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LOFAR calibration and wide-field imaging

Étalonnage de LOFAR et l'imagerie en champ large

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ABSTRACT

LOFAR is a revolutionary instrument, operating at low frequencies ($\nu \lesssim 240$ MHz). It will drive major breakthroughs in the area of observational cosmology, but its use requires the development of challenging techniques and algorithms. Since its field of view and sensitivity are increased by orders of magnitude as compared to the older generation of instruments, new technical problems have to be addressed. The LOFAR survey team is in charge of commissioning the first LOFAR data produced in the imager mode as part of building the imaging pipeline. We are developing algorithms to tackle the problems associated with calibration (ionosphere, beam, etc.) and wide-field imaging for the achievement of the deep extragalactic surveys. New types of problems arise in that context, and notions such as algorithmic complexity and parallelism become fundamental.

RÉSUMÉ

LOFAR est un instrument au design révolutionnaire qui opère à très basses fréquences ($\sim$ 10–240 MHz) dans un domaine d'énergie quasiment inexploré. Il est construit presque entièrement en software, et allie réseau phasé et interféromètre. Son utilisation conduira à des avancées scientifiques majeures, mais elle représente un défi technologique considérable. En effet, la sensibilité et le champ de vue de cet instrument étant accru de plusieurs ordres de grandeur par rapport à l'ancienne génération, des phénomènes subtils doivent

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être considérés. D'autre part, les nouvelles technologies utilisées comme les réseaux phasés entraînent des complications de taille. Dans le cadre du groupe de travail « relevés LOFAR » nous développons des procédures d'étalonnage (ionosphère, lobes de station). Dans le cadre de ces problématiques, de nouvelles difficultés émergent, et les concepts de complexité algorithmique et de parallélisabilité deviennent une base de réflexion.

1. Introduction

With the building or development of many large radio telescopes (LOFAR, EVLA, ASKAP, MeerKAT, MWA, SKA, e-Merlin), radio astronomy is undergoing a period of rapid development. The LOw Frequency ARray (LOFAR) is an instrument that observes in a mostly unexplored frequency range ($\nu \lesssim 240$ MHz), and will be one of the largest radio telescopes ever built in terms of collecting area. With its high sensitivity and large field of view one can address a wide range of key science cases including: HI emission at the epoch of reionization, transients (pulsars, exoplanets, supernovae, gamma ray bursts), cosmic rays and high-energy physics (10^{15}–10^{20} eV), galactic and cosmic magnetism, solar physics, and observational cosmology through the completion of large extragalactic surveys [1]. France is deeply involved in the LOFAR project with one operational station in Nançay, and the development of the LOFAR super station concept [2], similar to what an SKA low-frequency station might look like.

LOFAR's design is innovative, and built on a combination of phased array and interferometer (see [3] for a LOFAR system description). It is made of $\sim 40\,000$ high-frequency antennas (110–240 MHz) and ~ 5000 low-frequency antennas (10–80 MHz), spread over 40 stations in the Netherlands, and 8 international stations (5 in Germany, 1 in France, England, and Sweden). At the station level, signals are phased and summed by the *beam-former*, to synthesize a virtual antenna pointing at the desired position on the sky. This design also enables the user to form antenna beams pointing at different positions simultaneously. The data is transported from the various stations of the LOFAR array to the correlator (a Blue Gene/P supercomputer) situated in the Netherlands at the University of Groningen. From the beam-former to the imaging, LOFAR is mostly a software telescope.

The LOFAR survey team aims to develop a pipeline to achieve the deep extragalactic surveys, reaching the limit of ~ 6 µJy at 150 MHz with angular resolution of 5 arcseconds. These surveys should drive major breakthroughs in observational cosmology, far beyond what radio astronomy can usually do. Indeed, number counts will not any more be dominated by active galactic nuclei, but by star forming galaxies. Such sensitivity corresponds to star formation rates of a few tens $M_\odot\,\mathrm{yr}^{-1}$ at $z \sim 2$. Tens to hundreds of millions of starforming galaxies should be detected up to $z \sim 2$ in the deepest surveys, and many thousands diffuse cluster emission up to $z \sim 0.6$. LOFAR surveys will give important complementary information to the ASKAP and MeerKAT surveys (EMU and Mightee for example). Its survey speed will be higher than EVLA by a factor ~ 10, and will only be overcome with the arrival of SKA.

New issues arise with the development of these new types of interferometer, and the approximations (conscious or unconscious) made for the calibration of the older generation of instruments are not valid anymore. Neither LOFAR nor the precursors of SKA (ASKAP, MeerKAT) can be properly used without the development of new techniques to calibrate the many effects influencing the electro-magnetic field. Specifically, the calibration of LOFAR represents a major theoretical and practical challenge: the field of view and sensitivity of this new generation of instruments being increased by orders of magnitude, new effects have to be taken into account. In this contribution, we summarize the issues we are facing, and the solutions we are developing.

2. Calibration issues

2.1. Addressing the direction-dependent calibration using the measurement equation

At the station level, the signals from the individual antennas are phased and summed by the *beam-former* before being sent to the correlator. This step amounts to forming a virtual antenna pointing at the targeted field location. One of the main issues is that as compared to a mechanical antenna in a traditional interferometer observing in a relatively narrow frequency band, the beam correction cannot be applied in the image plane anymore (see Section 4), but it must be taken into account in the calibration step and corrected for in the imaging step while gridding and deconvolving because the LOFAR beam varies in both time and frequency (for dishes the beam is constant across time). This illustrates the common difficulty of most of the new generation of radio interferometers, the so-called "direction-dependent effects" (DDE).

In order to model those complex effects, we make extensive use of the Measurement Equation formalism developed by Hamaker et al. (1996) [4]. The Measurement Equation provides a complete model of a generic interferometer. Each of the physical phenomena that transform or convert the electric field before the correlation computed by the correlator is modeled by linear transformations (2×2 matrix). It can be written as follows:

$$V_{pq} = G_p\left(\sum_{i=1}^{N} E_{pi} X_i E_{qi}^{+}\right)G_q^{+} = G_p\left(\sum_{i=1}^{N} \mathrm{K}_{pi}\mathrm{B}_{pi}\mathrm{I}_{pi}\mathrm{R}_{pi}F_i.F_i^{+}\mathrm{R}_{pi}^{+}\mathrm{I}_{qi}^{+}\mathrm{B}_{qi}^{+}\mathrm{K}_{qi}^{+}\right)G_q^{+}$$

where V_{pq} is the correlation matrix between antennas p and q, E_{pi} is the product of direction-dependent Jones matrices corresponding to antenna p in the direction i (including ionosphere – I, beam – B, Faraday rotation – R), G_p is the product of direction-independent Jones matrices for antenna p (including electronic gain, polarization leakage), and X_i is the sky contribution in the direction i (the 4-component correlation of the electric field F). The symbol $^+$ stands for the Hermitian transpose operator.

This elegant formalism enables us to model the full polarization of the visibility as a function of the *true* underlying electric field correlation. It takes into account the direction-dependent and direction-independent effects in a simple and consistent way. Indeed most of the Jones matrices in the measurement equations have a fairly simple formulation and any calibration problem amounts to finding the various components of G and E to solve the measurement equation. In order to address the issue of DDE for LOFAR, we have to use softwares within which the structure of the measurement equation is fully implemented. We can make use of MeqTrees [5] or BBS (BlackBoard Selfcal). The first is very flexible, while the second has been designed to fit in the survey pipeline.

2.2. Calibration challenges: the beam and the ionosphere

As outlined above, one of the most important DDE we have to calibrate for is the station's beam. This amounts to finding each individual station beam Jones matrix as a function of pointing position and frequency. One of our main aims is to obtain an accurate model of the beam, valid even far from the primary lobe. We currently have models of both the high-band and low-band station beams (HBA and LBA respectively). Work is ongoing to include in the model the coupling between antennas within the stations. Some recent results indicate that obtaining such a model is possible at the level of $\lesssim 1\%$ in the LBA.

The other major DDE we have to understand and calibrate for is due to the combination of the effects of ionosphere and wide field of view associated with the LOFAR stations. At $\nu \lesssim 300$ MHz, the ionosphere located at an altitude of 50–1000 km causes time delays in the wavefront, depending on the local electron density. The resulting effect is that an incoming plane wavefront gets distorted when it reaches the array. For the more traditional interferometers such as the VLA, although the ionosphere influences the gain phases at $\nu \lesssim 300$ MHz, the beam width is in general small as compared to the angular scale of the ionospheric phase shift variation. In that case the ionosphere can be considered to be a direction-independent effect, and just amounts to a single scalar multiplication of the antenna gains. This is not true in the case of LOFAR.

Calibrating the ionosphere is equivalent to finding its Jones matrix as a function of station and direction. Intema et al. (2009) [6] and van der Tol et al. (2009) [7] have shown that the effect of the ionosphere at 74 MHz may be modeled by a 2-dimensional time-dependent phase screen situated at a certain height above the interferometers. Once a solution is found, the best fit model gives the ionosphere Jones matrix as a function of direction for all individual stations. This feature is not yet fully implemented into the imaging pipeline.

3. Bright source removal – The A-team sources

One of the challenging problem we are facing up to now is connected to the very bright sources dominating the low-frequency radio sky. Those are mainly Cygnus A, Cassiopeia A, Virgo A, Taurus A, Herculus A (the so-called "A-team sources" in the LOFAR community), and the Sun. In order to reach the specified dynamic range to accomplish the deep LOFAR extragalactic surveys ($\sim 10\,000$), the calibration has to be very accurate at the location of those sources. Again, this problem is connected to our wide field of view, especially in the low band ($\nu \lesssim 80$ MHz), where the primary beam diameter can be as wide as ~ 10 degrees, with at least one or a few of the A-team sources contributing to the measured flux, even when located far from the field center. Indeed, if these bright sources are not removed from the UV data, the residual noise in the data is completely dominated by the A-team sources modulated by the secondary lobes' time and frequency variations.

In order to do a proper A-team sources removal, we are currently exploring different observational and algorithmic strategies. The first method (known as *peeling*) consists in using a combination of direction-dependent calibration and self-calibration techniques: by doing simultaneous solving over different directions (target field, and the contaminating A-team sources), we can obtain accurate gain solutions in the different direction and remove the contributions from the A-team sources to the observed visibilities. For doing this one needs a good source model, but no beam or ionosphere model is required. This method works well, but is computationally very intensive. We are currently investigating a second technique, based on simultaneous observation of a target field and the A-team sources that contaminate the UV data. We can then phase-rotate the A-team sources UV data towards the target field and directly subtract them after re-normalizing by the beam. In the cases where cross-contamination between A-team sources datasets plays a role, we can solve linear systems well described by the measurement equation. Such types of methods have the advantage that they do not need any source model, but they need a good beam model. The third technique has been described in much detail in [7], and uses the fact that bright sources are in general far from the target field, so their fringe rate is high compared to the target field ones.

4. Wide-field imaging

With the increasing field of view of radio telescopes, wide-field imaging has been an active research field in the last twenty years. With the new generation of radio interferometers coming online, new algorithms are being developed to reach

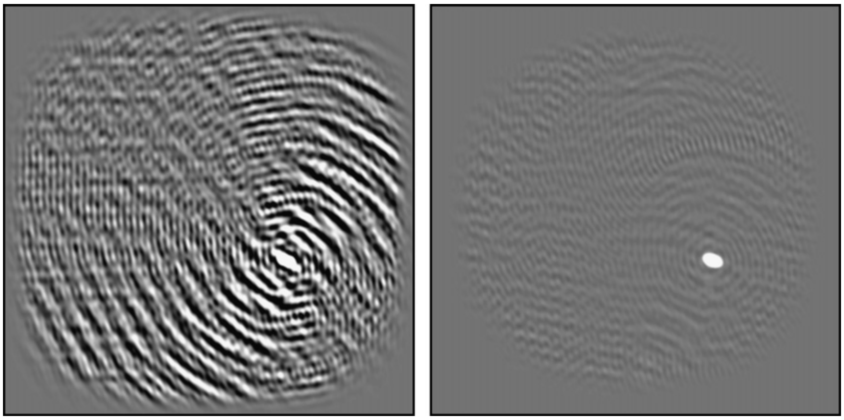

Fig. 1. A generalized full polarization framework based on the Measurement Equation is needed to understand and use LOFAR. It generates time-, frequency-, and direction-dependent calibration solutions, and drives complex mathematical and algorithmic problems in the imaging steps. In order to reach the high dynamic range needed to achieve the extragalactic LOFAR surveys, we have implemented the A-projection algorithm (Bhatnagar et al. (2008) [11]) which will allow us to apply direction-dependent calibration solutions in the imaging step (ionosphere, Faraday rotation, beam, etc.), in a fast way once optimized. The figure above shows the effect of taking the DDE into account (the beam only in that case) in the imaging step for a simulated HBA dataset having one off-axis polarized source (the visibilities are then modulated by the time-dependent beam). The left panel shows the restored image (8 degrees wide) not taking the beam's effects into account. The right panel shows the restored image produced by the A-projection algorithm, based on the Measurement Equation, and taking the beam into account (including polarization leakage). The resolution in the resulting images is poor because we have limited the data to a small number of baselines (10 over ~ 800). The color scale is the same on both images, and its amplitude is 1% of the source's flux density. The residual levels are different by more than an order of magnitude. The dynamic range in the right panel is driven by well controlled numerical errors, while the residuals on the left panel reach fundamental limits because the DDE are not corrected for (this approximation generates artifacts in the restored image).

the high dynamical ranges needed to achieve the deep extragalactic surveys. Currently, the main difficulty is to include the DDE discussed above into the imaging steps while keeping efficient algorithms. We give here a brief sketch of the issues associated with wide-field imaging focused on LOFAR, but a detailed review can be found in Bhatnagar et al. (2009) [8].

The measurement equation introduced above can be written in a more extended and continuous form better suited for imaging:

$$\mathrm{Vec}(V_{pq}) = \left(G_q^* \otimes G_p\right) \int_S \left(E^*_{q,\vec{s}} \otimes E_{p,\vec{s}}\right)\mathrm{Vec}(X_{\vec{s}}) \exp\left(-2i\pi\left(u_{pq}l + v_{pq}m + w_{pq}\left(\sqrt{1-l^2-m^2}-1\right)\right)\right) \mathrm{d}l\,\mathrm{d}m$$

where $\otimes$ is the Kronecker product, Vec is the operator that transforms a 2×2 matrix into a dimension 4 vector, $\vec{s} = (l, m, n = \sqrt{1-l^2-m^2})$ is a direction in the sky and $\overrightarrow{b_{pq}} = (u_{pq}, v_{pq}, w_{pq})$, is the baseline vector in wavelength units. The term $\exp(-2i\pi(u_{pq}l + v_{pq}m + w_{pq}(\sqrt{1-l^2-m^2}-1)))$ reflects the combination of the effects of the array geometry, and the delays introduced by the correlator when phasing the antennas signals in the pointed direction (the matrix K appearing in the previous equation). For the traditional interferometers at high frequencies, in general the field of view is small enough so that the W-term can be neglected ($\sqrt{1-l^2-m^2} \sim 1$), which implies that the projected array geometry is constant across the field of view. The matrix E can usually be assumed to be time- and frequency-independent. In that case a single 2D fast Fourier transform of the UV plane that contains all the visibilities across time range, frequency and baselines gives in the image plane the product of the sky with a time-independent, frequency-independent beam. In such case the deconvolution can be done using a traditional CLEAN algorithm, and the beam correction can be done in the image plane.

When the matrix E can still be assumed to be time- and frequency-independent, but the W-term cannot be neglected anymore, we can make use of two different techniques, already implemented in CASA.[1] The first is intuitive [9], and consists in imaging the field in different *facets* or *polyhedra* corresponding to different positions on the celestial sphere by phase rotating the UV data for each one of those. The second method ("W-projection" [10]) uses a W-dependent convolution function in the gridding step to retrieve an undistorted image after a simple 2D fast Fourier transform.

In the case of LOFAR, as described in Section 2 even at the higher frequencies, the antenna gains are always direction-, time-, and frequency-dependent. This includes the effects of the beam and ionosphere. When direction-dependent effects are to be taken into account in the imaging step the faceting method still holds, but direction-dependent gains have to be applied before the images are formed in each individual facets. Furthermore, the time and frequency dependence seriously complicates the deconvolution algorithms. We have recently fully implemented a facet-based scheme that can potentially take all DDE into account.

Recently, Bhatnagar et al. (2008) [11] have proposed a scheme (the *A-projection*) in which the DDE and the non-coplanarity of the array are corrected using an algorithm similar to the W-projection algorithm. This algorithm is very

[1] http://casa.nrao.edu.

promising in terms of computing efficiency (faster than facet-based algorithms by an order of magnitude), and it can potentially take all DDE into account in the deconvolution steps. We have implemented this algorithm for the LOFAR data in full polarization, and we are currently testing it on both simulated and real LOFAR data (see Fig. 1). The whole process and the pipeline architecture have been described in more detail in Heald et al. (2010) [12].

5. Conclusion

We have presented the calibration and imaging issues specific to the LOFAR array, and to the completion of the extragalactic surveys. This work is preliminary, and the issues we have to address are fairly new. They lie at the crossroad of many subjects such as interferometry, algorithmics, and computer sciences.

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