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LSS/NENUFAR: THE LOFAR SUPER STATION PROJECT IN NANÇAY

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Abstract. We summarize the outcome of the scientific and technical study conducted in the past 3 years for the definition and prototyping of a LOFAR Super Station (LSS) in Nançay. We first present the LSS concept, then the steps addressed by the design study and the conclusions reached. We give an overview of the science case for the LSS, with special emphasis on the interest of a dedicated backend for standalone use. We compare the expected LSS characteristics to those of large low-frequency radio instruments, existing or in project. The main advantage of the LSS in standalone mode will be its very high instantaneous sensitivity, enabling or significantly improving a broad range of scientific studies. It will be a SKA precursor for the French community, both scientific and technical.

Keywords: Radioastronomy, Low-Frequency, Array, LOFAR, Nançay, LOFAR Super Station, Antenna, Preamplifier, Receiver, Phasing, Exoplanets, Pulsars, ISM, Cosmology, Transients

1 Introduction

LOFAR is a new European multi-scale low-frequency (LF) radio interferometer in the range 30−250 MHz, with baselines from ∼50 m to ∼1000 km (van Haarlem et al. 2012). Its large effective area and extent will allow its users to address a variety of astrophysical topics, including cosmology (the Epoch of Reionization − EoR − of the young Universe), deep sky surveys, star formation, AGN, galaxy clusters, the distribution of cosmic magnetic fields, transient emissions at all timescales (from cosmic-ray-induced to pulsars, flare stars and other eruptive or variable souces), planetary (and hopefully exoplanetary) plasma physics, as well as Solar and space physics. The constitutive elements of LOFAR are phased arrays or "stations", distributed in The Netherlands and surrounding European countries. One of these stations – FR606 – is installed in the Nançay radio observatory (France). Each station consists of two arrays of antennas and a "backend" that preprocesses antenna signals (filtering, digitization, spectral channelization and beamforming). Preprocessed digital data are then sent at ∼ 3 Gbits/sec to the central computer (in Groningen, NL) that performs the correlations per interferometric baseline and/or final pencil beamforming. The Low-Band Antenna (LBA) array covers the range 30−80 MHz and consists of 96 elementary crossed dipoles in international stations such as FR606 (48 in Dutch stations). The High-Band Antenna (HBA) array covers the range 110−250 MHz and consist of 96 "tiles" of 16 analog-phased crossed dipoles (2×24 in Dutch stations). The radio FM band in between, saturated by man-made emissions, is carefully avoided. At any given time, the backend can be connected to either the LBA or the HBA (not both simultaneously). A third input to the backend exists, that was initially planned for an LBL (Low-Band Low, 10−50 MHz) array that never existed due to limited funding. The phasing of HBA tiles and the initial signal filtering before digitization are the only analog steps in LOFAR, which is essentially a digital radiotelescope.

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2 The LOFAR Super Station concept

The bandpass filtering of the LBL input to the backend is 10−90 MHz (thus including the LBA range). The basic idea underlying the LOFAR Super Station (LSS) concept is to add a 3^{rd} antenna array to a LOFAR station (FR606 in our case), that will be fully compatible with LOFAR operations in the LBA band (i.e. that can be correlated with LBA arrays of other LOFAR stations, instead of the FR606 LBA array) and at the same time provide a considerably increased instantaneous sensitivity and frequency coverage. In order to meet these constraints, the LSS will consist of 96 groups of dual-polarization antennas (or LF "tiles") with a large gain from 10-15 MHz to 85-87 MHz (i.e. a ratio f_{max}/f_{min} double of that of the LBA range). Each of these LF tiles should be analog phased (as the HBA tiles) in order to provide only 2 inputs (1 per polarization) to the LOFAR antenna backend digitizers. The number of antennas within each tile should be of the order of 16 (again as in HBA tiles) in order to provide at least an order of magnitude increase of the instantaneous sensitivity. As we explain below, the "ideal" number we have reached is 19 crossed dipoles per LF tile. The 96 tiles should be arranged in a relatively dense layout (within a few hundred meters diameter), providing a smooth overall beam with a low side lobe level and compatible with the available land in an observatory such as the Nançay station, and at the same time minimize the overlap between antennas' effective areas in order to maximize the LSS sensitivity.

An instrument of a few hundred meters diameter will provide an angular resolution of the order of 1° in the 10−88 MHz range, so that the LSS by itself is not a powerful imaging instrument. But its collecting area, and thus its sensitivity, will bring several significant improvements to LOFAR:

- The long LOFAR baselines including the LSS will be $\sim \sqrt{19}$ times more sensitive than long baselines between two LBA arrays; as the available radio power corresponding to fine angular details is generally weak, this increased sensitivity will give access to an increased number of calibrators (typically ×10) in the vicinity of the studied target; this will improve LOFAR's capabilities for high resolution imaging in the LBA range.

- By adding 96×19=1824 antennas to the present ∼2700 LOFAR LBA antennas, the LSS will almost double LOFAR's sensitivity in the LBA imaging mode.

- When most of the "core" (closely-packed) LOFAR stations will be used for time-demanding projects such as observing the EoR, the LSS will provide an alternative core and, by correlation with the "remote" LBA arrays, will preserve good imaging capability in parallel with the above projects; provided that the central correlator can handle two streams of data from two LOFAR sub-arrays (namely the core, and the LSS+remote stations) the LSS will improve LOFAR-LBA imaging capabilities for a significant fraction of the time.

- Correlation of signals from the LF tiles within the LSS will provide sensitive baselines 2 to 3 times shorter than a LOFAR station diameter − the shortest baseline presently available −, permitting to image large-scale structures, larger than an instantaneous station beam (∼ 10° at 30 MHz); short baselines are presently available by correlation of LBA antennas within a station, but with much lower sensitivity.

- The LSS will also be a very large standalone instrument: it will have an effective area (and thus sensitivity) ∼19 times larger than the LBA array of an international station, i.e. ∼70% to 85% of all LOFAR-LBA arrays, but this area will be instantaneously and fully available during use, especially in coherent tied-array (or phased-array) beam mode (TAB); by contrast, the coherent phasing of LOFAR-LBA array signals is limited to the 24 core stations that share the same reference clock (and have the same ionosphere above them); thus, the instantaneous sensitivity of the LSS in coherent TAB mode will be ≥1.6 times better than the LOFAR-LBA one (Figure 1).

- Finally, in standalone mode, the LSS will extend the observation bandwidth to significantly lower frequencies than the LBA range.

3 LSS design and prototyping

We performed feasibility and optimization studies of all elements of the LSS design:

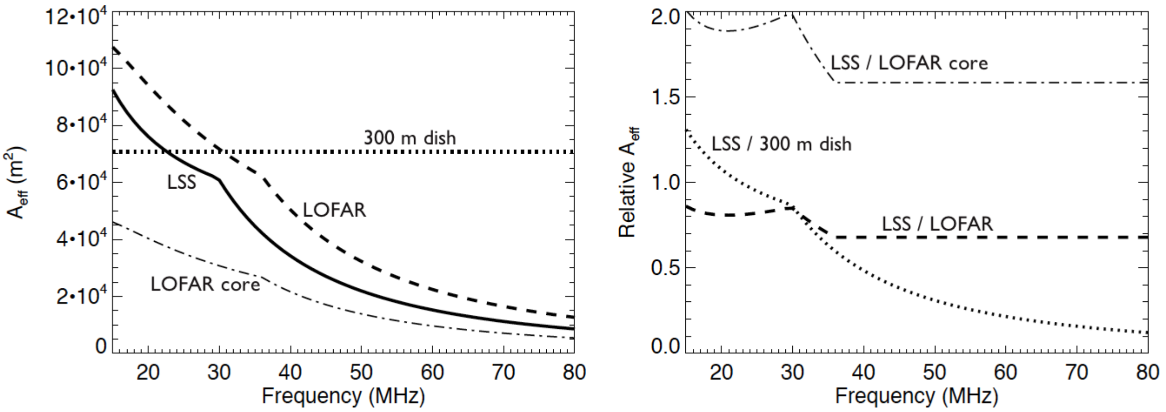

Fig. 1. LSS effective area compared to that of LOFAR, LOFAR's core, and an Arecibo-like antenna (∼300 m in diameter).

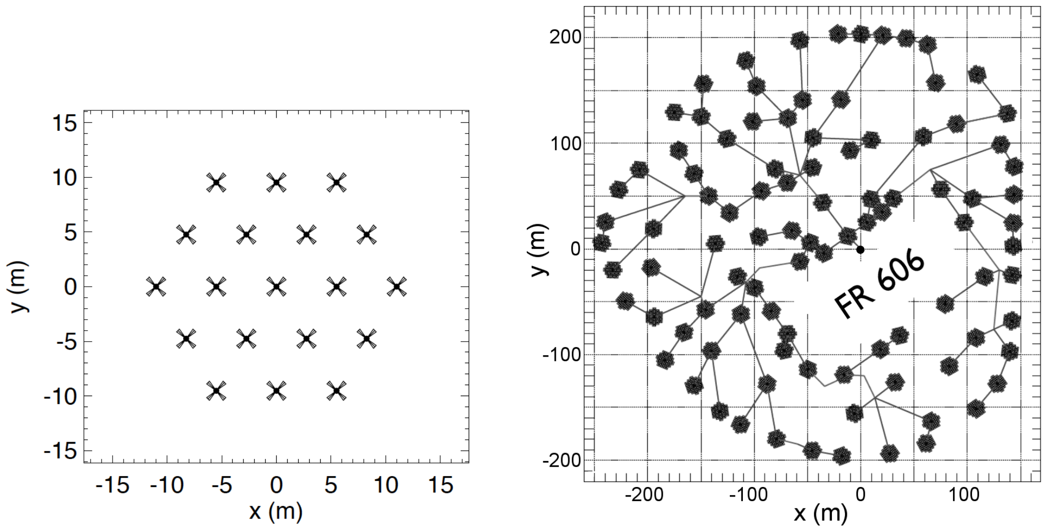

Fig. 2. Left: LF tile layout. Elementary crossed dipoles will always be at 45° from the meridian whatever the rotation of the tile. Inter-antenna distance is 5.5 m. **Right:** LSS antenna distribution optimized for a gaussian coverage of the (u,v) plane, taking into account local positioning constraints (forbidden zones). LF tiles are represented with their random rotations. The layout of the connections between LF tiles and the LOFAR backend (black dot at 0,0) follows from the optimization of the trench-cable problem applied to the LSS. The total length of trenches will be ∼4 km and that of RF cables connecting the tiles to the backend ∼21 km per polarization.

- First, we optimized the diagram of the antenna radiator via electromagnetic simulations with the NEC code and tests on the sky; optimized parameters include a broad and smooth beam (nearly isotropic, albeit with extinction below 20° elevation) and maximum efficiency (related to electrical and ground losses), over a large frequency bandwidth; this implies an antenna radiation resistance and (low) reactance as constant as possible over the band of interest and versus time; cost effectiveness and compatibility with LOFAR strongly favoured linearly polarized crossed dipoles; we found that the optimal compromise is a "thick" inverted-V dipole similar to the LWA Fork, with a metallic ground screen (Girard et al. 2011, 2012).

- Three designs have been studied and realized for the antenna preamplifier, which is a key element for the antenna gain and its susceptibility to radio-frequency interference (RFI): (1) the "GURT2" design from the Kharkov Institute of Radio Astronomy,(2) the Subatech/Nançay design, and (3) the Nançay microelectronics laboratory design. (1) is based on discrete components, whereas (2) & (3) are based on ASIC circuits. All have good characteristics, with a noise ∼10 dB below the sky noise level. The final choice will result from tests on the sky (see below).

- Then, the antenna distribution within each LF tile was optimized for a low side lobe level and a large field of view symmetrical around the zenith; Girard & Zarka (2012) found that a distribution with a central antenna surrounded by two circular rings of antennas meets these requirements, especially if the rings have different (or no) symmetry axes, i.e. if the global distribution cannot be superposed to itself by a rotation $< 2\pi$. In parallel, we have calculated that analog phasing of each LF tile using 7-bit delay lines (cable lengths) allows to perform achromatic phasing over the whole LSS band (10-87 MHz) with gain variations $\leq$10% across the beam, and provide one input per polarization to the backend. In order to be cost-effective, delay lines must be mutualized for groups of antennas, e.g. by arranging antennas with a regular spacing in two orthogonal directions. Taking into account this constraint we modified the above optimized antenna distributions to obtain an LF tile of 19 antennas (a central one surrounded by an hexagon of 6 antennas and a second one of 12 antennas, or equivalently regular lines of 3 / 4 / 5 / 4 / 3 antennas with each line shifted by 1/2 inter-antenna spacing relative to its neighbours − Figure 2 Left). The absolute value of inter-antenna spacing was set to 5.5 m in order to maximize the effective area without overlap at LF, while keeping the LSS extent compatible with its hosting at the Nançay station (see below). The instantaneous LF tile beam will have an angular size of $10°-50°$ over the LSS spectral range ($\sim 25°$ at 30 MHz).

- The optimal distribution of the 96 LF tiles was computed using the Boone (2001) algorithm, taking into account a "site mask" of the Nançay station including its limits and forbidden areas (the station FR606 itself and other antennas of the site). It provides a smooth, gaussian distribution of visibilities in the (u,v) plane, and thus a near-gaussian LSS beam pattern. The layout of trenches and cables connecting the LF tiles to the FR606 backend was optimized using a reasonable cost ratio per unit length of trench/cable in input to a specific optimization algorithm (Vasko et al. 2002). The obtained LF tiles distribution and layout is displayed in Figure 2 Right). It implies an LSS beam size of $0.5°-3°$ ($\sim 1.5°$ at 30 MHz). In order to reduce the side lobe level resulting from the regular antennas arrangement in the LF tiles, each tile will be rotated by a random amount with respect to each other, but all crossed dipoles within all tiles will be oriented along the same directions, at 45° from the meridian (Figure 2).

- The LSS pointing will be controlled by a dedicated LCU (Local Command Unit) connected to 96 electronic modules, one in each LF tile, specifying the phasing scheme to be applied at any given time (different for each LF tile due to their random rotations); these modules are designed to be completely "radio-quiet" outside pointing time; pointing will occur at intervals from 20 to 60 sec, ensuring low gain variation in the main beam direction. The LSS LCU will be connected to the LOFAR LCU of station FR606. When the LSS will be used jointly with other LOFAR LBA arrays (so-called "International" mode), pointing orders will come from the LOFAR operations center via the LOFAR LCU and be translated into LF tiles phasing commands by the LSS LCU; data recorded by the LOFAR backend will be sent to the LOFAR central correlator. In "Standalone" mode, pointing orders will come from a local command computer, and the data will be recorded locally (see below).

- Finally, a site study was conducted by ONF (Office National des Forêts) which granted the authorization to clear 10 hectares of land for constructing the LSS.

The antenna radiator and preamplifier designs are being tested on the sky. Figure 3 is an observation of Jupiter with a single LSS antenna (equipped with GURT preamplifier), allowing us to test the antenna characteristics in its LF part ($\sim$ 10 to 35 MHz). Jupiter's decameter radiation is detected at a fraction of dB above the galactic background (i.e. at a few % of the level of the galactic background integrated over the broad antenna diagram) down to 13−14 MHz, showing the correct behaviour of the antenna at LF. Comparison with a simultaneous observation by the Nançay Decameter Array allowed us to compute the directional gain of the LSS antenna over the observed range. This gain is $\sim$5 dB over the range 20−30 MHz, consistent with our NEC simulations, and the effective area of the LSS dipole appears to vary in $\sim \lambda^2/3$.

In order to fully test the LF tiles, including the antennas + preamplifiers and the phasing and command systems, 3 prototype LF tiles have been built in Nançay in 2012. The first one is displayed on Figure 4. Each prototype tile is equipped with a different set of antenna preamplifiers. Extensive tests on the sky are being performed, including point source and extended source measurements, gain / effective area / sensitivity measurements, immunity to RFI, polarization response, and comparison of the performances of the 3 preamplifiers. For these tests, a dedicated receiver has been built in Nançay that can acquire in parallel the 3 tiles $\times$ 2 polar-

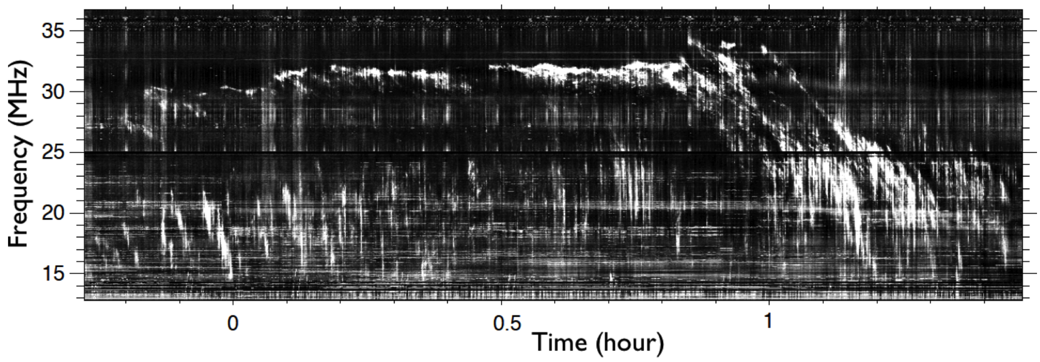

Fig. 3. Dynamic spectrum of Jupiter's decameter emission observed by a single LSS antenna with GURT preamplifier, on 9 oct. 2011. Jupiter bursts, inclined in the displayed time-frequency plane, have an intensity of a few % of the galactic background (the latter has been subtracted in the displayed dynamic spectrum). They are clearly detected down to 13−14 MHz.

Fig. 4. The first LF tile prototype of the LSS built in Nançay in 2012, consisting of 19 crossed dipoles.

izations, digitize these 6 inputs at 196 Msamples/sec, and compute their full correlation matrix over 2048 point spectra (∼47 kHz spectral resolution) with high time resolution.

4 Science objectives of the LSS

The LSS will bring new capabilities not available to LOFAR, as briefly described in the "concept" section above. These capabilities will enable new observations not possible with LOFAR, or improve on LOFAR observations in several domains. We summarize below the LSS science case sorted by broad scientific domains.

- **Exoplanets and binary/eruptive stars**: the larger instantaneous sensitivity of the LSS in standalone coherent TAB mode, and its access to lower frequencies, will bring new possibilities of detection and study of weak radio emission from stars, exoplanets (Zarka 2011), star-planet interactions, and comparative (exo-)magnetospheric physics. This is especially true *if the LSS can be used in standalone with a large duty-cycle*. Also, independent simultaneous detection of weak sources in parallel with the LSS and LOFAR will permit to confirm detections with a better immunity to local RFI or ionospheric perturbations. Correlation of the LSS with LOFAR LBA will increase the total sensitivity for imaging the environment of these sources.
- **Pulsars and Rotating RAdio Transients (RRATs)**: various figures of merit combining instantaneous sensitivity and field of view show that the LSS in standalone mode will be a more powerful transients detector than LOFAR, especially at LF (where the LSS effective area is largest − *again, a large duty-cycle will be crucial*). It will allow to address the physics of the environment of compact objects, the nature of RRATs, giant pulses, to search planets around pulsars (Mottez & Heyvaerts 2011), and study the structure of the ISM via propagation effects (Zakharenko et al. 2012).
- **Structure of the Galactic interstellar medium (ISM)**: when used jointly with LOFAR, the LSS short baselines will give access to extended radio sources (envelopes, nebulae . . .), whereas the more

sensitive long baselines will enable small-scale magnetic fields imaging via rotation measure measurements (without depolarization due to spatial integration), and to study radio recombination lines (Asgekar et al. 2012). Standalone LSS measurements of the temporal broadening of transient radio pulses will put constraints on the largest scale of the ISM turbulence.

- **Cosmology and galaxy formation**: LSS in standalone mode will allow us to search the spectral signature of pre-EoR dark ages, as predicted in the LBA/LSS range by e.g. Visbal et al. (2012). *This will require a careful calibration of the bandpass and ionosphere that can be performed via instantaneous auto- and cross-correlations of the LSS tiles.* Sensitive long baselines from the LSS used in correlation with LOFAR will permit to address large structures formation (AGN at $z < 1$, clumps up to $z \sim 2$, star formation in nearby galaxies, magnetic fields).

- **The "impulsional" Universe**: as for pulsars and RRATs, the LSS in standalone mode will be a powerful transients detector, *provided that an adapted backend is available with a high duty-cycle.* In coherent or incoherent TAB mode and/or with extended Transient Buffer Boards (i.e. antennas waveform data buffers – cf. (van Haarlem et al. 2012) and `http://www.astron.nl/radio-observatory/astronomers/users/technical-information/transient-buffer-boards/transient-buffer-b`), it will permit the blind exhaustive exploration of the impulsive Universe, ideal in LF radio due to absence of photon noise. Addressed topics will include time and frequency scales of (dispersed) pulses, the nature of emitters (Gamma Ray bursts, cosmic rays, neutrinos impacting the Moon), and a broad range of potential serendipitous discoveries.

- **Transient Luminous Events (TLE) in the Earth and planetary atmospheres**: in the same modes as above, the LSS will enable the radio exploration of counterparts of sprites and other TLEs, addressing their origin, distribution and dynamics over center France, time and frequency scales, and physical mechanisms.

LSS objectives will of course address Solar system physics (ionospheric scintillations and opacity, Jupiter radio emissions, Solar bursts, space physics: interplanetary scintillation and possibly active – Radar – studies), but these studies do not crucially depend on LSS capabilities. However, the LSS may bring in a larger duty-cycle than the one available with LOFAR, permitting monitoring studies.

5 Dedicated receiver and Standalone use

The importance of a high duty-cycle of LSS standalone mode and of a dedicated receiver have been stressed in italics in the previous section. The standard LSS concept consists of the 96 additional LF tiles and their phasing and command system, that are connected to the LOFAR backend of FR606. The contract of any European station owner with the International LOFAR Telescope board includes the right to use that station in standalone mode for $\geq$10% of the time. As the standard LOFAR station backend only allows to record low frequency-time resolutions observations (typically in 200 kHz $\times$ 1 sec bins), the full scientific exploitation of standalone LSS observations requires either LOFAR's "Single Station" mode (cf. `http://www.lofar.org/operations/doku.php?id=singlestation:start`) or a dedicated post-backend (Serylak et al. 2012). The former consists of a subarray formed by a single station, which high resolution data are sent to the central correlator for processing as TAB data. The latter is for example the ARTEMIS (Advanced Radio Transient Event Monitor and Identification System) post-backend dedicated to transients detection and study, that ingests high resolution station data and locally computes high-resolution time-frequency planes including parametric dedispersion (Armour et al. 2011).

If one wants to compute locally more than time-frequency planes with LSS standalone data (e.g. auto- and cross-correlations of tile signals), then a dedicated receiver is necessary. Such a dedicated receiver has been studied in the frame of the LSS design study. It will consist of either a post-LOFAR-backend (ARTEMIS-like), or a fully independent backend. The LOFAR backend digitizes the LBA or LSS tile signals, channelizes it in 200 kHz bands (called "subbands"), and computes beamforming within each subband. The beamformed signal of 244 subbands is sent to the LOFAR central correlator. The latter further channelizes (down to 0.76 kHz resolution) the signals of all subbands from all stations, and computes auto-/cross-correlations and/or incoherent or coherent (adequately time-shifted) summation in order to produced polarized images and/or TAB data (cf. `http://www.astron.nl/radio-observatory/astronomers/technical-information/lofar-signal-path/lofar-signal-path/`).

Table 1. Characteristics of *the LSS* compared to those of large LF radio instruments (capable of observing below 100 MHz), existing or in project. *(a) at 20 MHz. (b) at 30 MHz. (c) at 150 MHz.*

Name	Antennas	Eff. area	Freq. range	Ang. Res.	N beams	Polar.
NDA	144 circ. dipoles	4000 m^2 $^{(a)}$	10-110 MHz	11° $^{(a)}$	1 beam	4 Stokes
UTR-2	2040 dipoles	143000 m^2	8-32 MHz	0.5°	5 beams	1 lin. polar.
VLA	27 dish.× 25 m	∼2000 m^2	73-74.5 MHz	0.5'	1 beam	4 Stokes
LWA	256 X dipoles	8000 m^2 $^{(a)}$	10-88 MHz	9° $^{(a)}$	4 b.×20 MHz	4 Stokes
MWA	2048 X dipoles	∼2000 m^2 $^{(c)}$	80-300 MHz	3' $^{(c)}$	1 b.×30 MHz	4 Stokes
LOFAR-LBA	2688 X dipoles	72000 m^2 $^{(b)}$	30-80 MHz	2" $^{(b)}$	8+b.×4 MHz	4 Stokes
LSS standalone	*1824 X dipoles*	*62000 m*^{2} $^{(b)}$	*15-80 MHz*	*1.5°* $^{(b)}$	*4 b.×65 MHz*	*4 Stokes*
LSS+LOFAR	*4512 X dipoles*	*134000 m*^{2} $^{(b)}$	*30-80 MHz*	*2"* $^{(b)}$	*8+b. ×4 MHz*	*4 Stokes*
SKA	>3000 dish.+AA	1000000 m^2	0.07-10 GHz	<0.1"	many beams	4 Stokes

A post-LOFAR-backend dedicated receiver would ingest locally the station products (as does ARTEMIS) and channelize, auto-/cross-correlate, and integrate them. A fully independent backend would perform the tasks of both the LOFAR backend and the central correlator, but in an optimized integrated way. A large computing power is required, but a preliminary design study suggests that this is within the scope of new generation FPGAs. Additional "intelligent" processing like RFI mitigation or parametric dedispersion could be included. Transient Buffer Board data will also be processed in all cases.

A dedicated receiver is important not only because it allows local, flexible processing, but primarily because it will greatly increase the duty-cycle of the LSS standalone use beyond the "guaranteed" 10% fraction of the time, albeit with some pointing constraints. With a post-LOFAR-backend receiver, usable in parallel to all LSS observations (standalone or in correlation with LOFAR LBA), the standalone analysis of LSS data will be possible 100% of the time during which the LSS tiles are connected to the FR606 backend, but the target will necessarily be within the 0.5°−3° LSS beam fixed by the current LOFAR observation program. Conversely, with a fully independent backend that would process LSS data in parallel with the standard station backend, standalone mode becomes possible 100% of the time, whatever array (LBA, HBA or LSS) is connected to the LOFAR backend. The only pointing constraint of this standalone LSS mode is that the target must be located within the 10°−50° analog LF tile beam.

6 Conclusion

The LSS characteristics are compared to those of other existing international instruments in Table 1. In the european context, several instrumental projects are developed by LOFAR participants, such as ARTEMIS (from Oxford Univ. − see above) or AARTFAAC (from Univ. Amsterdam − it aims at cross-correlating the 288 LBA and HBA signals from the 6 central LOFAR stations to perform permanent all-sky monitoring (Prasad 2012)). LSS is a LOFAR extension and a standalone instrument with emphasis on very high instantaneous sensitivity. We foresee it as an "Arecibo in Nançay". It is also a SKA precursor for the French community, both scientific (see above objectives) and technical (for SKA-low).

The team involved in the LSS design and prototyping gathers about 25 researchers and 15 engineers and technicians from 8 french laboratories (Nançay (USN), LESIA, GEPI, & LERMA of the Observatoire de Paris, LPC2E & Prisme in Orléans, Subatech in Nantes, and IRAP in Toulouse), and a strong technical and scientific support from the Kharkov Institute of Radio Astronomy (Ukraine) and from the Graz Space Research Institute (Austria). Potential users of the LSS also belong to LUTh, CEA (SAp, DASE & AIM), OCA, IAS, IAP, Univ. Lyon, ENS/LRA, E. Polytechnique, APC, and IN2P3. Foreign support has been expressed from ASTRON (the main LOFAR institute), Radbout Univ. Nijmegen, Oxford Univ., and several national LOFAR consortia (UK, Germany, Sweden, Ireland, and Latvia).

The LSS design study and prototyping was performed in the frame of an ANR contract ending in Feb. 2013. The last (ongoing) phase consists of extensive tests and characterization on the sky. The project was fully costed and represents in total 4-5 times the cost of a standard LOFAR station (incl. the dedicated independent standalone backend). Funding for construction is being looked for. The calendar of the construction phase will extend over 30 months. It will involve major participation of industrial subcontractors (many of them being situated in "Région Centre"), and at the same time be a major project of the Nançay radio observatory. In construction and exploitation phases, the project code name will change from LSS to NenuFAR[i] (New extension in Nançay upgrading LOFAR). The outcome of the LSS design study will be made freely available to all European participants in LOFAR and more generally to all interested parties. If several LSS are built in Europe, they will collectively represent a further step in LF radioastronomy, beyond LOFAR.

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[i]Le projet dans les temps.