Invitation to propose Key Programmes with NenuFAR

https://nenufar.obs-nancay.fr

Proposal submission deadline: March 31, 2019

1. Invitation overview

NenuFAR (New Extension in Nançay Upgrading LOFAR) is a new radioastronomy instrument, operating in the 10 – 85 MHz frequency band, which is in the last stages of its construction at the Station de Radioastronomie in Nançay (France). At completion, the instrument will be composed of a compact core of 96 mini-arrays of 19 antennas each plus 6 distant mini-arrays. Four operating modes will be implemented: standalone beamformer, standalone imager, Transient Buffer mode, and LOFAR super-station.
The scientific goals of NenuFAR go from cosmology (dark ages/cosmic dawn) to the study of exoplanets/stars plasma interactions, as well as pulsars, lightning storms on solar system planets, AGN evolution…
The Comité Scientifique de NenuFAR (NenuFAR Scientific Committee, CSN) welcomes proposals for Key Programmes (KP) using NenuFAR for the Early Science phase of the instrument, from July 2019 to December 2021. During this period, we anticipate that a total of approximately 8000 hours of observations should be available for KPs. The KP proposals may include any of the standalone operating modes of NenuFAR, or a combination of these modes, but should consider the progressive availability of the observing modes (see details below). The LSS mode will be accessed through regular LOFAR calls.
Depending on the outcomes of the present call, a second call for Key Programmes could be issued before the end of 2019.
Note that during the Early Science phase, observations will be executed on a best effort, shared risk basis.
Any member of the French scientific community, and, by invitation, international researchers, may answer this call. The CSN expects proposals submitted by structured teams led by a KP coordinator. However, individuals wishing to join a KP may also apply.
This document gives an overview of the expected technical setup and capabilities of the instrument (section 2) and of its science objectives (section 3). The call and the format expected for proposals are presented in more details in section 4.

2. NenuFAR

2.1. General description (see details on https://nenufar.obs-nancay.fr and the astronomers page https://nenufar.obs-nancay.fr/en/astronomer/)

NenuFAR is both a large compact (~400 m diameter, or 62,000 m^2 effective area at 30 MHz) low frequency (10 - 85 MHz) standalone radio telescope and a giant remote LOFAR[1] station, compatible with the International LOFAR Telescope (ILT). The elementary antennas are designed from the LWA radiator and are erected on a metallic ground plane grid, with a custom-made preamplifier, optimized for this frequency range and yielding a nearly flat instrument response over the entire spectral range. The NenuFAR core is built of 1824 of those dual-

1 http://www.lofar.org/

polarization antenna elements. They are organized in 96 hexagonal sub-arrays of 19 antennas (noted MA for mini-array) that are phased analogically in each polarization through time-delay lines. Each MA forms a steerable beam of aperture (640/f)° with f being the frequency in MHz. The NenuFAR core is dense, ensuring a near perfect Gaussian coverage of the (u, v) plane and thus a regular phased array beam. The core provides an angular resolution of 40°/f(MHz) ~ 1° within the instantaneous MA beam (in each direction θ, φ), with high sensitivity for transient signals (from seconds to hours).
A dedicated FPGA-based receiver (LaNewBa) digitizes the signals from the MAs, forms ~200 kHz spectral bands (up to 768 simultaneously, i.e. 150 MHz total bandwidth), and phases each band in an arbitrary direction within the analog MA beam. NenuFAR is thus a multi-beam spectro-polarimeter with high instantaneous sensitivity.
Six supplementary distant MAs complement the 400m diameter core, providing additional baselines of 2-3 km. Together with multispectral measurements and rotational synthesis, they offer the capability of a low resolution imager (~8 arcmin at 40 MHz). Thanks to these distant MA, the confusion noise is reduced by a factor ~50, close to the thermal noise (~5 mJy for a polarized signal integrated over 1hx10 MHz).
Because of its scale, hierarchical structure, frequency domain, observing modes and output data rate, NenuFAR was declared a pathfinder of the future Square Kilometre Array (SKA[2]).

2.2. Observing modes

Four different observing modes will be eventually offered to the scientific user:

1) a standalone beamformer mode: all the 96 core MAs are phased coherently and the beamlets are collected and analyzed by a dedicated Time-Frequency backend (UnDysPuTeD). This instrumentation provides both real time coherent dedispersion and folding for pulsar observations (within 200 kHz channels, for DM<100, in N = 1 – 4 beams, with B = 37.5 or 75 MHz bandwidth per beam, within the limit $N \times B \leq 150$ MHz) and high-resolution dynamic spectra (4 stokes, up to 150 MHz bandwidth distributed in any number of beams up to 768, resolutions down to 1 ms and 1 kHz or equivalent). This mode will be fully commissioned by mid-2019. Waveform of beamformed signals can also be recorded for short time intervals (a few minutes).

2) a standalone imager mode:
Visibilities can be built from cross-correlation of the 96 core + 6 distant MA signals, over a bandwidth of a few tens of MHz, in the form of standard LOFAR-like Measurement Sets. The NenuFAR Imager will provide a spatial resolution up to 17' – 4' spatial resolution at 20 – 80 MHz. It should be available in 2020 starting with the core and one distant MA, then four distant MA.
In the meantime, imaging observations at ~1° resolution can be obtained using cross-correlation statistics, with limited instantaneous bandwidth (3 MHz). They will be available mid-2019.

3) the Transient Buffer mode will permit to record a few seconds of waveform data per MA (pre-beamforming). This mode should become available in the course of 2019.

4) a LOFAR super station mode (LSS): this mode will give access to high spatial resolution imaging (up to ~0.4") in the LBA frequency range. Moreover, NenuFAR increases the overall ILT sensitivity and improves the balance between short and long baselines in LOFAR. Note

2 https://www.skatelescope.org/news/french-nenufar-telescope-granted-ska-pathfinder-status/

however that this mode can only be used through International LOFAR Telescope coordination and time allocation process. It is thus mentioned here for completeness, but is not concerned by the present call for the formation of Key Science Programs. This mode should be available at the end of 2019.

2.3. Present status of NenuFAR

As of December 2018, NenuFAR consists of 56 operational core MA (out of 96 planned). During the second semester of 2019, this number will reach 72 MA. The beamformer mode has been commissioned since 2018. Phase calibration (coherent beamforming) is now performed and applied in real time to the data. The pulsar observing mode of UnDySPuTeD is able to handle up to 4 beams of 37.5 MHz (or 2 beams of 75 MHz) within each steerable MA beam and delivers dedispersed and folded pulsar archives at a typical resolution of 200 kHz channels and 5 seconds integrations. The spectrometer (time-frequency) mode development is completed and will be commissioned in early 2019. The NenuFAR Imager still requires the deployment on site of 4 distant MAs and related cable paths, and the final design and construction of the correlator. This phase should be completed by end 2019 and allow first tests and commissioning of imaging mode in the second half of 2019, for full operation in early 2020. The LOFAR super station mode has been tested in close collaboration with ASTRON, and first results are due in March 2019.

3. Science with NenuFAR

3.1. Science areas

The **beamformer** mode is expected to be intensively used for pulsar observations and high resolution dynamic spectra acquisition. The main emerging topics are the following:

a) For pulsar science, this should cover the census of the population at low frequency (through targeted and blind surveys), the characterization of the pulsar spectrum and pulse profile evolution between 10 and 85 MHz, and the investigation of the interstellar medium imprint, i.e. dispersion measure (DM) short and long term variations, scattering and scintillation characteristic scales, and the study of Faraday rotation to investigate the local magnetic field structure.

b) In transient search, we expect the two main applications to be the search for fast transients (ms scale) like Fast Radio Bursts and the detection of cosmic or gamma ray air showers. The latter requires the acquisition of each MA independently and the availability of transient buffer boards, before the combination of the signals in post-treatment.

c) Solar activity and stellar flares will be an important target for the dynamic spectrum mode. Concerning the Sun, several characteristic features, revealing local disturbances in the solar corona, are observed between 10 and 85 MHz: signatures of the propagation of interplanetary shocks (type II emission), propagation of energetic electrons accelerated during flares (type III bursts), drifting emission related to magnetic field loops in active regions (type III storms). Various classes of flaring stars emit intense decameter emission, although few observations have been reported so far. Flares occur in young stars like Herbig Ae and T-Tauri stars from their interaction with their proto-planetary disc and low frequency radio emission has been detected in red dwarf (UV Ceti type) stars, as well as in active binary systems of massive stars like Wolf-Rayet or OB-type stars subject to supersonic colliding wind and large mass-loss rate.

d) In the Solar System, NenuFAR will detect Saturn and Uranus lightning, probably some rare intense events from Neptune, and possibly also from Venus and Mars. The decametric magnetospheric emission from Jupiter will also be a major target of the instrument, following on from the long term monitoring performed by the Nançay Decametric Array (NDA). The very high spectral resolution will allow to study the fine spectral features such as impulsive S-burst, narrowband emission, Faraday rotation and modulation lanes. Finally, radio emission counterparts of Terrestrial Gamma ray Flashes or sprites and other transient luminous events associated with lightning and thunderstorms, will be observed by NenuFAR, in correlation with space mission detection by ASIM[3] and TARANIS[4]. Meteors, using passive radar techniques, will also be an interesting target.

e) Exoplanets are another main science topic of NenuFAR, which can use either imager or beamformer mode to identify and characterize their emission properties. The radio emissions looked for are primarily driven by the interaction between planetary magnetospheres and the stellar wind, or the interaction between the planetary ionosphere and its satellites. Radio detection will be information rich, including the characterization of many planetary properties: the magnetic field amplitude and tilt, rotation period, orbital period and inclination, nature and characteristics of the electrodynamic coupling, exo-moons...

The **NenuFAR imager** will allow both multi-frequency long integration imaging and snapshot (0.1-1.0 sec) imaging mode. The scientific topics covered might include:

(a) The detection of the cosmological HI signal from the "dark ages" to the reionization era (EoR) through the "cosmic dawn" (CD). The CD signal can in principle be detected as a spectral dip of a few hundred milliKelvin (i.e. one order of magnitude larger in absolute value than the predicted EoR signal) at ~70-80 MHz in the all-sky spectrum[5]. This measurement is however dramatically dependent on foreground sources and galactic diffuse background. Alternatively, the CD signal can also be detected by its angular fluctuations power spectrum, measured via interferometric imaging at 0.1°-1° resolution (the dominant scale of the predicted fluctuations). This measurement is perfectly accessible for a compact radio imager such as NenuFAR and much less limited by foreground effects.

b) As mentioned above the systematic and sensitive search for yet unconfirmed low frequency radio signatures of exoplanets and star-planet plasma interactions will also benefit from the imager mode, by looking at the flux variation at the position containing the targeted planet.

c) The imager mode may also be used to detect the radio afterglows of high energy collapses generating gravitational waves and Gamma Ray Bursts.

d) With a sensitivity of 50-100 mJy/beam in 8 hours integration, NenuFAR will detect the diffuse low frequency emission from galaxy clusters and giant radio galaxies, as well as bright compact active galactic nuclei (AGN) and their variability. We expect up to ~10^5 galactic and extragalactic sources to be detectable.

e) In low-density regions of the interstellar medium (ISM), free electrons can be captured by ions at very high quantum numbers (n > 100). As the atom cascades into a series of successively

[3] https://www.asim.dk/
[4] https://taranis.cnes.fr/fr
[5] Bowman et al 2018, Nature 555, 7694

lower ionization states, each transition produces a radio recombination line (RRL); RRL generated in this way are typically called "diffuse" RRL. Such emission has already been detected in the NenuFAR frequency range, and its study provides valuable information on the interstellar medium (density, temperature, ionization state). Besides spectral resolution and stability, the primary instrumental factor limiting detection and study of diffuse RRLs is the area filling factor of the array. With its flexible setup (high frequency resolution) and its dense core, NenuFAR will be a prime instrument for this type of research.

f) Finally, the snapshot imager mode can be used for the systematic sensitive search for fast radio transients in a broad field of view, including the prompt emission associated with gravitational waves, pulsar giant pulses, Fast Radio Bursts, and exoplanetary / stellar / star-planet interaction bursts.

3.2. Schedule towards full science operations

At the date of this call, NenuFAR is currently in commissioning with its beamformer mode mostly operational, while tests of the LSS mode have started. A tentative schedule towards full science operation of the 4 operating modes is the following:

- Early Science phase: from July 2019 to December 2021.
  - Start of Key Programmes. Observations will be conducted on a shared risks basis in 3 modes: beamformer, transient buffer and imager through cross-correlation statistics. The NenuFAR team will do its best efforts to provide the data requested, but the completion of the observations requested by the KP cannot be guaranteed. Return on data quality and lessons learned will be welcome;
  - Commissioning of the LSS mode;
  - Imaging: Construction of the remaining mini-arrays, selection of the correlator. The imager mode should be available at the beginning of 2020, starting with one then 4 distant mini-arrays;
  - During this period, depending on the technical progress and the outcome of the first call for KP, a new call for KP could be issued, open to the French and international scientific communities.
- Mid-2021: Call for PI proposals to the French and international scientific community; appointment of an international Time Allocation Committee;
- Beginning of regular exploitation: from January 2022 to end 2024:
  - A call for proposals will be issued every semester.
  - PI proposals, once accepted, are executed during the semester, except exceptional circumstances;
  - Observations comprise PI proposals and Key Programmes. It is our intention that the fraction of observing time devoted to KP progressively decreases to reach an indicative fraction of less than 25% maximum at the beginning of 2025;
  - We also foresee the possibility of Discretionary Director's Time for urgent and exceptional observations;
  - Targets of Opportunity: we foresee that these observations should be requested in the frame of a KP or a PI proposal;
  - Completion of the commissioning activities.
- Full science operations: from January 2025 (TBC), with ≥ 75% time open to PI proposals.

3.3. Data and publication policy

When proposing a Key Programme on NenuFAR, teams explicitly agree to the NenuFAR data and publication policy, which is summarized below.

Proprietary period: It is intended that NenuFAR scientific data will be publicly available via the Centre de Données de Nançay (the Nançay Radio Data Center) at the expiration of a one-year proprietary period after the program completion, which means:

- For PI programs, one year after the end of the semester during which the observations have been executed;
- For KPs, one year after the end of the two-year period for which the KP has been accepted. Exceptions from this rule can be considered for monitoring programmes that need long series of observations; they should be requested for, and duly justified, in the proposal, with a strict limit of the proprietary period of three years.

Builders list: Many people have contributed to the development and completion of NenuFAR. Among these, "NenuFAR builders" are those people that contributed more than one Full Time Equivalent (FTE). The list of NenuFAR builders will be maintained by the CSN. All scientific publications using NenuFAR data taken during the Early Science phase or the commissioning time may be cosigned by NenuFAR builders, upon their request.

Acknowledgements: All publications using NenuFAR data should acknowledge the funding sources of the project in the following way: "This paper is based on data obtained using the NenuFAR radiotelescope. The development of NenuFAR has been supported by personnel and funding from: Station de Radioastronomie de Nançay, CNRS-INSU, Observatoire de Paris-PSL, Université d'Orléans, Observatoire des Sciences de l'Univers en région Centre, Région Centre-Val de Loire, DIM-ACAV and DIM-ACAV+ of Région Ile de France, Agence Nationale de la Recherche ».

4. Call for Key Programme proposals

4.1. Key Programmes

We invite applications for Key Programmes to be conducted with NenuFAR. Key Programmes are programmes which address a broad scientific question through the best possible use of NenuFAR, and for which long-term observations (typically 2 years), or/and a large amount of observing time are needed to reach meaningful scientific results.
For this first call for KP, we expect applications from the French scientific community and, by invitation, international researchers. During the Early Science phase, the CSN suggests that proposals have either a French coordinator or a French deputy coordinator.
The CSN has identified a preliminary list of following science topics for which a Key Programme proposal is expected:

- Cosmic Dawn and Dark Ages;
- Exoplanets, stars and star-planet plasma interactions;
- Pulsars;
- Radio Recombination Lines;
- Transients: RRATs, Fast Radio Bursts, possible coherent radio pulse counterpart of gravitational waves or gamma ray bursts, etc.;
- Atmospheric showers (Cosmic rays, Gamma rays);
- Solar system (or terrestrial) planetary lightning;

- Pilot program on galaxies, clusters, AGN (possibly in conjunction with LOFAR or LSS observations);
- SETI (provided that a dedicated receiver can be installed at NenuFAR – this is under study).

There are 3 ways to answer to this call:

- Proposals from structured groups formed in response to this call, with an identified coordinator, on a theme in the above list;
- Proposal to join a KP; for efficiency, this request should be made well before the proposal deadline, in order to arrange contacts;
- Proposals from structured groups with an identified coordinator on a theme not yet identified by the CSN.

4.2. NenuFAR data workshop

NenuFAR will be a hopefully powerful but certainly complex instrument. In order to help the teams to prepare their proposals in the best possible way, and to introduce observers to NenuFAR data, a 2-day NenuFAR data workshop is organized in Nançay from March 2019, 18th at 12 am to March, 20th at 12 am.

The workshop format will be the following: after a presentation of the instrument, of its different data products and of the available analysis tools, the workshop participants will get "hands-on" experience on real data. The NenuFAR building and commissioning teams and experts will be available to interact with the KP representatives on their scientific needs so that they can optimize their proposals.

Teams that intend to propose a KP are expected to send a least one team member to attend the workshop.

The preliminary program and practical information can be found on the workshop website https://nenufar2019.sciencesconf.org/. Since attendance is limited, it is necessary to register before February 10th.

4.3. Local data storage and computing

Presently, the Nançay Radio Data Centre provides data storage capacity on site for a total volume of 420 Tb. A set of 3 bi-Xeon multi-core nodes is currently available to users for data reduction.

By mid 2019, the data storage will be increased to > 1 Pb, and two new bi-Xeon nodes will be added.

4.4. Demonstrating the capacities of NenuFAR

We expect Key Programmes to demonstrate the capabilities of NenuFAR and, as far as possible, to yield early scientific results and "First light publications". We thus encourage teams to indicate in their proposal the possibilities for early results.

4.5. Proposal format

Key Programme proposals must be sent to nenufarcsn@obs-nancay.fr before March 31, 2019. They should be in PDF format and contain the following sections:

1. Summary (maximum 1/2 page);
2. Name of the coordinator with full contact details, the list of team members, their affiliations and their roles in the project, including PhD students and postdocs;

3. Scientific rationale and the need for NenuFAR observations; relevance to the preparation of the SKA, if any;
4. The need for a Key Programme, the results that should be obtained at the end of the two-year programme; a longer term perspective should be indicated if observations are needed after the Early Science phase;
5. A first detailed description of the observational strategy, including:
    - Observing time needed (hours); optimal scheduling;
    - Observing mode (s), number of beams, observing band(s);
    - Sources names and positions, fields to be observed;
    - Night/day constraint if any, scheduling constraints;
    - Complementarity or coordination with other instruments or observations, and their availability;
    - Local data storage requests;
    - Local computing requests;
    - Need for technical support or expertise;

    The proposed observation strategy must take into account the planned schedule for the availability of the observing modes (see section 5).
6. Strategy for data analysis, including a schedule and proposed milestones;
7. Publication strategy;
8. If deviations from the general NenuFAR data policy are requested, a detailed justification; however, the proprietary period cannot exceed 3 years;
9. Public outreach plan.

Individuals wishing to join a KP are invited to contact nenufarcsn@obs-nancay.fr well before the proposal deadline.

4.6. Points of contact

For more information, please visit the NenuFAR astronomers web site:
https://nenufar.obs-nancay.fr/en/astronomer/
or send an email to nenufarcsn@obs-nancay.fr.

5. Tentative schedule of the Early Science period of NenuFAR

The tentative schedule of the first Key Programmes selection and implementation, and of the Early Science period, is the following:

- Call for KP proposals: January 2019, 15th
- NenuFAR data workshop registration deadline: February 2019, 10th
- NenuFAR data workshop: March 2019, 18th to 20th
- KP proposals deadline: March 2019, 31st
- KP proposals selection: May 2019, 31st
- KP execution begins: July 2019, 1st
- Beamformer mode available: mid 2019
- Imager mode, coarse resolution (cross-correlation statistics) available: mid 2019
- Transients Buffer mode available: not earlier than mid 2019
- LSS mode through LOFAR calls: not earlier than end 2019
- NenuFAR imager, low resolution mode: not earlier than 2020 (in a first stage, NenuFAR core and one MA, then 4 MA)

6. Acknowledgements

This announcement is a major step in a 10-year effort, still ongoing, that would not have been feasible without the constant involvement and support of a large number of participants, from the administrative and support personnel to engineers, scientists, students and post-doctoral fellows. Their contribution to the development, building and commissioning of NenuFAR is gratefully acknowledged.
It is also a pleasure to acknowledge the strong and friendly international support that we have enjoyed, including technical advice, contributions to the NenuFAR science case, or the constant support of the LOFAR scientific and technical community.

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7. List of acronyms

ASIM Atmosphere-Space Interactions Monitor
CD Cosmic Dawn
CMB Cosmic Microwave Background
CSN Comité Scientifique de NenuFAR (NenuFAR Scientific Committee)
DIM-ACAV Domaine d'Intérêt Majeur en Astrophysique et Conditions d'Apparition de la Vie
DM Dispersion Measure
EoR Epoch of Reionization
FoV Field of View
FPGA Field-Programmable Gate Array
FRB Fast Radio Bursts
FTE Full Time Equivalent
GPU Graphic Processing Unit
GW Gravitational Waves
ILT International LOFAR Telescope
ISM Interstellar Medium
KP Key Programme
LaNewBa LOFAR advanced New Backend
LBA Low Band Antenna (LOFAR)
LOFAR LOw Frequency ARray
LSS LOFAR super station
MA Mini-Array of 19 dual-polarized antennas
MS Measurement Sets (interferometric data standard)
NDA Nançay Decametric Array
NenuFAR New extension in Nançay upgrading LoFAR
PI Principal Investigator
PSL Paris Sciences et Lettres University
RFI Radio Frequency Interference
RRAT Rotating Radio Transient
RRL Radio Recombination Line
SKA Square Kilometer Array
TBB Transient Buffer Board
UnDySPuTeD Unified Dynamic SPectrum, Pulsar & Time Domain receiver