LOFAR Calibration Challenges

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ABSTRACT

The LOw Frequency ARray (LOFAR) will observe at 20-200 MHz. At those frequencies, large ionospheric phase variations considerably distort the observed brightness distribution. Fortunately, the image may be stabilized for long integrations by using bright radio sources in the sky. The downside is that LOFAR fields will be very crowded, which presents calibration challenges of its own. This is expecially true for the bright and extended sources that enter via the relatively high sidelobes of the LOFAR station beams. An extra complication is that these beamshapes vary rather strongly in frequency and time. Altogether, LOFAR will require much more processing than existing radio telescopes, and has only just become possible with the new generation of computers. Even so, new processing techniques like 'peeling' had to be developed to speed things up by several orders of magnitude.

Keywords: LOFAR, radio astronomy, aperture synthesis, calibration, ionosphere, low frequency, SKA

1. INTRODUCTION

The LOw Frequency ARray (LOFAR) is a radio aperture synthesis telescope that will operate at 20-200 MHz. Earlier instruments have observed the sky at these low frequencies since the 1950's. They are responsible for much of our knowledge about the conditions that LOFAR will encounter. But they did not have the advantage of modern calibration techniques, and the vast processing power that is needed to overcome the effects of the ionosphere. Moreover, LOFAR is designed to be sensitive enough to detect, among many other things, the extremely faint signature of the Epoch of Re-ionisation (EOR), which is expected to be an important discriminator between current cosmological theories. This elusive signature will have to be studied in the presence of many thousands of much brighter foreground sources. It is clear that this requirement presents some extraordinary challenges to the LOFAR calibration process. In order to set the scene, we will start with a brief outline of aperture synthesis, and its very succesful self-calibration technique.

1.1. Radio Aperture Synthesis

The radio sky may be observed with antennas of many forms: from a single receptor (e.g. a dipole) to a phased array, possibly in the focus of a parabolic reflector. An antenna, or 'station', usually has two outputs, tuned to different polarizations. Each output is associated with its own spatial response pattern, or voltage beam, on the sky. A phased array may form multiple beams for simultaneous observations in different directions.

A pair of such stations, separated by a *baseline*, may be used as an interferometer to sample the Visibility Function (Fourier Transform) of the observed brightness distribution. This separation allows a much higher spatial resolution than the width of a station beam. Both stations are pointed in the same direction, and their output signals are correlated with each other after correction for the pathlength delay difference.

The projected length and orientation of an interferometer baseline defines a point in the Fourier plane. This plane is sampled by the rotation of the Earth, which slowly changes the baseline. The sampling may be speeded up considerably by using an array of N stations, in which each of the $N(N-1)/2$ pairs forms a separate interferometer. The visibility samples are often called 'uv-data', after the coordinate axes (u, v) of the Fourier plane.

After Fourier Transforming the sampled Visibility Function, the resulting image will be convolved with a Point-Spread Function (PSF). The shape of the PSF is determined by the sampling function, and by instrumental

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errors, which will usually depend on sky position. Since the PSF covers the entire image, and its side-lobes may be a percent or more, it is clear that the PSF of the bright sources will hide the much fainter objects that we are interested in. Therefore, by a somewhat unorthodox definition, the purpose of calibration is **to remove the PSF of the brighter sources from the image as completely as possible**.

The dynamic range of an observation is defined as the ratio between the brightest source and the image noise, which includes the remains of incompletely removed sources and their PSF. Existing radio telescopes reach a dynamic range of up to 1:500.000 (WSRT). LOFAR is expected to require up to 1:10.000.000.

1.2. LOFAR

For quick reference, we include a very brief description of LOFAR. More detailed information, can be found in[1] and.[2] Since the design of the LOw Frequency ARray (LOFAR) is not completely finalized yet, the following numbers are only approximate.

LOFAR will consist of an array of about 100 stations, in a 3-5 arm spiral configuration with an outer dimension of 100-200 km. The density of stations will increase towards the centre, to maximize the sensitivity for extended features. A socalled 'compact core' will have a diameter of about 2 km, and will contain about half the receiver elements. In the future, the outer size of the LOFAR array may be extended to several 100 km, while its compact core may be more densely populated.

Each station will contain 2 separate phased arrays, optimized for different frequency bands. The 30-90 MHz array will have about 100 dipoles in a 3-5 arm spiral configuration with a size of about 100m. The 110-220 MHz array will have about 100 'racks' of 4x4 dipoles each, in a similar but somewhat smaller configuration. Up to 8 simultaneous beams will be formed by these arrays, which may be engaged in completely different observing programs.

1.3. Self calibration (selfcal)

As mentioned above, the the purpose of calibrating a radio aperture synthesis telescope is to remove the PSF of the brighter sources from the image as completely as possible. This requires a precise knowledge of the value of instrumental parameters at all times. Since the instrument, including the ionosphere, is not very stable, its parameters must be measured **during** the observation. This is done by comparing the measured values of the visibility data $\vec{D}_{ij}(u,v)$ with values $\vec{V}_{ij}(u,v)$ that are predicted with a so-called *Measurement Equation* (M.E.). This is a mathematical model of the instrument, but also of the observed brightness distribution. For an interferometer ij between stations i and j, we can write[34]:

$$\vec{V}_{ij}(u,v) = \sum_k \int_{\Delta f} df \int_{\Delta t} dt \; (J_{ik} \otimes J_{jk}) \; S \; \vec{I}_k \tag{1}$$

The visibility vector $\vec{V}$ has four elements since a complete measurement of the incoming E.M. radiation requires four complex numbers. Its value is the sum of the contributions of all sources $\vec{I}_k$ in the source model, each of which is characterised by its four Stokes parameters I, Q, U, V. The 4×4 Stokes matrix S selects the polarization representation, i.e. linear or circular. All instrumental effects are modelled by the 2×2 Jones matrices J_{ik} and J_{jk}, which are multiplied to a 4×4 matrix by the Kronecker product $\otimes$. Note that a Jones matrix is associated with a station and a source, i.e. it describes the instrumental effects of a station in the direction of that source. Each sample is of course integrated over a certain integration time Δt and channel bandwidth Δf.

In a well-designed instrument, instrumental effects can be attributed to a station, i.e. they are fully described by a station Jones matrix. Since the number of data samples is proportional to the square of the number of stations in an array, this assumption considerably reduces the number of independent parameters in the M.E.. It is called the *selfcal assumption*, because it makes selfcal converge. A station-based Jones matrix J_{ik} can be split up in a product of 2×2 matrices, each of which describes an instrumental effect along the signal path:

$$J_{ik} = G_i \; D_i \; P_i \; E_{ik} \; T_i \; F_{ik} \; I_{ik} \; K_{ik} \tag{2}$$

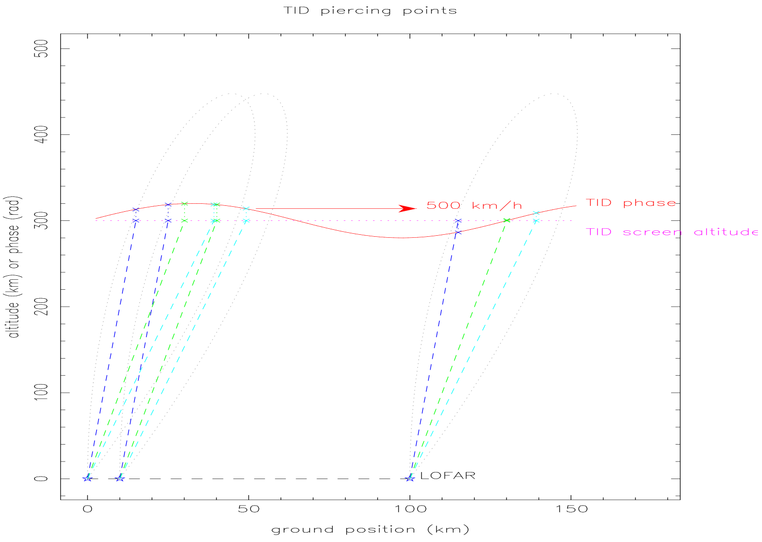

Figure 1.
Schematic diagram of some of the main LOFAR calibration challenges. Travelling Ionospheric Disturbances (TID) cause large phase variations in time, frequency and direction, which move and distort the image. In addition, the beamshapes of the phased-array stations (drawn without sidelobes here) also vary in time and frequency.

in which G_i is the complex electronic gain, D_i is the on-axis polarization leakage, P_i is the nominal orientation w.r.t. the sky, E_{ik} is the beam gain in the direction of source k, T_i is the tropospheric phase, F_{ik} is the ionospheric Faraday rotation, I_{ik} is the ionospheric phase, and K_{ik} is the Fourier kernel w.r.t. to the phase centre of the observation. Not all these matrices are relevant for all instruments, and some can be subsumed into others.

The vector and matrix elements of the M.E. are mathematical expressions, which will differ between instruments. The object of selfcal is to solve for the parameters of the M.E. by minimising the difference between measured and predicted values. After selecting a judicious subset s of parameters to be solved for, a subset of the measured samples is used to generate *selfcal equations* of the form:

$$\Delta V_m = D_m - V_m = \sum_s \frac{\partial V_m}{\partial p_s} \Delta p_s \tag{3}$$

These equations are accumulated in a matrix, which is then inverted to yield incremental improvements Δp_s for the selected parameters p_s. Since the M.E. is non-linear in most parameters, the selfcal process is of course iterative. Various calibration strategies involve solving for different sequences of different subsets of parameters. Note that we make no distinction between instrumental parameters, and parameters of the source model.

2. LOFAR CALIBRATION CHALLENGES

In principle, LOFAR is just another radio aperture synthesis telescope, just like WSRT, VLA, AT, GMRT, EVN, MOST, etc. This would suggest that, apart from having to handle much larger data volumes, traditional self-calibration should suffice for LOFAR. However, because of its greater sensitivity, and the greater brightness of radio sources at LOFAR frequencies, the required dynamic range is considerably larger (1:10.000.000) than for existing telescopes. At the same time, calibrating LOFAR will be more difficult in almost every aspect. This can best be explained in terms of the ability to remove bright sources from the uv-data. For LOFAR, this has to be done with an accuracy of (at least) 0.01 degr in phase, and 0.01 % in amplitude. This can only be achieved if all M.E. parameters vary *smoothly* in time and frequency. This minimizes the total number of parameters, and it also allows us to integrate over larger domains of frequency and time when solving for them.

Some of the main challenges to LOFAR calibration are:

- **Pathological ionosphere:** As fig 1 indicates, the ionospheric phase may vary by many radians as a function of time and frequency and viewing direction. For instance, at 74 MHz, the large-scale linear component may cause the apparent position of a source to vary by as much as a degree in 15 min. Higher-order components will distort the source, in different ways for different sources in the field. Paradoxically, it is probably not the spectacular large-scale effects that will be most difficult to calibrate, since it is smooth enough to be tracked. It is the rapidly varying small-scale component that may prove to be a limiting factor.

  The ionosphere can best be modelled as independent 2D phase screens across the field-ov-view of individual stations. The use of a single 2D screen over the entire array is only suitable for relatively small arrays ($< 20km$). It is also very unlikely that 3D models of the ionospheric 'blanket' will be accurate enough to predict the integrated phase along an arbitrary path with sufficient precision.

- **Radio Frequency Interference (RFI):** One of the greatest challenges for LOFAR will be to filter out the many sources of man-made RFI. The brightest ones may make the LNA non-linear, thus spreading its effects over the band in a way that is difficult to predict. Some may be treated in the same way as bright celestial sources, and subtracted from the data.

  On the positive side, narrow-band fixed RFI sources like TV transmitters may be very useful as *calibration beacons*, to stabilize the gain and phase of individual dipoles in the phased array of a LOFAR station.

- **Variable station beamshapes:** The response beams of the phased array stations are formed electronically. The resulting beamshapes will be less well defined, and more variable in time and frequency, than the beams of more traditional parabolic reflectors. On the positive side, the beamshapes are guaranteed to be *smooth* in its spatial dimensions, which will make it easier to solve for their parameters, and to interpolate them.

- **Changing beamforming coefficients:** This is needed for tracking the sky, or to 'null out' RFI sources in a particular direction. Again, it is vital that the resulting beamshape variations are *smooth* in time and frequency.

- **The BSR effect:** LOFAR signals will be processed in sub-bands of 150-250 kHz, each of which has its own beamformer. This arrangement is efficient, but causes a position-dependent Bandpass Sawtooth Ripple (BSR) in the gain, which contravenes the requirement of smoothness in all M.E. parameters. Fortunately, its distinctive signature provides a handle for dealing with it.

- **High station beam sidelobes:** The sidelobe level of a beam of a phased array of N elements is of the order $1/N$. This is much higher than the sidelobes of parabolic reflector antennas. This means that many many bright sources outside the main lobe will have to be taken into account. This will be difficult, since the shape of the sidelobes cannot be measured easily, and some sources (like the Galactic plane) will be very extended.

- **Very crowded fields:** LOFAR fields are large (several degrees), and radio sources are brighter at low frequencies. This means that many more sources will have to be subtracted from the uv-data. At the very least this means more processing, but it also increases the possibility of residual (un-subtracted) flux in the residual image. In addition, the very large number of (Cat III) sources with fluxes $< 5\sigma$ that are too faint to be in the GSM, will increase the noise (PSF sidelobe confusion).

- **Short-spacing excess noise:** There are some poorly substantiated reports of considerable excess noise at very short baselines ($< 100m$) between phased array antennas. If true, this might be rather troublesome, depending on its origin.

- **Polarization impurity:** A phased-array station cannot be tuned to a 'pure' polarization, like a parabolic antenna with its dipoles perpendicular to the incoming radiation. Fortunately, the full-polarization matrix formalism of the M.E. (see equ 1) makes the concept of *polarization purity* superfluous. However, the problem is to find suffient sources with known polarization to solve for the relevant M.E. parameters.

- **Quality of residual imaging:** After subtracting all the known sources ($> 5\sigma$) from the uv-data, the many that remain are often the ones that we are most interested in. They must be studied in the image-plane, but since uv-data can only be corrected for a single point in the sky (e.g. the image centre), the image quality will be worse towards the edges due to residual instrumental errors. This problem may be addressed, at the cost of more processing, by making many smaller 'facet' images.

- **Huge data rate and volume (Tbyte/hr):** Because of the demands of wide-field imaging, it will be necessary to process the data at their full resolution of 1 sec and 1 kHz. This is a huge amount of data, which will come in at a very high rate. It is fair to say that LOFAR could not have been built before the new generation of computers and storage devices became available. Even so, it will be difficult to keep up with on-line calibration, or to find ways to store and re-process the data for ultra-deep (100hr) observations like EOR detection.

  Obviously, it will be very important to process the data as efficiently as possible, i.e. to minimize the number of iterations (number of times the data have to be accessed), and to minimize the number of operations per iteration. A new selfcal selfcal strategy called *peeling* (see section 4.3) reduces the processing by several orders of magnitude, but more may be necessary.

Undoubtedly, this list is not complete. But it gives a good impression of the range of problems that have been identified and are being addressed.

3. LOFAR CALIBRATION PROCEDURE

It is assumed that the LOFAR hardware, and thus the signals from the stations, will be calibrated to an accuracy in the 1-10% range. Although this will be quite an achievement in itself, and will provide us with a good starting position, we will have to rely on self-calibration of the post-correlation visibility data for the remaining orders of magnitude. As mentioned before, a Global Sky Model (GSM) will play a large role in this. The GSM is a collection of models of all the sources can be detected or inferred in the LOFAR sky. Initially, these may be extrapolated from earlier radio surveys at other frequencies. The GSM will be updated over the lifetime of LOFAR, and will be one of its main deliverables.

Individual source models in the GSM will often be in the form of (expressions of) source parameters for flux (I,Q,U,V), position (RA,DEC), spectral index, Faraday rotation measure, shape, etc. The shape could be parametrized in many ways, e.g. as elliptic gaussians, or pixons, or shapelets. Some could be functions of time or frequency. Very extended sources might be modelled as images (cubes) or even CLEAN components.

For a particular LOFAR observation, a subset of GSM sources is selected for a Local Source Model (LSM). In LOFAR processing we distinguish three categories of sources:

- **Cat I sources:** The 100-1000 brightest sources in the sky. Their parameters are converted into M.E. parameters, and may be solved for. *Only Cat I sources are used for selfcal, i.e. for estimating M.E.parameters from the uv-data.* Because they are very bright, Cat I sources must be subtracted from the uv-data with maximum accuracy before imaging.

- **Cat II sources:** The rest of the sources in the LSM. Most of them will be in the main lobe of the station beam. They are subtracted from the uv-data before making an image. Their parameters are *not* used as M.E. parameters. However, they may be improved with the help of the residual images.

- **Cat III sources:** The many sources that are too faint to be detected with any certainty above the noise (e.g. $> 5\sigma$), and put into the GSM. Therefore, they cannot be subtracted from the uv-data, and will suffer from imaging errors (see below).

Note that the dividing line between Cat I and II sources is rather arbitrary. The rule is that any Cat II source that 'causes trouble' may be turned into a Cat I source for special attention. However, since Cat I processing is much more expensive, their number should be kept to a minimum. The LOFAR calibration procedure consists of the following major steps:

1. Track the largest ionospheric phase variations by solving every 10 s for the phases (M.E. parameters) in the direction of at least 3 very bright Cat I sources in the main lobe of the station beam. Use these phases to estimate the two gradients(t,f) of a linear phase screen for each station. Use these numbers to estimate the ionospheric phases in the direction of other Cat I sources to well with a radian at all times. This allows longer integration on fainter Cat I sources in the next step. Note that, initially, some kind of trial-and-error scheme is needed to remove any 2π ambiguities in the phases (acquiring phase-lock).

2. Solve for the *primary* instrumental M.E. parameters *in the direction of* about 100 Cat I sources, in the main lobe and the side lobes. The sources are treated one by one, in order of brightness, in a novel strategy called *peeling* (see section 4.3 below). The integration time for a solution will depend on the apparent brightness. If the latter happens to be too low for a particular uv-sample, it will be ignored.

3. Use the primary M.E. parameters for the Cat I sources in the main lobe to estimate the *secondary* M.E. parameters that describe the station beamshapes and the (curved) ionospheric phase screens across them.

4. The above steps might be regarded as **on-line calibration**. The instrumental parameters are known with an accuracy of well within a percent, which may be sufficient for many types of observations like transient detection, pulsar timing, shallow surveys, tied array mode etc. The data may now be stored for later processing. If the application allows it, they might be compressed a bit by integration over frequency and/or time.

5. Optionally, solve for improved source parameters(t,f) of the Cat I sources. Since these are regular M.E. parameters, this is just another selfcal solution for a suitable subset of parameters, using a suitable subset of uv-data.

6. Subtract all Cat I sources in the LSM from the uv-data, using their individual (primary) M.E. parameters. Very importantly, the accuracy of subtraction will be roughly proportional to the apparent brightness of the source, because their solution was driven by minimizing their residuals (closed loop).

7. Subtract all Cat II sources in the LSM from the uv-data. Their contribution is predicted by collecting all the source models in a small *patch* of sky into a gridded image, which is then transformed efficiently with an FFT. Instrumental effects for the centre of the patch are calculated by interpolating (or extrapolating) the beamshapes and phase screens characterized by the secondary M.E.parameters estimated above. Obviously, the accuracy will be better if the patches are smaller.

8. Transform the residual uv-data into *facet* residual images. Since uv-data can only be corrected for a single point in the sky (e.g. the image centre), the image quality will degrade towards the edges due to residual instrumental errors. This problem may be addressed, at the cost of more processing, by making many smaller 'facet' images. The maximum size of a facet is determined by the angular distance over which the ionospheric phase error changes by a radian. After correcting (a copy of) the uv-data for a facet centre position, and shifting the phase centre, the uv-data may be integrated over frequency and time. Each facet 'image' is in fact a 4D image 'cube' (RA, DEC, freq, pol).

9. Use the residual images to find/update the parameters of Cat II sources in the LSM. The first step is to inspect the positions where LSM sources have been subtracted. Any bumps or holes in the 4D cubes must somehow been translated in improved source parameters. After that, new Cat II sources may be identified, and tentatively translated into new LSM/GSM sources.

10. Integrate many hours of observations, either in the uv-plane or in the image-plane. It may be necessary at some point to reprocess all the data, for instance to subtract a greatly enhanced Source Model.

11. Analyze the residual images for astrophysical information, e.g. the EOR signature. It is very important to realise that the subtraction of so many bright sources will inevitably leave many low-level traces in the residual images, which might easily be mistaken for radio emission. There will never be such a thing as a 'clean image cube'. Therefore, more study is necessary to understand the signature of incompletely subtracted sources.

Obviously, it is crucial to have at least three sources that are bright enough to give $S/N > 3$ in 10 sec, for at least one baseline per station. This is complicated by the fact that many bright sources are extended, and are thus less visible for long baselines. However, it has been established that, for stations of more than about 50 dipoles, this requirement is always met for baselines shorter than 50 km.

4. ALGORITHMIC INNOVATIONS

It has been necessary to develop some new algorithmic approaches to meet the LOFAR calibration challenges. These will be reported extensively elsewhere. Here is a brief overview of the main points.

4.1. Generalized Selfcal

Traditional self-calibration, as practised with existing radio telescopes, has been so spectacularly successful that, until now, it has not been necessary to investigate its limits. Fortunately for LOFAR there still is considerable scope for improvement. The main elements of *Generalized Selfcal* are:

- The use of explicit and more accurate, matrix-based Measurement Equations of the form of equ 1. Inevitably this means more parameters, especially if instrumental effects are assumed to be position-dependent. Most of the existing data reduction packages have rather *ad hoc* and implicit M.E.'s, which are inflexibly implemented.
- Easy generation of different M.E.'s, to suit specific needs, or for experimentation.
- Support arbitrary calibration strategies, i.e. solving for arbitrary sequences of arbitrary subsets of M.E. parameters.
- Easy introduction of arbitrary constraints on a solution, e.g. phase referencing, or baseline redundancy.
- Allow the use of arbitrary subsets of the uv-data for particular solutions. Allow criteria that cause some data to be ignored dynamically (e.g. because it would only add noise).
- Treat each M.E. parameter as a (smooth) function of frequency and time. For instance, low-order 2D polynomials. Among other advantages, this reduces the number of independent parameters by solving for the coefficients of these functions.

Some of these elements have been pioneered in one way or another by experienced users of the existing packages. The LOFAR calibration system will offer them explicitly.

4.2. MeqTrees

The core of any LOFAR calibration system is the implementation of its Measurement Equation, and solving for its parameters. Although we know that the general form of the M.E. will look like equ 1, the optimum mathematical expressions and parametrization of its vector and matrix elements are not yet defined. Moreover, these might be different for different observing modes. Also unclear is the optimum sequence in which we should solve, iteratively, for subsets of M.E. parameters.

Therefore, the M.E. will be implemented in the form of 'MeqTrees', which are trees (graphs, really) of nodes that perform mathematical operations on their child nodes. The endpoints ('leaves') are special nodes that represent M.E. parameters. Solver nodes accumulate selfcal equations like equ 3 into a matrix, which is inverted to yield incremental improvements of the values of a selected subset of M.E. parameters. The equations are obtained from special nodes that subtract measured and predicted values (supplied by separate trees), and calculate partial derivatives w.r.t. the selected parameters. Multiple solvers may be active simultaneously.

The MeqTree processing kernel is completely *policy-free*, i.e. it does not know anything about the application. Arbitrary M.E.'s may be defined externally, and converted into 'forests' of MeqTrees. A calibration strategy consists of defining arbitrary sequences of arbitrary subsets of M.E. parameters that are to be solved by particular solvers. The latter only know about its children, from which its gets equations, and about its particular subset of parameters.

4.3. Peeling

In traditional selfcal, the entire model of the observed brightness distribution is taken into account when predicting the values of measured data. The processing is minimized by using simple source models, and by assuming that the same instrumental errors are valid for the entire field. LOFAR will be different in the sense that much more sophisticated source models are needed, and the instrumental errors will vary considerably over the field. The result is that, even with the much greater computing power that is available, the traditional approach to selfcal would be prohibitively expensive.

Fortunately, it appears to be feasible to treat the various sources one by one, and to solve for relatively small subsets of the M.E. parameters at a time. The idea is to assume that the brightest source is the only one in the field, and to solve only for the instrumental parameters *in its direction.* The contribution of this source is then subtracted ('peeled') from the measured data, and the next brightest source is treated in the same way. This continues until all Cat I sources have been peeled off.

The main advantage of this 'peeling' technique is a potentially huge (10^4) reduction in processing. First of all, since we concentrate on a single 'peeling source' at a time, we may shift the phase centre of the data to its position. This will *flatten* its visibility function over a given domain(f,t), so it only needs to be predicted for a much smaller (10^3) number of large domain cells. Secondly, since we only solve for a small number of n M.E. parameters for each of the m peeling sources, the solution matrices are much smaller: $m \times n^3 \ll (m \times n)^3$. Finally, when solving for fewer parameters simultaneously, fewer iterations tend to be necessary, and the solution is more stable.

There are other advantages to peeling. For instance, the fact that source after source is peeled from the data opens the possibility of a hierarchical scheme for flagging bad data points. Because the threshold may be lowered at each step, the simplest possible clipping criterion may be applied, which is safe and reliable, and saves processing too.

The only potential problem is the *contamination* of the other sources in the field. The easy answer is that it is always possible to include an arbitrary number of contaminating sources in the prediction (while still solving for only the M.E. parameters associated with the peeling sources). However, since this is expensive, it pays to analyze carefully how much this contamination really affects the solution. It tursn out that there are many factors working in our advantage here. Firstly, the celestial flux curve is rather steep, so that the brightest source tends to dominate at all levels. Secondly, the contribution of a source far from the phase centre (i.e. the position of the peeling source) will be averaged out over large domain cells. Thirdly, the sum contribution of another source over all baselines is attenuated by the instantaneous point-spread function centered on the peeling source. The conclusion is that the contamination by other sources will be intrinsically small, and can always be reduced to arbitrarily low levels by including them in the predict.

5. CONCLUSIONS

From this necessarily brief outline of the many challenges, it will be clear that LOFAR calibration will be a formidable task. As was the case with some very successful radio telescopes like WSRT and VLA, it will take a number of years to learn how to use LOFAR most effectively, and to fully develop the necessary software. However, the following indicators are reasons for cautious optimism:

- We appear to have a reasonably complete understanding of the various problems that LOFAR calibration will face, and we certainly do not under-estimate them.
- A number of important enhancements of existing calibration techniques have been identified. The various aspects of *generalized selfcal* will certainly improve the quality of the result. Equally important, strategies like *peeling* will greatly reduce the vast amount of processing that is needed.
- The needs of calibration have been among the major design drivers for LOFAR from the start. In particular the requirement that M.E. parameters do not have to be particularly stable, as long as they only vary *smoothly* in time and frequency.

- Most important of all, there seems to be sufficient *information* available, in the form of bright and compact calibration sources, to allow LOFAR to be calibrated eventually. This is a crucial difference with other problems, like optical interferometry through the atmosphere.

Finally, our present efforts are also very relevant to the Square Kilometer Array (SKA), which is being discussed by the international community.[7] Since SKA will operate at higher frequencies than LOFAR, its calibration will be different, but probably less difficult. Therefore, a successful LOFAR data processing system will be a superset of what is needed for SKA.

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