model is predicted and corrupted by the effects presented in Section 3 in LoSiTo. Underneath, LoSiTo uses LOFAR software to efficiently perform these tasks. The simulation took 53 h of computation time using eight six-core compute nodes. The raw data is made publicly available³.

4.1 Calibration

Simultaneous LBA and HBA observations will offer new prospects for ionospheric calibration. Since the same ionosphere will be observed in both systems of the array, the underlying parameters describing the ionospheric corruption in the data are the same. Consequently, combining the information of the low- and high-band observation could allow to determine the ionospheric parameters more accurately. This could especially benefit the LBA, where calibration is harder due to the increased noise level and severity of ionospheric errors.

The calibration of the simulated observation is split into three parts, if not stated otherwise, calibration is performed independently for the LBA and HBA observation. First, the instrumental systematics are derived from the calibrator observation using the strategy described in de Gasperin

²github.com/lofar-astron/LOFARBeam

³https://www.fdr.uni-hamburg.de/record/8587



Figure 3. Each of the four tiles shows directionindependent d*TEC* solutions as a function of time for a selected LBA station. The grey curves in the background show the input corruptions towards different directions. The values are referenced to station *CS001LBA*.



Figure 4. Phase solutions ϕ in radians for one direction and two stations as a function of time (*x*-axis) and frequency (*y*-axis).



Figure 5. Differential *TEC* extracted from LBA and HBA phase solutions towards one direction (colors except red) and residuals with respect to the simulation input (red) for six distant RS. Grey lines show the ground truth. All values are referenced to *CS001*.

et al. [6]. The second step is the direction-independent calibration of the target field, employing an adjusted version of the pipeline presented in de Gasperin et al. [3]. In this step, we perform two rounds of self-calibration to determine the direction-averaged dTEC and dRM and derive an improved sky model for further calibration. We display the resulting dTEC-solutions for four LBA stations and compare them to the input corruptions in Figure 3. As expected, the *TEC*-variation is stronger for more distant stations, and the direction-averaged dTEC that is solved for lies within the spread of the direction-dependent dTEC of the ground truth.

The final step is the direction-dependent calibration, for simplicity, we limit our analysis to eight calibrator directions. We pursue an approach based on the peeling-strategy [5]. In an iterative procedure, all sources but one calibrator are subtracted from the data. Then, phase self-calibration is performed on this direction. The improved solutions and source model for this calibrator are used to continue with calibration of the remaining directions. The phase solutions as a function of time and frequency are displayed in Figure 4 for one direction and two stations. It is evident that these phases are largely dominated by ionospheric errors.

We use the resulting phase solutions to fit the d*TEC* towards the different directions across the combined frequency range of LBA and HBA according to Equation 1. The results are displayed in Figure 5 for one direction and eight stations. Depending on the station and direction, the root-mean-square error (*rms*) of the estimated d*TEC* ranges from $\mathcal{O}(0.1 \mu \text{TECU})$ to $\mathcal{O}(10 \mu \text{TECU})$, the mean *rms* across the thirteen most distant stations and all eight directions is 7.2 mTECU. If we use only the LBA phase solutions to fit the d*TEC*, this results in a higher mean *rms* of 10.1 mTECU. While our joint-calibration approach is more accurate, further improvements will be necessary to use the simultaneous calibration to its full potential.

5 Conclusion

In this summary paper, we presented models for the ionospheric and instrumental systematic effects in LOFAR 2.0 observations. We embedded these models in the LoSiTo simulation code and employed this code to simulate a full simultaneous LBA and HBA LOFAR 2.0 observation. We presented the analysis of the simulated data, where we carried out the full data reduction process from the calibrator observation to the direction-dependent calibration of the target field using adjusted LOFAR calibration pipelines. As a proof-of-concept, we investigated new strategies for direction-dependent calibration in LOFAR 2.0. We find that estimating d*TEC* jointly form LBA and HBA is superior to the LBA as standalone system, but further work will be required to make the strategy more reliable.

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