LOFAR Super Station : Science Case

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1. Description of the LSS

1.1 What is the LSS ?

The LOFAR super station (LSS) project presently under study in Nançay consists of adding to the standard Nançay LOFAR station (FR606) 96 LF tiles that will be connected to the 96 dual-polarization RCUs of the LOFAR backend via the LBL input (10-90 MHz). The LSS will be included within a disk of ~300m in diameter (~4 LOFAR station diameters). Each LF tile will be a phase array of ~19 LBA-like antennas, the antennas being analog phased within a tile. The basic idea is to add to FR606 a LOFAR-compatible mode with increased sensitivity (in an instantaneously (Field of View) FoV reduced by a factor $\sim 4^2$ relative to that of a LOFAR station), in which the signals from the LF tiles are beamformed and sent to Blue Gene for correlation with the other LOFAR stations, while remaining fully compatible with its use as a standard LOFAR station. The LSS will also be a large standalone instrument. Its frequency range, from ≤20 MHz to ≥80 MHz, includes the LOFAR LBA range and extends it, especially toward low frequencies. It will have full polarization measurement capabilities and the same multi-beam capabilities as a LOFAR station (except for the instantaneous FoV limitation).

1.2 Calibratability

The ionospheric propagation effects will be homogeneous above the whole LSS, leading to source/psf jitter but no distorsion. Using adequately distributed calibrators, it will be possible to follow the source motion during short exposures, owing to the sensitivity of the LF tiles, and then calibrate in the image plane, as done for the MWA (see e.g. http://www.mwatelescope.org/instrument/rt_software.html). As a result, LSS calibration may be easier that for a standard international LOFAR station.

1.3 LSS capabilities

LSS will enhance the capabilities of LOFAR via :

1) added collecting area ;
2) strongly increasing the weight of the baselines it forms within the other LOFAR stations (~2× more long baselines with high sensitivity - this is to be understood as follows : long baselines formed by e.g. an international station and each of the 6 superterp stations are closely packed in the (u,v) plane and actually equivalent to one baseline with higher (×√6) S/N ratio ; the LSS will provide ~40 such baselines (with $\sim(10\text{-}20)^{1/2}$ higher S/N ratio) ;
3) acting as a second virtual core, correlated with other remote stations when LOFAR uses only its core stations, leading to up to 30% or more increase of observing time, provided that Blue Gene – *or some alternative facility (Julich ? other ?)* – has the capability to perform the required correlations in parallel. Also, international stations alone, having only long baselines, would have very few strong sources to calibrate on, making difficult the ionospheric calibration; improved long baselines sensitivity will help;
4) acting as a second, independent, virtual core, for confirming by (t,f) coincidence the occurrence of weak radio bursts and discriminate with RFI (likely to be uncorrelated at the 2 cores) ;
5) providing very short baselines (≤20-25 m) that are not available even within the Superterp (where minimum baselines are 60-70m) and can be combined to LOFAR's (u,v) coverage to facilitate the observation of diffuse structures (10's of ° extent) ;
6) extending the LF range down to 15 or 20 MHz with good sensitivity ;

7) excellent stand-alone characteristics in various fields **(see below)**, including the possibility to calibrate locally for the ionosphere, using the LSS a a standalone interferometer.

Point 2) may require a quiet ionosphere, but also provides access to weaker calibrators for correcting its effects, while 4) will be applicable even or preferably when the ionosphere is in a pertured state.

1.4 LSS as a standalone instrument

As a standalone instrument, LSS will have a maximum angular resolution of the order of 1° (frequency dependent). The classical confusion limit will be about 50 mJy for the LSS (for the Poisson noise of background sources), reached in ~100 sec, Confusion limits due to self-cal and side lobes must also be taken into account. These limits do not apply for transient sources (especially known ones).
The LSS will have a densely filled area ~2/3 that of LOFAR (even a larger ratio at low frequencies), 5-8 times that of LWA1 (over the same frequency range – cf. http://www.phys.unm.edu/~lwa/specs.html), and ≥40% that of UTR2/Kharkov (which covers the range 10-30 MHz without polarization measurement capability).
The LSS intantaneous FoV will be ~4^2 smaller that of a LOFAR station (thus ~4-5$°^2$ at 30 MHz, approximately twice that of UTR2), but multiple beams can be synthezised within the >100x larger FoV of each LF tile. Coherent Tied Array Beam (TAB) forming, with full polarization capability, will be especially easy and powerful with the LSS (common clock, ionosphere, and RFI), possibly as/more powerful than LOFAR.
Imaging at 1° resolution will also provide a powerful capability to discriminate RFI, which is absent at all existing non-imaging LF arrays.
The LSS may have access to a substantial fraction of observation time in standalone mode (minimum 10%, possibly more subject to negociation), allowing it to pursue specific science programs complementary to LOFAR.
A long-term evolution of the LSS includes signal digitization with >12 bits (present situation) which, combined with high quality antenna preamplifiers may increase further the sensitivity, flexibility, and immunity to RFI & saturation at LF.

Basic technical information can be found

- on the LSS at :
  http://www.obs-nancay.fr/lofar/images/telechargement/LOFARinaugFR606-Girard.pdf
  http://www.obs-nancay.fr/lofar/images/telechargement/Girard-JS2011URSI.pdf
  and an early oncept description at
  http://www.lesia.obspm.fr/perso/philippe-zarka/LSS/Super-station-LOFAR_V5.pdf
- on LOFAR at :
  http://www.astron.nl/radio-observatory/astronomers/technical-information/lofar-technical-information

A first science case for the LSS is presented below, sorted by thematic objective. It appears to be very complementary to LOFAR's science case, and an ideal bridge between LOFAR and UTR2 capabilities, especially in the ~20-40 MHz range with a high interest for LF surveys and high sensitivity studies.

2. Science Case

2.1 Key Scientific Highlights

• *Exoplanets & Binary/Eruptive stars : existence and characteristics of radio emission, Star-Planet interactions, comparative (exo-)magnetospheric physics = new subject to explore*
→ LSS + LOFAR simultaneously, + UTR-2 ; targeted observations

• *Pulsars, RRATs : detection especially at LF, physics of the senvironment of compact object, nature of RRATs, planets around pulsars ?, structure of ISM via propagation effects effects (cf. next point)*
→ LSS standalone (in addition to LOFAR)

• *Structure of Galaxy/ISM : extended objects, B field, turbulence*
→ LSS short baselines + LOFAR

• *Transients : serendipitous / blind / exhaustive exploration of impulsional Universe (ideal in LF radio due to absence of photon noise) ; time & frequency scales of pulses, nature of emitters*
→ LSS standalone + dedicated backend

• *Cosmology : signature of pre-EoR dark ages, history of Universe formation*
→ LSS standalone

• *Transient Luminous Events in Earth atmosphere : radio exploration of counterparts of sprites and other TLEs ; origin, distribution / dynamics over center France, time & frequency scales, physical mechanisms*
→ LSS standalone

• *Very high resolution deep images on restricted fields, taking advantage of increased sensitivity (requires excellent calibration)*
→ LSS + LOFAR

+ LSS as SKA precursor (calibration & imaging techniques, data processing, etc.)

2.2 Other scientific studies organized in major scientific domains

1) Solar system (including Earth environment : atmospheric/ionospheric/magnetospheric physics, Solar system planets, comparison to exoplanets, interplanetary medium structure)
→ Earth's ionosphere structure and variability, Solar and space physics, Jupiter as a radio source, compared to exoplanetary radio emissions, planetary lightning physics (comparative planetology, synergy with space missions)

2) Galactic/stellar/ISM physics (including stellar and exoplanetary radio emissions, star-planet plasma interactions, pulsars, RRATs, microquasars etc., large-scale structure of Milky Way, ISM, turbulence, magnetic field)

3) Extragalactic/Cosmology (including jets, relics, B field, pre-EoR dark ages signal)

4) Transients / Impulsional Universe (including GRB counterparts, Crs, neutrinos impacting the Moon, serendipity)

2.2.1 Atmospheric physics

• Terrestrial lightning & sprites : frequent events over central France ; LSS will address their frequency of occurrence, fine structure (down to the full waveform), and energetics ; observation can be triggered internally or by a external VLF antenna (e.g. in LPC2E/Orléans) ; joint studies will be conducted with TARANIS (small scapecraft dedicated to Transient luminous events & Gamma ray flashes - http://lpce.cnrs-orleans.fr/www_experim/experim_espace_taranis_fr.php)

• Planetary lightning : LSS sensitivity permits to study Saturn's lightning, and search for lightning at Uranus, Venus… as well as discharges in Martian dust storms ; no imaging is possible nor required, beyond the mere identification of the planetary source and discrimination from RFI, which is doable with ~1° resolution ; LSS obsservations will be supported by Cassini in orbit around Saturn until 2017, and help prepare a Uranus pathfinder mission.

• Cosmic ray shower studies : tbd.

⇒ these objectives would take advantage of an extended TBB (5+ sec ?)

2.2.2 Ionospheric physics

• Ionospheric scintillation of broadband radiosources (such as Jupiter, the Sun and the « A » team – Cas-A, Cyg-A, Vir-A, Tau-A) will allow to map the local ionospheric structure, including density waves (TIDs), man-made ionospheric disturbances ; combined with LOFAR, 3D information may be retrieved via tomography.

• Ionospheric opacity (absorption of radio waves) will be monitored to identify time variabilities relative to the reference quiet-day curve of sky background ; these variabilities at various timescales can be related to magnetospheric space weather, to bursts of X-ray radiation from solar flares or to Gamma ray bursts ; an alternative/complementary possibility is to monitor the signal of a radio emitter (of known frequency, intensity and polarization) embarked on a spacecraft orbiting above the ionosphere.

2.2.3 Planets / Exoplanets

• Jupiter : dynamic spectral studies, fine structures, polarization of the decameter emission (≤40 MHz), systematic survey, Faraday probing of Io torus electron densities ; radio observations can be correlated with UV & IR observations of aurorae (with HST & ground-based IR facilities) ; LSS observations will provide context for JUNO (≥2016, NASA) in-situ observations in the range 0-40 MHz.

⇒ the possibility to dedicate N subbands to the observation of Jupiter at LF, following the example of the Nançay Decameter Array, should be adressed.

• Jupiter : monitoring of synchrotron emission from radiation belts at LF (lower energy belt electrons acceleration, transport and scattering), rotational modulation, correlation with solar wind fluctuations ; possible joint studies with decimeter radiotelescopes (such as the Nançay RT) ; detailed comparison with simulation studies.

• *Exoplanets : search for radio emission from extrasolar planets via LF high-sensitivity long surveys of candidate exoplanets (around magnetized stars, or highly luminous UV/X stars, or with suspected plasma Star-Planet Interaction) aiming at large burst detection ; dynamic spectrumof detected objects if any ; searches using the LSS may have a large duty cycle, allowing for targeted and blind searches, and hence maximum orbital phase coverage ; 4 Stokes (full polarization) will be used ; simultaneity (coincidences) with LOFAR's core will considerably enhance weak detection capability ; comparison to theory/simulation results will* *allow for comparative physics of exo-magnetospheres, or star-planet plasma interactions, and determination of exoplanetary rotation, magnetic field magnitude and tilt, orbit inclination…*

2.2.4 Sun / Stars

• Solar type II and type III bursts : dynamic spectrum and 1° localization/imaging on the sky ; systematic survey, fine structures (at high and low intensities), polarization, identification of fundamental vs harmonic emission, providing test/constraints for generation models and coronal heating mechanisms, measurements of electron density fluctuations in the corona, jointly with space observations and simulations ; LSS observations will support/provide context for STEREO, Solar Orbiter, and Solar Probe+ observations ; LSS will be the only instrument capable of covering the ≤20 to ≥80 MHz band quasi-instantaneously with high sensitivity.

⇒ the possibility to dedicated N subbands to the observation of the Sun at LF, in tight coordination with the Nançay RadioHeliograph at frequencies >150 MHz, should be adressed.

• Interplanetary medium 2D cartography : via LF radio propagation / scintillations effects (on Solar emission in particular) ; long time-delays in correlations will be provided by joint use of LSS with LOFAR, with high sensitivity.

• Space physics studies : CMEs, magnetosphere, ionosphere… via active RADAR probing, with LSS as reception antenna (emission can be produced by LOIS or other RADAR facilities) ; tentative detection of photon angular momentum by adequate phasing of LSS antennas ? (tbd).

• Interstellar medium 2D cartography : via LF radio propagation / scintillations on broadband radio sources (intensity fluctuations, temporal broadening).

• Magnetic binary or flaring stars, brown dwarfs : LF high-sensitivity long surveys of candidate stars aiming at large burst detection ; dynamic spectrum of detected objects (including 4 Stokes polarimetry) ; the same methodology as for exoplanet searches will be applied ; radio observations can be correlated with / guided by Espadons/Narval optical Zeeman-Doppler spectropolarimetry (IR in the future with Spirou).

2.2.5 Pulsars and InterStellar Medium

• Pulsars, RRATs (Rotating RAdio Transients), magnetars : the LSS will have a very high Figure of Merit for LF transient surveys, especially in the range 20-40 MHz (LSS alone could find as many LF new pulsars as the whole LOFAR) ; it will allow to conduct blind survey statistics, pulse profile variations with observing frequency (and thus altitude in the pulsar magnetosphere), spectrum, polarization, timing at LF ; this will allows, jointly with theoreticians, to study the distant pulsar magnetosphere, emission mechanisms, acceleration, and seach for interacting exoplanets.

• Giant / anomalously intense pulses : these pulses >10-1000 times more intense than usual pulsar pulses have been observed for 11 pulsars (long period to millisecond), first and mostly for the Crab pulsar ; they can be as short as a few nanosec, and their origin is not understood ; LSS will efficiently cover a broad spectral range, allowing to measure spectral indices, pulse intensity statistics, and full polarization – and thus to test/constrain theoretical models -, and discovering new sources of giant pulses ; giant pulses ca provide constraints for Interstellar Medium propagation studies ; their detection with LSS could rely on systematic surveys, external triggering, or real-time detection capabilities.

• Strong interstellar propagation effects : propagation effects vary in f^{-2} (dispersion) to f^{-4} (temporal broadening and scattering) and can thus be studied much more accurately at LF ;

LSS will determine accurate DM (dispersion measures), RM (rotation measures) of nearby pulsars and thus put new consraints on ISM density and magnetic field structure ; variations from the f^{4} variation of temporal broadening can reveal departures from cold plasma dispersion or a cutoff in Kolmogorov turbulence scale law ; deconvolution from propagation effects is essential for accurate pulsar timing (and thus stochastic gravitational waves background studies) at LF ; high dynamic range pulsar dynamic spectra will allow to calculate the so-called secondary spectra and perform « ISM holography ».

⇒ detailed information ca be found in the « Pulsars » science case for the LSS (Griessmeier et al.)
⇒ parametric dedispersion capability should be implemented in the LSS backend, e.g. using the ARTEMIS/Oxford system.

2.2.6 Galaxy / Extragalactic

• Deep all-sky survey between ≤20 and ≥80 MHz : as explained above, in standalone mode, the LSS will give access to an angular resolution range from ≤1° to 10's of °, allowing for surveys in the range ~20-80 MHz comparable to those performed by Kharkov/UTR-2 in the range 10-30 MHz. The lower resolution, compared to LOFAR's, will increase the confusion limitation. The reduced FoV (~4^2 x smaller than for a LOFAR station) should reduce the negative impact of bright sources outside the beam. Standalone LSS surveys will be performed both for broadband and spectral line emission, allowing to study the structure of sources versus frequency, the spectral indices of all sources detected at HF, diffuse emission maps (for lines + continuum), the large scale structure of Milky Way's ionized gas (warps), absorption by galactic HII regions (disk-halo physics).

• High resolution (VLBI) deep images in limited FoV (~1° ?) Adding the LSS to the existing international LOFAR network will increase (i) the total sensitivity of the whole array and (ii) the sensitivity in individual baselines, which will help for the long-baseline calibration. Because most sources are resolved on international baselines, we will generally have SNR limitations so that any very sensitive station can make a significant difference. LSS may therefforre be an important key to wide field imaging at low frequency with arcsec resolution.

• Imagerie sur bases courtes et polarisation, B galactique → à mettre dans ISM ?
The LSS provides a valuable instrument to measure the short (u,v) spacings between the station-to-station baselines of normal LOFAR and the antenna-to-antenna baselines of a standard LOFAR station. These baselines are extremely poorly sampled in the current LOFAR low band hardware while they are crucial for the imaging of large-scale structures in the sky --- specifically for the study of the Milky Way and large structures within the Milky Way. While specifically true for total intensity imaging, polarization imaging may also be possible if the absolute ionospheric Faraday rotation can be calibrated.

• Radio relics in nearby clusters (Virgo, Coma…) ; low-resolution maps of nearby galaxies (M31, M33 and other Local group galaxies) ; extended disks of ionized gas may be related to extended UV disks, to synchrotron emission from past star formation.

• Magnetic fields from polarization in the galactic and extragalactic sources : high angular resolution is crucial for studying polarization at LF avoiding beam depolarization ; when used in conjunction with LOFAR, the LSS will provide high sensitivity long baselines allowing for a better polarization calibration at high angular resolution, and then for more accurate magnetic field measurements (though Faraday RM observations).

• Radio recombination lines (RRLs) are excellent probes for studying characteristics of the Warm Ionized interstellar Medium since they suffer little attenuation, unlike optical and higher-energy radiation, allowing to study the whole galactic plane, including the most distant parts of the spiral-arm structures. At the lowest frequencies, 10-90MHz, RRLs (lines from Carbon, Nitrogen and Oxygen have also been observed recently) will be in absorption, but we may detect a few emission lines. RRLs will be vital to study the physics of the disk-halo connection, the large-scale structure of the ionized gas in the Milky Way, and photo-dissociation regions.

• Monitoring of the radio flux of extragalactic and galactic sources : extragalactic sources are generally not known to be variable at LF (this is attributed to synchrotron self-absorption), except for SNRs decay ; strong sources used as calibrators will be monitored (relative to each other) for detecting possible variations ; besides revealing previously undetected variations, this will provide a better knowledge of primary calibrators and of their stability, that will in turn improve the calibration of all LSS observations. Galactic microquasars may exhibit shorter term variations, that will be monitored to track activity variations and compare them to snapshot high resolution images.

2.2.7 Cosmology

One of the key science project for LOFAR is to detect the HI 21 cm at the epoch of reionisation (z=6-11), measure the spacial fluctuations to constrain the state and dynamics of the gas when the first objects reionized the Universe. Models predict that further away, during the Late Dark Ages at z~20 (HI at ~70 MHz), the total sky temperature drops down by Tb=100 mK and can be measured in a matter of hours. The LSS (even more so than the MPA LOFAR station) will be perfect for such a measurement because it combines both the cross-correlations between LBA dipoles and the auto-correlations, but it requires dynamical range on the level of level of $\sim 10^{-(5-6)}$.

2.2.8 Transients / Serendipity

LSS is well adapted to transient studies, especially the detection of weak transients not accessible to single LOFAR stations. It will also be as or more powerful than LOFAR for Tied Array Beam observations due to the simplicity of its TAB mode (single clock, common ionposphere). Parametric dedispersion capability should be implemented in the LSS backend in order to detect isolated (non-periodic) dispersed pulses, both incoherently (e.g. using the ARTEMIS/Oxford system), and coherently if possible (using extended TBBs). LSS should be a significant addition/improvement of the ARTEMIS program. Such pulses are real astrophysical counterparts of the "Lorimer" burst, that may be produced by exotic sources such as the collapse or merging of compact objects, black holes, etc.
Radioastronomy of short astrophysical pulses is largely unexplored, so that there is room for serendipitous discoveries, especially in the LF (~20-40 MHz) range where LSS characteristics will surpass all existing instruments.

• Radio counterparts of gamma ray bursts (GRBs) : targeted search for broadband/narrowband emission trigered by GRB detection (automatic remote triggering response capability is in development at LWA), determination of DM, detection statistics. The powerful capabilities of LSS in TAB mode will make it well suited to such observations.

• Wide-field imaging + search for transients (at ≤sec timescale) : 100% duty-cycle in piggyback with all LSS observations ; complementary to superterp all-sky AARDVARK project.

• LF emission from neutrinos impacting the Moon : same as homonymous LOFAR project.

• Reflections of LF radio waves from ionized meteor trails : can provide trail distribution, physical characteristics…

2.3 Methods

Calibration of the new generation of interferometers represent a science on its own, and the development of innovative algorithms is required. LSS being fairly compact, many of the calibration problems can be adressed in the image plane. Because LSS is very close to the ideal SKA low frequency station, many of the station-level calibration issues can be adressed (the idea here is that ionosphere will produce time/frequency dependent pointing errors).

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