NenuFAR Phase 1 : Concept, Technical Characteristics & Science Case

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1. NenuFAR & NenuFAR-1

Radioastronomy experiences a period of rapid change, with many new radiotelescopes under study, construction, commissioning or operation (LOFAR, LWA, MWA, MeerKAT, ASKAP, SKA[2]). They bring in an increase in sensitivity and resolution by orders of magnitude, over wide fields of view (FoV), thanks to the development of new technologies in the fields of telecommunication and massive parallel computation. This instrumental revolution will have a major impact in 21st century astrophysics and in fundamental physics, much beyond what radioastronomy can usually do.

The project NenuFAR – the LOFAR super station in Nançay – is a major extension of the LOFAR array, that will dramatically increase its total sensitivity and resolution and allowing astronomers to address such fundamental scientific questions as : (i) What is the nature of the processes that couple the stellar winds to the planetary systems? (this applies to our solar system as well as to exoplanets) (ii) What is the spatial structure and dynamics of the interstellar warm plasma in the Milky way? (iii) What are the populations and physical processes underlying the unveiled Impulsional Universe? (iv) What were the physical processes controlling the evolution of the baryonic matter at very high redshift ($z>10$) ? And (v) How did the Universe take its local shape over cosmic time scales ?

The concept of a LOFAR super station "NenuFAR" is described in [Zarka et al., 2012]. NenuFAR 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). Each tile is an regular hexagonal cluster of 19 crossed-dipole antennas, analogically phased (it is hereafter noted MA_{19} for « 19-antennas mini-array »). The 96 MA_{19} will be included in a disk of 350 to 400 m in diameter (~5 LOFAR station diameters). The frequency range of operation will include the LOFAR-LBA range 30-80 MHz and extend it mostly to lower frequencies (~10-85 MHz). NenuFAR will be both a high-sensitivity LOFAR-compatible « super-LBA station » and a large, sensitive standalone instrument with its dedicated receiver. The possibilities offered by NenuFAR in terms of observation mode are described in [Zarka et al., 2012]. In summary, NenuFAR will be used either as part of the LOFAR network as a super-sensitive LBA station improving LOFAR's global sensitivity and imaging capabilities, or as a standalone instrument with large instantaneous sensitivity (~2x LOFAR's core) rather oriented toward coherent phased-array observations, especially toward low frequencies. A dedicated receiver will allow NenuFAR to be used simultaneously in both modes, within the instantaneous FoV of the MA_{19}.

The science objectives of NenuFAR are also briefly listed in [Zarka et al., 2012]. They include searches and studies of (1) exoplanets and binary or eruptive stars, (2) pulsars and Rotating RAdio Transients (RRATs), (3) the structure of the Galactic Interstellar Medium (ISM), (4) galaxy formation and pre-EoR dark ages cosmological signal, (5) the « impulsional » Universe, (6) Transient Luminous Events (TLE) in the Earth and planetary atmospheres, and (7) Solar system physics.

A design study conducted from 10/2009 to 2/2013 allowed us to define and test all the elements of NenuFAR's design [Girard et al., 2012a ; Girard, 2013]: antenna radiator and preamplifier, MA_{19} topology and phasing, MA_{19} distribution, control/command and dialog with LOFAR. The optimal antenna radiator was found to be similar to the LWA one, but the preamplifier is an original design with improved characteristics. All technical studies and reports are available at https://www.obs-nancay.fr/lss/. The construction of NenuFAR was also fully costed.

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[2] All acronyms and abbreviations are defined at the end of the document.

Obtaining funding for NenuFAR will impose its realization in several phases. The hierarchical design of NenuFAR consisting of many identical elements (antennas, MA_{19}, phasing systems, … – the dedicated receiver itself will have an evolutive architecture, with its number of acquisition/processing boards increasing with the number of MA_{19}). NenuFAR Phase 1 (hereafter simply NenuFAR-1), for which the budget has been secured, will consist in the deployment of 15±1 MA_{19} of 19 dual-polarization LWA-like antennas, with their specifically designed preamplifiers, phasing systems, control/command systems and dedicated receiver. This phase will also include the preparation of infrastructures for the whole project. With 15x19 = 285 dual-polarized antennas, NenuFAR-1 will have capabilities similar to :

- 3 international LOFAR stations or, equivalently, the LOFAR Superterp [van Haarlem et al., 2013];
- 3-4 times the sensitivity of the Nançay decameter array (NDA) [Boischot et al., 1980];
- the LWA1 instrument (256 antennas [Taylor et al., 2012]) but with a slightly improved sensitivity.

The main differences will consist of the hierarchical antenna phasing scheme (digitization of groups of analog-phased-arrays of 19 antennas in NenuFAR-1), the possibilities of operation (standalone only for the LWA1 or NDA, mostly within LOFAR for the Superterp, standalone of with LOFAR for NenuFAR-1), and the expandability of NenuFAR-1 into NenuFAR.

2. Technical characteristics of NenuFAR-1

- Number of antennas : 285, distributed within 15 mini-arrays of 19 antennas each (MA_{19})
    - each MA_{19} is an hexagon physically included in a disk of 25 m diameter
    - the minimum distance between MA_{19} centers is 27.5 m (in order to minimize the overlap of antennas' effective area)
    - NenuFAR-1 will be includes in an ellipse ~110 m x ~ 140 m
- Frequency range : ~10-85 MHz ; this is also the bandwidth per beam
- Frequency and time resolutions : down to δf = 3 kHz and δt = 5 μsec, with the limitation $\delta f \times \delta t \geq 1$. Waveform snapshots capture mode at 5 nsec resolution (TBB).
- Polarizations : 2 linear polarizations measured by each antenna, NW-SE & SW-NE ; 4 Stokes parameters computed from these 2 measurements
- Declination of pointing : -23° to +90° (corresponding to an elevation ≥20°, at the latitude of Nançay 47.38° N)
- Effective area : $\lambda^2/3$ per antenna, ~$95\lambda^2$ for NenuFAR-1, with an upper limit ~10^4 m^2 due to overlapping of antenna's effective areas below 30 MHz
- Field of View :
    - each antenna sees ~2π sr
    - the instantaneous FoV of a phased MA_{19} is 34° – 9° at 20 – 80 MHz
- Number of beams : 2
- Angular resolution / pencil beam size : 7° – 2° per beam at 20 – 80 MHz
- Sensitivity S_{min} : 12 –3 Jy at 20 – 80 MHz (5σ, 1 sec x 10 MHz, polarized signal)
  55 – 200 mJy at 20 – 80 MHz (5σ, 1 h x 10 MHz, polarized signal)
- Confusion noise at zenith[3] : 400 – 10 Jy at 20 – 80 MHz (140 m diameter)

The whole ~10-85 MHz band will be digitized and channelized via polyphase filters of ~200 kHz bandwidth. The output of the polyphase filters will be streams of complex amplitudes at 1/200 kHz = 5 μsec resolution. Acquisition and FFT of these streams at up to 64 channels per 200 kHz band will define the final time and frequency resolutions.

Transient Buffer Boards (TBB) analog to LOFAR's will permit full waveform capture at 5 nsec resolution from all MA_{19} for snapshots of a few seconds. It will also be possible to record the waveform of the beamformed NenuFAR-1 signal for longer durations.

Signals from the 15 MA_{19} of NenuFAR-1 will be either coherently summed to produce a pencil beam at full time-frequency resolution, or cross-correlated to produce visibilities at a lower rate (TBD, ~1 sec). Low rate cross-correlation statistics will be produced systematically, especially for calibration purposes. The NenuFAR-1 backend will be coupled to an ARTEMIS-like post-backend in Nançay [Armour et al., 2011], that ingests high resolution station data and locally computes high-resolution time-frequency

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[3] Theoretical estimate from [Condon, 2005].

planes including parametric dedispersion.

3. Scientific objectives of NenuFAR-1

The scientific objectives of NenuFAR-1 largely overlap those of the whole NenuFAR, but with ~6x lower sensitivity and ~3x lower angular resolution. NenuFAR-1 will allow to address some of them with high relevance, and prepare the optimal study of the others. The main objectives that NenuFAR-1 will address in standalone mode are described below.

3.1 Exoplanets and binary or eruptive stars

Theory strongly suggests that LF radio emissions are produced by Star-Planet plasma Interactions (SPI), although quantitative frequency ranges and intensities are largely uncertain [Zarka, 2007 ; Nichols, 2011]. It has also been shown that radio detection of exoplanets would also permit to measure exoplanet rotation, magnetic field magnitude and tilt, and orbit inclination, in addition to identifying the type of SPI and measuring its characteristics [Hess & Zarka, 2011]. All observations have yielded negative or unconfirmed results up to now [Zarka, 2011 ; Lecavelier et al., 2013], which may be due to intrinsically low intensities and/or relatively rare strong emitters. Furthermore, planetary radio emissions are potentially bursty with a low duty cycle [Zarka, 1998 ; Zarka et al., 2004a]. Less than a few % of presently known exoplanets (http://exoplanet.eu/) have been observed, for no more than a few hours each, thus the parameter space is still largely unexplored.

NenuFAR-1 will have a moderate sensitivity but a broad frequency range (more than a factor 2 lower than LOFAR or UTR-2/Kharkov [Braude et al., 1978]), and full polarization measurement capability. It will be able to conduct high duty-cycle searches of variable/periodic polarized signals from a large fraction of candidate « radio-exoplanets » (including all those with suspected plasma SPI, especially hot Jupiters around magnetized stars, giant planets orbiting highly luminous UV/X stars). Accurate calibration will give access to long integrations. Tracking of target sources will ensure low confusion noise.

The same type of observations will be carried out to study the Solar-like (but more powerful) radio flares of isolated or binary stars (magnetic stars, cool/brown dwarfs, young stellar objects…) [Osten et al., 2005, 2008, 2009]. This domain is still largely unexplored, especially at LF. An extended search with NenuFAR-1 may permit to enlarge the population of known objects, in order to constrain radio emission processes via flux and polarization measurements, and to compare star-star interaction with SPI.

These observations will allow us to study coherent processes, possibly partly common between stars and planets magnetospheres, binary stars and SPI, aiming at comparative (exo-)magnetospheric physics.

3.2 Pulsars and Rotating Radio Transients (RRATs)

NenuFAR-1 will efficiently detect pulsars and permit to study the physics of their environment and the unknown nature of RRATs (similar to pulsars, but with irregular pulsing behaviour [McLaughlin et al., 2006, Keane et al., 2011]). A possible figure of merit (FoM) for pulsar detection/study, inspired by [Smits et al., 2009] can be written as: $N_{beams} \times FoV \times (A_{eff} / T_{sky})^2 \times \Delta f \propto N_{beams} \times A_{eff}^2 / D^2 \times \Delta f$ with D the diameter of the instrument and Δf the instantaneous bandwidth of observation. LOFAR, being a sparse array, has a relatively small FoM, and only its core or its Superterp is useful for surveys. More densely filled, NenuFAR-1 will have (with 2 beams) a FoM ~10x that FR606, equivalent to that of LOFAR's core (with 100 beams) or ~1/4 of that of the Superterp (with 100 beams). The whole NenuFAR will have a considerably higher FoM. NenuFAR-1 has the advantage on UTR-2 of full polarization capability and a large FoV, and the access to low frequencies (10-30 MHz, compared to LOFAR).

The number of potential LF pulsars is difficult to estimate. Today, only 40 of the currently known 2000 pulsars are known below 30 MHz [Zakharenko et al., 2013]. LOFAR is expected to find some 10^3 new pulsars [van Leeuwen et al., 2010], which will increase the number of targets for LF observations. Only UTR-2 is doing a high-time-resolution survey of the sky below 40 MHz range (but without polarization measurement), so that only a fraction of the potentially observable sources may be known. NenuFAR-1 will help exploring systematically this parameter space, preparing the way for NenuFAR. Besides surveys, NenuFAR-1 will also search for radio counterparts of γ-ray sources (e.g. from Fermi observations [Abdo et al., 2013]). While the spectrum of most regular pulsars turns over at frequencies below ~100 MHz, there is a number of pulsars where this is not the case, including some millisecond pulsars [Kuzmin et al., 2001]. Pulsars from this population may thus be easier to find at LF. Although the effective time resolution of a LF survey will be limited by scattering, the study of enough additional sources is expected, that should shed light on the properties of LF radio pulsars, currently not well known.

NenuFar-1 will also contribute to blind surveys for RRATs, the discovery and study of which requires a large duty cycle, especially for rare events (e.g. 1 burst per day, or less). The search for such events in piggy-back mode is planned at several international LOFAR stations (e.g. at Oxford within the ARTEMIS project), but the 10x larger FoM of NenuFAR-1 (that will also be acquired by an ARTEMIS-like system) make it well-suited for this work. It will allow to either cover the sky multiple times or to spend more time on each patch of the sky.

The spectral range of NenuFar-1 is well suited to study the pulsars distant magnetosphere, emission mechanisms, acceleration processes, etc. via pulse profile variations versus observing frequency (and thus altitude in the pulsar magnetosphere), spectrum, polarization, timing at LF [Stappers et al., 2011].

“Giant” pulses are rare, bright events, that have been occasionally observed in 11 pulsars (long period to millisecond), first and mostly in the Crab [Popov et al., 2006]. They are usually defined as pulses 10-1000 times brighter than average, that can be as short as a few nanoseconds, and have only been observed in narrow bands and at LF (e.g. with UTR-2). Their origin is not understood. NenuFAR-1 has the sensitivity to detect giant pulses and a FoV much wider than UTR-2. This should permit to discover new sources of giant pulses (via systematic surveys, external triggering, or real-time detection capabilities) and subsequently measure spectral indices, pulse intensity statistics, and full polarization, in order to test/constrain theoretical models. NenuFAR-1 will also search for exoplanets orbiting pulsars or RRATs [Mottez & Heyvaerts, 2011].

3.3 Structure of the Galactic interstellar medium (ISM)

The warm magnetized plasma of the interstellar medium (ISM) has a large impact on radio wave propagation and polarization state at LF, so that pulsars and ISM can barely be studied independently in this spectral domain [Zakharenko et al., 2013]. The ISM effects vary as f^{-2} (dispersion) to ~f^{-4} (temporal broadening and scattering) and can thus be studied much more accurately at LF. Deconvolution from such propagation effects is essential for accurate pulsar timing (and thus stochastic gravitational waves background studies) at LF [You et al., 2007]. NenuFAR-1 will determine dispersion measures and rotation measures of nearby pulsars, permitting to study the local density and magnetic field structure [Stappers et al., 2011]. Departures from the f^{-4} variation of temporal broadening can reveal effects beyond cold plasma dispersion or a cutoff in the Kolmogorov turbulence scale law of ISM plasma inhomogeneities at large scales. High dynamic range dynamic spectra of strong pulsars will allow us to perform “ISM holography” [Walker et al., 2008].

NenuFAR-1 will be used to build multi-frequency Galactic intensity maps (diffuse synchrotron, free-free emission). Its sensitivity will permit to detect Radio Recombination Lines (RRLs) with a few dB contrast with the background emission [Stepkin et al., 2007 ; Peters et al., 2011 ; Asgekar et al., 2013]. Suffering little attenuation, RRLs are excellent probes for studying characteristics of the warm ionized ISM (a major fraction of the ISM, >25% in mass), in the galactic plane and spiral arms. In the ~10-85 MHz, RRLs (lines from Carbon, Nitrogen and Oxygen have been observed recently) will be in absorption against background sources (such as Cas-A). At the lowest frequencies, NenuFAR-1 may be able to detect RRLs against the bright galactic synchrotron background or in emission. RRLs permit to address the disk-halo connection, the role of HII-regions in supplying metals to the halo, the large-scale structure of the ionized gas in the Milky Way (e.g. warps), its chemical evolution (though C,N,O abundances), and photo-dissociation regions. Detection by NenuFAR-1 will require long integrations (hours to 10s of hours) that are partly doable in piggyback mode, as RRLs are ubiquitous (~5 per MHz of bandwidth at LF).

3.4 Radiosources monitoring and spectra

A-team radiosources (Cas A, Cyg A, Vir A,Tau A) are flux references for LF measurements [Baars et al., 1977]. But they have been long demonstrated to fluctuate (possibly in a frequency-dependent, periodic way) [Baars & Hartsuijker, 1972]. Long-term monitoring of these radiosources with well calibrated measurements may help understanding the origin of these variations and refining reference flux density spectra. This program is also pursued by the LWA1, and synergies may be found.

NenuFAR-1 will also measure discrete radiosource spectra, identifying steep-spectrum sources for further LF studies [Braude et al., 2002].

3.5 Pre-EoR dark ages /cosmic dawn cosmological signal

Detection of HI signal during the Epoch of Reionization (EoR, z=6-11) is one of the principal science drivers of new generation radio telescopes including LOFAR. The spatial and evolutionary characteristics of HI is a promising way to study how galaxies and black holes changed the phase of the early universe and break the degeneracy between various determinations of cosmological parameters. Radio telescopes that are studying the EoR focus on the statistical detection of brightness temperature fluctuations due to HI at redshifts below z~15-20 (the "Late Dark Ages"). These fluctuation are small, of the order of a few mK at 150 MHz at 3' resolution. But models predict background spectral features of ΔT_b=-0.1 K around z=20 (≤70 MHz). This is when the temperature of IGM is below that of the background radiation field and the HI is mostly seen in absorption [Pritchard & Loeb 2008].

Because these spectral features occur over the entire sky at the same redshift, they cannot be detected with an interferometer but rather in total-power spectra using dense arrays and receivers with filling factor close to unity, as is the case for NenuFAR-1. ΔT_b=0.1 K measurement accuracy can in principle be achieved in ~1 hour x 1 MHz integration, but in practice gain pattern variations on the sky and bandpass calibration limit the signal-to-noise these observations can reach [Bowman & Rogers, 2010; see also Harker et al., 2012].

Using the auto- and cross-correlations of array (such as MA_{19}) signals rather than single dipole signals, the gain patterns and sky brightness (incl. correction for the ionospheric response) can be estimated separately with good precision using the A-team and bright sources from the Million Sources Shallow Survey (MSSS), and foreground emission can be subtracted away. Bandpass calibration can rely on strong natural sources (Cas-A, Cyg-A...), noise-loads or an emitter in the field. The target is to reach 10^{-4} to 10^{-6} calibration accuracy. The physical compactness, large filling factor, significant collection area, large internal redundancy (15 ~identical MA_{19} elements) and large number of baselines (15x14/2=105) make NenuFAR-1 (and later even more NenuFAR) a better suited instrument for detecting the EoR/Late Dark Ages signal than LOFAR, single LOFAR stations or the Superterp.

3.6 The « impulsional » Universe

With a sensitivity equivalent to 3 international LOFAR stations or the LOFAR Superterp, NenuFAR-1 is well adapted to the blind study of the largely unknown transient/impulsional radio Universe (at timescales of 10's of nanoseconds to seconds, taking advantage of the absence of photon noise in the LF radio range). Parametric dedispersion capability will be implemented in the NenuFAR-1 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 with several sec transient buffer). This will be a significant improvement of the ARTEMIS program, giving access to weaker transients as compared to an international LOFAR station (due to the factor 3 above and to the extent to LF < 30 MHz).

Expected dispersed pulses may originate from RRATs [cf. Keane et al., 2011], or be real astrophysical counterparts of the "Lorimer" burst [Lorimer et al., 2007]. The latter could be coherent emission produced by exotic sources such as the collapse or merging of binary compact objects (neutron stars or black holes), also producing impulsive gravitational waves. Strong pulsar magnetosphere-like emission has been predicted before the merging, as well as excitation of MHD modes by strong gravitational waves after the merging, finally converted to radio waves : predicted radio fluxes are uncertain but could reach several kJy [Moortgat & Kuijpers, 2004 ; Pshirkov & Postnov, 2010].

NenuFAR-1 will also be among the most efficient phase arrays performing Tied Array Beam (TAB) observations due to the simplicity of its TAB mode (single clock, common ionosphere). This will enable the targeted search or follow-up of broadband/narrowband synchrotron bursts associated to explosive phenomena (magnetar giant flares, Gamma Ray Bursts …) triggered by detections in other energy domains, the detection of LF emission from neutrinos impacting the Moon (complementary to the homonymous LOFAR project[4]), the study of cosmic ray showers (in synergy with the CODALEMA project in Nançay [Dallier et al., 2011]), or the observation of reflections of LF radio waves from ionized meteor trails (see below).

Beyond these foreseeable objectives, radioastronomy of short pulses is largely unexplored, so that there is a broad room for serendipitous discoveries, especially in the LF (~15-40 MHz) range where NenuFAR-1 (with its dedicated, ARTEMIS-like backend) will be among the lead instruments for

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[4] LWA1 also looks for μsec-length ElectroMagnetic Pulses generated by meteoroid impacts on the Moon.

measuring dynamical spectra (and the parameter space to be searched is huge, leaving room for several competing/complementary instruments). Addressed topics will include time and frequency scales of (dispersed) pulses, aiming at the determination of the nature of the emitters. The use of the dedicated backend in parallel/piggyback with all NenuFAR-1 observations will permit this exploration with a duty-cycle close to 100%.

3.7 Transient Luminous Events (TLE) and Gamma-ray flashes in the Earth and planetary atmospheres

In the same modes as above, NenuFAR-1 will enable the radio exploration of counterparts of sprites and other Transient Luminous Events (TLE), frequent over central France, addressing their origin, distribution and dynamics, time and frequency scales, and physical mechanisms.

Sprites have been recently observed to be associated with radio emissions in the frequency range 50-350 kHz [Füllekrug et al., 2010]. These radio emissions may be related to the propagation mechanisms of expanding filaments (streamers) constituting especially powerful sprites [Qin et al., 2012]. Moreover, a newly-recognized runaway breakdown mechanism inside thunderclouds, related to the production of Gamma-ray flashes observed by astrophysical satellite payloads, initiates at ~1/10 of the conventional breakdown electric field threshold and requires a population of energetic seed particles to trigger the non-linear electron avalanche [Dwyer et al., 2012]. The runaway avalanche can result in a population of 10’s of MeV electrons, whose radio signature may extend to tens of MHz, where it is very uncommon to perform waveform recordings as a result of the large data load. NenuFAR-1 with extended TBBs (~5 sec recording from > 250 antennas simultaneously at 5 nsec resolution) will enable such measurements, whose post processing will permit beam steering at an extraordinary high sensitivity level in atmospheric research, looking for the theoretically predicted radio signatures from relativistic electron beams above thunderclouds. Triggering may be internal or provided by an external VLF antenna or optical observations. Also, it is well known that intense positive lightning discharges are a necessary but not sufficient ingredient to produce sprites. The missing ingredient could be sporadic charged aerosol layers in the stratosphere, produced by solar UV and cosmic rays. Correlation of NenuFAR-1 and optical observations may help to determine the role of these aerosols.

Looking at solar system planets, NenuFAR-1 alone (in TAB mode) or combined with LOFAR (for high resolution imaging) will provide the sensitivity permitting to study lightning from Saturn (addressing questions such as electrification processes compared to Earth's, atmospheric dynamics and composition, geographical and seasonal variations). It will also attempt to detect Uranus’ lightning, contribute to solve the controversy on lightning existence at Venus, and search for electrical discharges in Martian dust storms [Zarka et al., 2004b]. However, the latter objectives will be fully addressed only with the whole NenuFAR.

3.8 Solar system physics

The Sun: NenuFAR-1 will regularly record dynamic spectra of Solar bursts in the ~10-85 MHz range, corresponding to plasma frequencies from the surface of the Sun to 1.5 – 2 $R_\odot$ altitude. It will focus on the study of the fine time-frequency structures occasionally detected in the coronal emission. The latter features are weak and occur irregularly, and require an instrument more sensitive than the NDA. Their drift in the time-frequency plane permits to deduce the speed of the electrons beams that emit these fine structures. Nonrelativistic electron speeds have been found in early measurement, for which a theoretical model has been proposed, based on localized heating events in the solar corona [Briand et al., 2007, 2008]. Being the only instrument capable of covering the ~10-85 MHz band quasi-instantaneously with good sensitivity, with a duty cycle likely to be higher than LOFAR’s, NenuFAR-1 will permit to study the occurrence of these weak emissions, in relationship with the Solar cycle and activity, and to constrain the heating processes over a large altitude range. It will also help to answer the question of fundamental or harmonic plasma radio emission. High time resolution (~1 msec) may reveal density fluctuations in the corona [Mc Connell, 1982].

Jupiter: Dynamic spectral survey of the decameter emission (≤40 MHz) with NenuFAR-1 will provide context for in-situ spatial exploration (e.g. by JUNO ≥ 2016), and the basis for the study of the variability and dynamics of the Jovian magnetosphere and Io plasma torus [Hess et al., 2010, 2012]. Its full polarization capabilities will permit Faraday sounding of the Jovian plasmas [Zarka, 2004]. Waveform capture will enable to explore the emerging topic of radio emission fine structures, giving clues on the microscopic physics at work [Ryabov et al., 2007, 2013].

Measuring the unresolved synchrotron flux density (and polarization) from the Jovian radiation belts between 40 and 85 MHz, will provide new information on its spectral shape and variability, bringing information on the lower energy belt electrons acceleration, transport and scattering, or the role of solar wind fluctuations [de Pater, 2004; Girard et al., 2012b].

Earth's Ionosphere & Space Physics: Scintillation and absorption/opacity studies of bright broadband radiosources (A-team) will allow to derive information about the local ionospheric structure, including density waves (TIDs), and man-made ionospheric disturbances, as well as on the solar wind structure, subject to space weather (enhancement of magnetospheric precipitations, bursts of X-ray radiation from solar flares, Gamma ray bursts …). NenuFAR-1 could also be the receiving station of active RADAR experiments aimed at probing the dynamics of Coronal mass ejections (CMEs) and magnetospheric or ionospheric plasmas.

Meteor trails: Using passive illumination of the atmosphere by VHF emitters (TV/radio stations, Radars), NenuFAR-1 will monitor reflexions due to ionized meteor trails. Their interest lies both in the scattering phenomenon itself and in the informations it allows to derive on the incident meteoroid (rate, velocity, …). The velocity information will be especially valuable in complement to optical detections (e.g. from the French network FRIPON - http://ceres.geol.u-psud.fr/fripon/) aimed at locating meteorites on the ground and their origin in the Solar System. LWA1 also looks for μsec-length ElectroMagnetic Pulses generated by meteoroid impacts on the Moon (http://www.phys.unm.edu/~lwa/obssched.html).

4. NenuFAR-1 combined with LOFAR

NenuFAR-1 is not by itself a powerful imaging instrument. But MA_{19} signals will also feed the LOFAR FR606 backend via 15 LBL 10-90 MHz dual-polarization inputs. Beamformed signals analog to LOFAR station LBA signals can thus be produced and sent to the central LOFAR processor for correlation with the signals from other LOFAR LBA stations. NenuFAR-1 specificities will thus bring two significant improvements to LOFAR :

(1) Long LOFAR baselines (>1000 km) make possible for the first time high spatial resolution images (with sub-arcsec resolution) in degree-scale FoV. Those including NenuFAR-1 will be $\sqrt{3}$ times more sensitive than with the standard FR606 LBA field. As errors on calibration of the instrumental and ionospheric effects are the main limiting factor for high resolution imaging, adding extra sensitivity to long baselines will help calibration (especially direction-dependent solutions for correcting ionospheric effects). Because most sources are resolved on international baselines, high resolution imaging will generally meet signal-to-noise limitations, so that a more sensitive station such as NenuFAR-1 will represent an advantage, by giving access to more calibrators. Of course, it is with the whole NenuFAR instrument that this advantage will become a real breakthrough in wide field LF imaging at arcsec resolution. The first step, to which NenuFAR-1 will contribute, is to image bright MSSS sources in order to construct high spatial resolution models for wide field calibration.

Then, sensitive high resolution wide-field imaging in the LBA range with LOFAR+NenuFAR-1 (and later with LOFAR+NenuFAR) will permit to study black hole formation and AGN activity at moderate redshifts (z<1), details of star formation in nearby galaxies (resolving star formation clumps up to z=1-2), and conduct extragalactic surveys in dense extragalactic fields already observed by LOFAR (where strong calibrators are available).

High resolution full polarization observations (provided that the absolute ionospheric Faraday rotation is properly calibrated) will be very valuable to image small-scale magnetic fields via rotation measure measurements without depolarization due to spatial integration, and study shocks in the hot intergalactic medium at galactic haloes to cluster scales (where 0.1-1 Mpc shocks have been detected).

Detection of time-correlated scintillation effects between distant LOFAR stations (including NenuFAR-1) will also provide the possibility to perform 3D tomographic reconstruction of the ionospheric structure.

These observations can be performed with NenuFAR-1 and LOFAR international stations only, when the Dutch LOFAR is busy and not available,

(2) Correlation of signals from the MA_{19} within NenuFAR-1 will provide 15x14/2=105 baselines 2 to 3 times shorter than a LOFAR station diameter − the shortest baseline presently available −, but far more sensitive than the antenna-to-antenna baselines within a standard LOFAR station. These measurements

at short (u,v) spacings, poorly sampled in the current LOFAR low band hardware, are crucial for the imaging of large-scale structures. Specifically they will permit the study of the warm plasma radio emission from the Milky Way and large structures within it. LOFAR+NenuFAR-1 will thus permit to study the ISM at both large and small scales, in addition to pulsar measurements.

As a conclusion of sections 3 & 4, NenuFAR-1 thus appears as a promising instrument that will allow the associated community to tackle new problems in a large variety of astrophysical research fields.

5. Technical objectives

NenuFAR-1, as a first phase of the development of NenuFAR (that will consist of 96 MA_{19}), will also have several technical objectives, essentially aimed at demonstrating and fine-tuning the operations and developing the tools for the subsequent full-scale NenuFAR project. In particular, NenuFAR-1 will allow us :

- to optimize gain pattern and bandpass calibration techniques (based on strong natural sources, noise-loads and/or an emitter in the field) ;
- to quantitatively document first order mutual coupling effects ;
- to set up the dialog with LOFAR, both for commanding NenuFAR-1 and for beamforming and returning to the central correlate the signal from the 15 MA_{19} ;
- to build, test and operate the first slice of the dedicated receiver, with 15 dual-polarization inputs ;
- to set up the procedures for external and internal triggering ;
- to set up and operate piggyback programs.

6. Comparison and Synergies with existing or planned LF instruments

The table compares a few characteristics of ***NenuFAR*** and **NenuFAR-1** to those of large LF radio instruments (capable of observing below 100 MHz), existing or in project.

Name	Antennas	Eff. area	Freq. range	Ang. Res.	N beams	Polar.
NDA	144 circ. dipoles	2400 m^2 (*)	10-100 MHz	7.5◦ (*)	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 (LWA1)	256 X dipoles	~8000 m^2 (*)	10-88 MHz	6◦ (*)	4 beams ×20 MHz	4 Stokes
OLWA	256 X dipoles (→2000)	~8000 m^2 (*) (→ 65000 m^2)	10(28)-88 MHz	≤5◦ (*) (→ ≤1°)	Full-sky imaging	4 Stokes
NenuFAR-1	**285 X dipoles**	**~9000 m^2 (*)**	**10-85 MHz**	**5° (*)**	**2 beams**	**4 Stokes**
AARTFAAC-LBA	288 X dipoles	~8000 m^2 (*)	30-80 MHz	2° (*)	All-Sky	4 Stokes
LOFAR-LBA	2688 X dipoles	72000 m^2 (*)	30-80 MHz	2” (*)	8+beams ×4 MHz	4 Stokes
NenuFAR standalone	***1824 X dipoles***	***62000 m^2 (*)***	***15-80 MHz***	***1.5◦ (*)***	***4 beams ×65 MHz***	***4 Stokes***
NenuFAR +LOFAR-LBA	***4512 X dipoles***	***134000 m^2 (*)***	***30-80 MHz***	***2” (*)***	***8+beams ×4 MHz***	***4 Stokes***
SKA	>3000 dishes +Apert. Array	~10^6 m^2	0.05 - >10 GHz	<0.1”	many (?) beams	4 Stokes

Table : A few characteristics of ***NenuFAR*** and **NenuFAR-1** compared to those of large LF radio instruments (capable of observing below 100 MHz), existing or in project. (*) at 30 MHz. Adapted from [Zarka et al., 2012].

The LWA1 station has characteristics closest to NenuFAR-1 and, as a consequence, overlapping science objectives [cf. Taylor et al., 2012 ; and http://lwa.unm.edu]. However, the LWA1 is more image oriented, all 256 antennas (+outliers) being digitized and correlated. NenuFAR-1, owing to its hierarchical design in 15 MA_{19}, is more oriented towards coherent phased array beam observations. Its main advantages with respect to LWA1 are (i) its possible use within the LOFAR network, correlated with all other LBA stations, and (ii) its expandability by a factor x6 toward the full-scale NenuFAR instrument. No such extension is planned today for the LWA1.

LOFAR's Superterp, and its related project AARTFAAC [Prasad &Wijnholds, 2012], consisting in an all-sky imager by correlation of the 288 antennas (LBA or HBA) of the Superterp, is also imaging oriented. The larger diameter of the Superterp (300m, i.e. close to that of the full NenuFAR) results in a ~10x smaller FoV. AARTFAAC is computationally intensive, and will be used in parallel with LOFAR. The advantages of NenuFAR-1 are (i) its broader FoV, (ii) its participation to sensitive long baselines, and again (iii) its expandability by a factor x6 toward the full-scale NenuFAR instrument, that will gather a collecting area >1.6x that of LOFAR's core (24 Dutch stations) within a diameter of the order of the Superterp's, ensuring high instantaneous sensitivity.

The NDA, operated since the 1970's in Nançay, is a instrument 3-4x smaller than NenuFAR-1, single beam, built from circular polarization antennas, essentially automated and dedicated to systematic observations of Jupiter and the Sun. It was also involved in the development of the CODALEMA experiment. Its observations feed databases that provide the basis for statistical studies and context for spacecraft observations. Its sensitivity is too low to address most of the NenuFAR-1 objectives listed above (e.g. pulsars), and it is used up 14 hours/day for its systematic observations. Being well-calibrated, it has been and will be used for cross-calibration with NenuFAR-1.

The UTR-2 radio telescope in Kharkov is a much larger instrument (with an effective area larger than LOFAR's) but it is restricted to frequencies ≤32 MHz and has no polarization capability. A smaller URAN array also operated in Ukraine has characteristics similar to NenuFAR-1, including dual-polarization measurements, but it is an analog instrument whose phased output is acquired by a digital receiver, offering less possibilities than NenuFAR-1. Again, the inclusion of NenuFAR-1 in LOFAR and its expandability are decisive advantages.

Finally, LOFAR is a large interferometer offering immense possibilities, dominantly imaging-oriented. Being fully multipurpose, it offers few possibilities of large duty cycle observations as it is already involved in large programs (surveys, EoR, pulsar studies…). It provides a frame for the use of NenuFAR-1 (and later NenuFAR) within it. When completed, NenuFAR will offer better possibilities in terms of instantaneous observations in coherent phased array mode.

NenuFAR-1 thus appears to have specific exploitation areas not redundant with existing instruments. Furthermore, it will offer and benefit from complementarity with the use of these instruments, e.g. complementary longitude coverage with LWA1 and UTR-2, joint use with LOFAR, possibilities of simultaneous observations/detections of weak sources (e.g. with NenuFAR-1 and UTR-2) ensuring a better confidence and a better immunity to local RFI or ionospheric perturbations.

7. Further steps

NenuFAR-1 is an operational instrument, but it is also the first step in the development of the full NenuFAR project, with 96 MA_{19}. Its construction will include the elements and infrastructures required by the full-scale project and that cannot be built efficiently in slices (e.g. power lines, integrated antenna amplifiers, terrain preparation and trenches for the inner parts of NenuFAR…). The expansion of NenuFAR-1 will rely upon these bases and be facilitated in terms of technical work and funding requirements. NenuFAR-1 represents a cost of 1.1±0.1 M€, out of a full cost for NenuFAR below 4.5 M€.

As an instrument per se, NenuFAR-1 will serve broadly (in terms of observation topics) the French LF community (with international collaborations), and prepare it for SKA. It can be considered as a scientific pathfinder for SKA in France, and will likely provide technical lessons for SKA-low.

The full-scale NenuFAR will be a cost-effective large instrument, with unique capabilities, that should expand the above objectives of NenuFAR-1.

Acronyms or Definitions

AARTFAAC	Amsterdam-ASTRON Radio Transients Facility And Analysis Centre
AGN	Active Galactic Nuclei
ARTEMIS	Advanced Radio Transient Event Monitor and Identification System
ASKAP	SKA precursor in Australia
CME	Coronal Mass Ejection
CODALEMA	COsmic ray Detection Array with Logarithmic ElectroMagnetic Antennas
EoR	Epoch of Reionization of the early Universe
FFT	Fast Fourier Transform
FoM	Figure of Merit
FoV	Field of View
FR606	The French LOFAR international station (in Nançay)
FRIPON	French Fireball Recovery and InterPlanetary Observation Network
IGM	InterGalactic Medium
ISM	InterStellar Medium
JUNO	Jupiter polar orbiter (NASA)
LBA	LOFAR Low Band Antennas (30-80 MHz)
LBL	LOFAR Low Band Low antennas (descoped)
LF	Low Frequency
LOFAR	The Low Frequency ARray (NL/Europe)
LSS	LOFAR Super Station (design study of NenuFAR)
LWA	The Long Wavelength Array (USA)
LWA1	The 1st (and presently only) LWA station
MA_{19}	NenuFAR's Mini-Arrays of 19 antennas
MeerKAT	SKA precursor in South Africa
MHD	MagnetoHydroDynamic
MSSS	LOFAR's Million Sources Shallow Survey
MWA	The Murchison Widefield Array (80-300 MHz)
NDA	The Nançay Decameter Array
NenuFAR	New extension in Nançay upgrading LOFAR
NenuFAR-1	Phase 1 of NenuFAR
RCU	LOFAR's Receiver Units
RFI	radio Frequency Interference
RRATs	Rotating RAdio Transients
RRL	Radio Recombination Lines
SKA	The Square Kilometer Array radiotelescope
SPI	Star-Planet Interactions
Superterp	LOFAR's central core consisting at LF of 6 x 48 LBA antennas
TAB	Tied Array Beam mode
TBB	Transient Buffer Boards (LOFAR's waveform capture RAMs)
TID	Travelling Ionospheric Disturbances
TLE	Transient Luminous Events
URAN	Ukrainian Radio Interferometer of NASU (National Academy of Sciences of Ukraine)
UTR-2	Ukrainian T-shape Radiotelescope, mark 2 (in Kharkov, Ukraine)
VLF	Very Low Frequencies (3-30 kHz range)
VHF	Very High Frequencies (30-300 MHz range)

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