Antenna design and distribution for a LOFAR Super Station in Nançay

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Abstract

The Nançay radio astronomy observatory and associated laboratories are developing the concept of a "Super Station" for extending the LOFAR station now installed and operational in Nançay. The LOFAR Super Station (LSS) will increase the number of high sensitivity long baselines, provide short baselines and an alternate core, and be a large standalone instrument. It will operate in the low frequency band of LOFAR (30–80 MHz) and extend this range to lower frequencies. Three key developments for the LSS are described here: (i) the design of a specific antenna, and the distribution of such antennas (ii) at small-scale (analog-phased mini array) and (iii) at large-scale (the whole LSS).

1 The LOFAR Super Station

1.1 Principle and general design

The Nançay Radio Observatory ($www.obs-nancay.fr$) hosts the LOFAR international station "FR606". Each LOFAR station is a subset of two arrays of antennas: the "Low Band Antenna" (LBA - [30-90] MHz) array and the "High Band Antenna" (HBA - [110-250] MHz) array, both connected to the two inputs of the station back-end (more details about LOFAR in [1]). A third input to the cabinet's receivers exists, which was initially dedicated to a "Low Band Low" (LBL) antenna field. The main idea underlying the LOFAR Super Station (LSS) concept is to build and connect to this input a new field of 96 new antennas operating in the LBA range (and extend it to $\leq$ 15 MHz). Each of these new antennas will actually consist of an analog-phased mini-array of 10–20 antennas, increasing thus the sensitivity of the station in the LBA range, while remaining fully compatible with the whole LOFAR array.

Each LSS mini-array of 10-20 antennas (dual-polarized) must be analog-phased because only 96 dual-polarization inputs available. These mini-arrays are actually very similar in their principle to the HBA tiles of 16 (4×4 square grid) high frequency antennas, phased using delay lines. However, the mini-array layout will not be necessarily square. The signals beamformed at the tile level are the signals that are digitized and numerically combined in the cabinet's back-end, either in summation (phased array mode) or in correlation (interferometer mode). The LSS will consist of 96 mini-arrays distributed within $\sim$150 m of the LOFAR station cabinet (see Figure 1 right). Its layout must then be optimized at two different scales : mini-array and full LSS.

1.2 Interests of the LOFAR Super Station

Within the LOFAR array: The LSS will provide several improvements to the present LOFAR design and capabilities. First, the $10-20$ times improved sensitivity of the mini-array compared to a standard LBAs will increase the sensitivity of all long baselines involving the LSS. It will thus approximately double the number of long baselines with high sensitivity. Second, only station-to-station correlations were planned in the initial LOFAR project, which implies in the LBA range a minimum baseline length of one LBA field

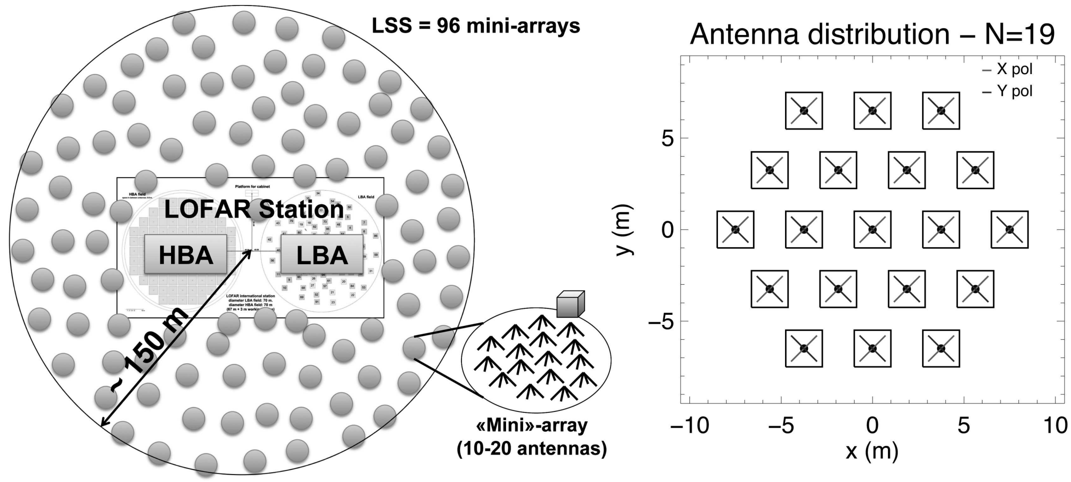

Figure 1: Left: The LOFAR Super Station is a set of 96 mini-arrays (or tiles) of 10-20 antennas analog-phased, spread around the Nançay international LOFAR Station within a range of ∼150 m. Right: Possible antennas distribution within a mini-array, here with $N = 19$ elements arranged on an hexagonal grid.

diameter (B_{min} ∼60 m). This implies that LOFAR would be blind to structures larger than λ/B_{min} at wavelength λ. With the LSS, tile-to-tile correlations will be performed, providing baselines as short as a mini-array diameter (10–15 m) and up to the LSS diameter (∼300 m) with 10–20 times better sensitivity than antenna-to-antenna correlations. The LSS will thus fill very efficiently a missing part of LOFAR present (u,v) coverage in the low band. Third, several LOFAR observation programs need large bandwidths and excellent calibration rather than high angular resolution and will consequently use only the stations of the core. In the meantime, remote and international stations may be correlated in parallel by the central computer and run other programs. By correlating the LSS to all remote and international stations, sensitive long baselines will be restored. The LSS can thus be viewed as an alternate core providing a decent (u,v) coverage and a good sensitivity. In this way, the LSS can contribute to "create" up to 30% of additional LOFAR observing time in parallel with core-only observations.

As a stand-alone instrument: With $N = 19$ antennas (Figure 1 right), the LSS will have an effective area $\simeq 96 \times 19\lambda^2/4 \simeq 40000 \times (\lambda/10)^2$ comparable to that or the Giant Meterwave Radio Telescope (GMRT) in India, $\simeq 3\times$ the Very Large Array (VLA) in New-Mexico, or $\simeq 10\times$ the Nançay Decameter Array (NDA). It will thus be a large instrument by itself, with relevant standalone use independent of LOFAR, with no loss for LOFAR when the Nançay FR606 is not included in ongoing obsevations.

Scientific objectives: Scientific programs of the LSS (within LOFAR or in standalone mode) will include low frequency surveys, detection of weak sources in time-frequency (coherent phased-array) mode, contribution to the study of large-scale diffuse structures, etc. and it will in addition provide a better calibration for VLBI imaging. A standalone LSS is also well adapted to student training purposes.

2 Three key design studies for the LSS

LSS feasibility, design, cost and prototyping studies are presently ongoing. We present below the results of three design studies that are crucial for the LSS: (i) the antenna design, (ii) the antenna distribution in a mini-array, and (iii) the 96 mini-arrays distribution in the LSS.

Antenna design: Several low frequency ground-based instrument are presently under development : LOFAR [1], the Long Wavlength Array - LWA [2], the Murchison Widefield Array - MWA, the Giant Ukrainian Radio Telescope - GURT, etc. For each of them, specific antennas have been developed in order to meet their scientific and technical requirements.

Antenna design implies the determination of physical (geometrical) and electrical parameters of the antenna radiators. These parameters are the antenna beaming pattern in E & H planes (constraining the array's Field of View (FoV)), the level of side lobes, the frequency bandwidth, and the efficiency (related to electrical and ground losses). In a sky-dominated noise regime ($T_{sky} \approx 23000K$ at 30 MHz), we can neglect the noise contribution from the antenna itself. To limit the noise of instruments beyond the antenna (cables, electronics, etc.), a low noise amplifier (LNA) is directly attached to the antenna radiators, forming a so-called "active" antenna. For a phased-array application, a large and smooth beam pattern is required, close to that of an isotropic antenna, as it will condition the final FoV of the array, which is expected to go down to an elevation of 20° with LOFAR. We also wish to obtain a broadband antenna that can operate down to 15–20 MHz.

Considerations of cost effectiveness constrain the design space to linearly polarized dipoles, thus we carried out comparative studies of different geometry of radiators using the numerical electromagnetic code (NEC – *www.nec2.org*). This method of moments code, can derive among the simulated far field pattern and the electrical parameters of any antenna defined by a wire model and feed (characteristics in reception are obtained by application of the reciprocity theorem). We investigated the two classes of radiator designs ("butterfly" or "bow-tie", and "inverted-V" antennas) and the influence of a ground plane (metal grid), and we performed optimization studies of their parameters (height, length, droop and fork angles, grid mesh size and step, etc.).

These studies led us to select a "thick" [3] inverted-V dipole similar to the LWA Fork [2]. We found that - as for LOFAR and the LWA - a metallic ground screen is necessary for inverted-V antennas in order to reduce ground losses (efficiency $> 50\%$ – resp. $> 80\%$ – of that of a Perfect Electrical Conductive plane at 20 MHz – resp. 80 MHz), and to ensure the stability of the antenna impedance against variations of the ground characteristics (dry or wet ground). In parallel, various LNA architectures and matching have been considered. A first prototype of this thick dipole has been built in Nançay in order to test the relevance of our simulation results against measurements on the sky.

Distribution of antennas within a mini-array: The role of the mini-array is to combine analog antenna signals to synthesize a single wide beam and coarsely point it toward the direction of interest. The fine pointing of the LSS beam (96 mini-arrays) will be done either by the LOFAR beamforming system in the station back-end or a stand-alone beamformer, and will be therefore tapered by the beam pattern of the mini-array. The constraints on the distribution of the antennas within a mini-array include : a smooth & symmetric primary beam, with a low level of side lobes, a large effective area (high sensitivity), a not too complex phasing scheme, a low mutual coupling between antennas, etc. We first performed an optimization study of the mini-array distribution aiming at the maximum reduction of side lobes. We used global minimization algorithms such as the simulated annealing [4] based on a thermodynamically-controlled Monte-Carlo displacement of the positions of the antennas. The resulting distributions are dense arrays (whose compactness is limited by a threshold distance between antennas) displaying circular symmetries around the phase center but without any kind of periodicity. Such an axisymmetric and aperiodic shape guarantees the minimization of the side lobes (down to -30 dB attenuation or more) and the absence of strong grating lobes. But it is also very difficult and costly to phase by analog means in practice.

Thus, we opted for an array of antennas presenting regularities along two orthogonal x and y directions (as in NDA or GURT). This implies large savings in cable lengths. A good compromise between beam characteristics and phasing complexity is shown in Figure 1. By using a triangular lattice, it is possible to find a balance between periodicity (which causes large grating lobes but cheaper phasing) and axisymmetry (give an axisymmetric primary beam).

Regular arrays also present the advantage to reduce the mutual coupling variability from an antenna to another because all embedded antennas (i.e. not at the edges of the mini-array) behave in a similar way. Conversely, in irregular/aperiodic arrays, the coupling may vary substantially from one antenna to the next.

Further studies of distribution, phasing, and coupling effects are ongoing.

Distribution of mini-arrays within the LSS: The LSS will consist of 96 mini-arrays distributed in an area of ∼300 m diameter around (or off-centered) the back-end of the FR606 station. It will work either in a phased-array mode or in interferometer mode. The digitization of each mini-array output gives a large flexibility in the distribution of the 96 mini-arrays. The main constraints that the LSS must fulfill are a low side lobe level and a good (u,v) coverage by the $96 \times 95/2$ baselines. As the filling factor of a disk of 300 m diameter by mini-arrays of 19 antennas is high (∼64% at 30 MHz), the LSS will be a rather dense array/interferometer at low frequencies. A pseudo-random homogeneous distribution of mini-arrays over the whole LSS area, taking into account specific constraints of the station environment (pond, building, other instruments, etc.) is an acceptable baseline solution. We are in the process of optimizing this first solution by using the algorithm described in [5]. It is a "pressure-driven" algorithm that optimize the (u,v) coverage (relatively to a target (u,v) model) of a "gas" of individual antennas, taking into account a "site mask".

Another major improvement of the LSS response is brought by rotating by a random angle each mini-array relative to a reference direction and rotating back the antennas within the mini-array in order to keep all antennas along the 2 main polarization axes, as it was done for the LOFAR antenna fields. We computed that this decreases by ∼8 dB the side lobes level in our case. But it come with an increase the complexity of its calibration and the mutual coupling variability. We are currently modeling the whole LSS in interferometer mode using the MeqTrees software package [6]. It enables one to establish the Measurement Equation (product of "Jones" matrices) describing the instrument and to solve for its parameters.

3 Conclusion

LSS detailed design, prototype and tests studies (including the construction of 3 mini-arrays), and cost evaluation, will be pursued in the next ∼20 months. Its detailed scientific case is being developed in parallel (and inputs are permanently welcome). We expect LSS construction to start in 2013. If the concept is successful, it could be applied by other European participants to LOFAR, preparing a future "super LOFAR".

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