Overview of NenuFAR project & data products

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and the NenuFAR-France team

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Motivations

• Interesting scientific «niches» for a large compact LF array:
  - more sensitivity at low / very low frequencies
  - more sensitivity to extended structures (short baselines)
  - compactness, large FoV, high sensitivity (multi-)beam formed mode
⇒ large programs: cf. KP list & discussions

• Complementarity with LOFAR
  - enabling very high resolution in LBA with sensitive international baselines

• Developing the French LF radio community
Basic Principle
From LOFAR (FR606) to ...
NenuFAR

New extension in Nançay upgrading LOFAR
96 **Mini-Arrays**
(LF tiles)
of 19 antennas, analog phased
$\Delta f \supset LBA$ range
(10-87 MHz)
+ 6 distant MA
→ 1938 antennas

- **Standalone Beamformer**
- **Standalone Transient Buffer**
- **Standalone Imager**
- **LOFAR Super Station**
Antenna (+ preamplifier) & Sensitivity

- Good LF antenna radiator + LNA [Hicks et al., 2012; Girard et al., 2012; Charrier et al., 2014]
- Ground plane improves antenna response and avoids variation / t of ground properties
Mini-Array

-15 dB sidelobes
-32 dB sidelobes

- Optimized 19-antenna distribution within Mini-Arrays
**Mini-Array**

- $f = 20 \text{ MHz}$

- $f = 80 \text{ MHz}$
NenuFAR imager

- $\sigma_{\text{confusion}} \ [\text{mJy/beam}] \sim (\nu/100 \ \text{MHz})^{-0.7} \ (\theta / ')^2 \ \ [\text{Condon, 2002, 2005}] \rightarrow 1-50 \ \text{Jy} \ @ \ 20-80 \ \text{MHz} \ \text{(unpolarized signal)}$
- 6 \ \text{distant MA} + \text{multi-} \lambda \ \text{synthesis} \rightarrow \ \text{angular res.} \times 7 \ \text{for stationary broadband sources} \rightarrow \ \sigma_{\text{confusion}} / 50$
- Relative sensitivity beyond compact core = $(N_{\text{distant}}/N_{\text{core}})^{1/2} \sim 25\%$
- Synchronization via White Rabbit
- Correlator under study (COBALT-2 vs FPGA)
# NenuFAR array

<table>
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<th>Frequency (MHz)</th>
<th>Wavelength (m)</th>
<th>$A_{e\text{-dipole}}$ (m$^2$)</th>
<th>$A_{e\text{-MA}}$ (m$^2$)</th>
<th>$A_{e\text{-core}}$ (m$^2$)</th>
<th>$A_{e\text{-all}}$ (m$^2$)</th>
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<th>$FoV_{MA}$ (°$^2$)</th>
<th>$\theta_{core}$ (°)</th>
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Receivers

Compact core (400 m): 96 MA x 2 polar.

Distant MA (≤ 3 km): 6 MA x 2 polar.

- Digitization
- Channelization
- Beamforming
- Correlation
- Calibration + Imaging

LaNewBa

- Digitization
- Channelization
- Beamforming

UnDySPuTeD: pulsar
- Coherent dedispersion
- Folding / Integration

UnDySPuTeD: dynamic spectra
- Channelization
- Integration

SETI Machine

NenuFAR Beamformer

NenuFAR Transient Buffer

Correlator
- Channelization
- Correlation
- Calibration + Imaging

NenuFAR Imager

LOFAR FR606 backend
- Digitization
- Channelization
- Beamforming
- Correlation
- Calibration + Imaging

NenuFAR Super Station

Broadcast on VLAN
LANewBa  (LOFAR-like Advanced New Backend) 

- **Digitization** (96 x 2 x 200 MHz, 14-bits ADCs)
  (~400 MB/s/input, 77 GB/s for full NenuFAR Core, 24/7)

- **Signal processing** implemented on 24 FPGA compute nodes (ALSE+USN+LOFAR RSP)
  - **Channelization** (PFB+FFT) in 512 x 195.3125 kHz subbands (hereafter 200 kHz SB)
  - **Beamforming** (phased array mode)
    - Beamlet = 200 kHz SB in selected (θ,φ) direction  (200 k-complex/s per beamlet)
    - Selection of up to 768 beamlets from 512 ~ 2 full-band 75 MHz beams
    - Phasing using complex weighting (Narrow band approximation)
    - Distributed sum over a ring, synthesized beam exported at 2x 300-600 MB/s
    - Broadcast to multiple listeners on VLAN

- **Output** selected subbands to a 102 x 102 correlator

- **Parallel computation of Crosslet SStatistics** (XST, 16 SB/s)

- **TBB** :
  - 5 s of raw ADC data from all Mini-Arrays
  - Software trigger and built-in hardware trigger
LANewBa (LOFAR-like Advanced New Backend)

2 beams full-band (~10-85 MHz), full-polar.
Receivers

Compact core (400 m): 96 MA x 2 polar.
Distant MA (≤ 3 km): 6 MA x 2 polar.

- **LOFAR FR606 backend**
  - Digitization
  - Channelization
  - Beamforming
  - Correlation
  - Calibration + Imaging

- **LaNewBa**
  - Digitization
  - Channelization
  - Beamforming

- **UnDySPuTeD: pulsar**
  - Coherent dedispersion
  - Folding / Integration

- **UnDySPuTeD: dynamic spectra**
  - Channelization
  - Integration

- **Correlator**
  - Channelization
  - Correlation
  - Calibration + Imaging

- **NenuFAR Transient Buffer**

- **NenuFAR Imager**

- **NenuFAR Beamformer**

- **SETI Machine**

- **LOFAR Super Station**

- **Broadcast on VLAN**
UnDySPuTeD calculators

- **2 identical servers** CPU + GPUs (~2 GFlops)
- **2 operating modes** : Pulsar & Time-Frequency (Dynamic Spectrum)
  - Processing per lane of 192 beamlets (2 lanes / server)
  - **Pulsar** : coherent dedispersion in 200 kHz SB, folding, integration, 4 Stokes
    (incoherent sum mode possible only with 200 kHz spectral resolution)
  - **Dynamic spectrum** : channelization down to 0.2 kHz (FFT, 1024 channels), integration / t down to 1 msec, 4 Stokes
- **Waveform dump** (beamformed, in 200 kHz beamlets)

SETI receiver in project

- In discussion with Berkeley/Breakthrought Listen lab. + ICRAR/Curtin Univ.
- Plugged to VLAN
- Piggyback mode only
Receivers

Compact core (400 m): 96 MA x 2 polar.

Distant MA (≤3 km): 6 MA x 2 polar.

analog signals

LOFAR FR606 backend
- Digitization
- Channelization
- Beamforming
- Correlation
- Calibration + Imaging

LOFAR Super Station

LaNewBa
- Digitization
- Channelization
- Beamforming

UnDySPuTeD: dynamic spectra
- Channelization
- Integration

UnDySPuTeD: pulsar
- Coherent dedispersion
- Folding / Integration

SETI Machine

NenuFAR Beamformer

NenuFAR Transient Buffer

Correlator
- Channelization
- Correlation
- Calibration + Imaging

NenuFAR Imager

Broadcast on VLAN
Correlator and TBB

- Correlator, tbd COBALT-2 or FPGA-based
  - fed by LaNewBa
  - 75 MHz instantaneous bandwidth, 384 beamlets, df = 3 kHz, dt = 0.5-2 s
- TBB: 5 s of raw ADC data from all Mini-Arrays, Software trigger and built-in hardware trigger
Pointing

- **Analog** pointing of Mini-Arrays:
  - 128 x 128 pointable positions > 20° elevation
  - from declination $\delta = -23^\circ$ to $\delta = +90^\circ$
  - beam squint (elevation >20° !)
  - silent pointing system, 10 sec scheme
Pointing

- **Digital** pointing of NenuFAR:
  - real, computed: tracking (RA,δ), fixed pointing or table (az,el)
  - IMCCE Web-service for Solar system bodies
  - 10 sec scheme (±5 sec) → <0.5% gain variations

- **Pointing error (~LWA):**
  - 10' - 100' depending on az (el)
  - correction from multi (9) beam multi-transits
  - ≠ global sky rotation (≠ LWA)
  - order 3 polynomial vs azimuth
  - accuracy reached ~5' (1 σ)
Pointing
Summary of NenuFAR characteristics

- **Number of antennas**: 1938 = 96 core + 6 remote MA of 19 antennas each
- **Dimensions**: MA diameter = 25 m, core diameter \(~400\) m, remote MA up to \(~3\) km
- **Number of baselines**: 5151
  = 4560 baselines from 25 m to 400 m + 591 baselines from 400 m to 3 km
- **Frequency range**: 10-85 MHz ($\lambda = 3.5 – 30$ m)
- **Time-Frequency resolutions**: $\delta f = 195.3125$ kHz x $\delta t = 5.12$ µs
  Channelization down to 3.05 kHz x time integration down to 1 ms
  Waveform at 5 ns time resolution
- **Full polarization**: (4 Stokes)
- **Collecting area**: from \(~220\ \lambda_2\) to \(~650\ \lambda_2\) (function of effective area overlap within MA)
  from \(~83000\ \text{m}^2\) at 15 MHz to \(~7500\ \text{m}^2\) at 85 MHz for the core
  from \(~88000\ \text{m}^2\) at 15 MHz to \(~8000\ \text{m}^2\) at 85 MHz for core+remote MA
- **Pointing**: from declination $\delta = -23^\circ$ to $\delta = +90^\circ$
- **Field of View**: \(~46^\circ\) (1650$^\circ$2) at 15 MHz to \(~8^\circ\) (51$^\circ$2) at 85 MHz
- **Angular Resolution**: from 2.9° at 15 MHz to 0.5° at 85 MHz for the core
  from 23’ at 15 MHz to 4’ at 85 MHz for the core+remote MA (down to 0.4” in LSS mode)
- **Sensitivity** (thermal noise):
  from \(~130\ \text{mJy}\) at 15 MHz to \(~9\ \text{mJy}\) at 85 MHz with $\Delta f=10$ MHz x $\Delta t=1$ h
  (similar values for the core & core+remote MA)
- **Confusion at zenith**:
  from \(~120\ \text{Jy}\) at 15 MHz to \(~2\ \text{Jy}\) at 85 MHz for the core
  from \(~5\ \text{Jy}\) at 15 MHz to \(~100\ \text{mJy}\) at 85 MHz for the core+remote MA
Data products (see details on Astronomers page)

- **Beamformer mode:**
  - **Pulsar** (PSRFITS format → Presto, DSPSR...): coherently dedispersed at known DM + folded, or filterbank/search mode, full polar
  - **DynSpec** (proprietary format): down to 0.2 kHz & 1 msec, full polar
  - **Waveform** (proprietary format): 200 k-complex/s X & Y signals written to disk
  - **SETI** data
  - **BST** (Beamlet STatisics) data (FITS format): systematically recorded in //, 200 kHz x 1 s resolution, X & Y, include full setup info

- **Transient Buffer mode:**
  - **TBB** (Transient Buffer Board) data (proprietary format): last 5 seconds of 200 MHz waveform per MA (or selected antenna), X & Y, written to disk

- **Imager mode:** (2-hour files max)
  - **Visibilities** data (LOFAR MS format): 75 MHz, 384 SB, down to 3 kHz, 0.5-2 s, 1 MS / SB, phased to RA,δ (incl. fringe stopping + delay tracking)
  - **XST** (Cross-Correlation STatistics) data (Fits → MS format v.0): 16 SB / s ~ 3 MHz bandwidth, 1 MS / SB, phased to zenith; tracking computed at conversion to MS → calibration
  - **LOFAR Super Station mode**: **Visibilities** data (LOFAR MS format): 48+ MHz, 244+ SB, produced by LOFAR

- **Other products**:
  - **SST** (Spectral STatistics) data (FITS format): 1 spectrum at 200 kHz x 1 s resolution per MA, X & Y; integrated to 10 s after 6 months → engineering
  - **Incoherent summation** data (format tbd): summation of the intensities from each MA at 200 kHz resolution
Calibration

- **Phase calibration** of beamformer mode
  - from XST (rephased) tracking obs. of A-team sources (Cas, Cyg),
  - NDPPP (X & Y) with 1 source sky model $\rightarrow$ complex gains of each MA, X & Y
  $\rightarrow$ delays $\rightarrow$ calibration table in LANewBa
Calibration

- **Flux calibration** of beamformer mode
  - from Galaxy and A-team sources (LFmap, GSM)

- **Polarization calibration** of beamformer mode
  - from XST using NDPPP in full polarization (full Jone matrix)

Figure 1: GSM low-frequency sky model at 72 MHz.
Telescope operation

- parset files, GUI → LD (AC)
Simulations

- Instrument (MA or NenuFAR) + GSM, necessary for proper use/interpretation of BF mode

- RFI localization
  - rotating phased beam 0°-360° by 5° steps, elev. = 20°
Tests / Qualification (commissioning)

- Radiosource transits
- Jupiter, Sun, compared to Nançay Decameter Array
- Pulsars
- RFI monitoring & localization
Tests / Qualification (commissioning)

- Radiosource imaging from XST (A-team, LOFAR calibrator, weaker sources ongoing → wide field imaging quality assessment)
Data output

- To Nançay Data Center (databf storage + nancep computing nodes) → ET, BC
- Archive under study

User software

- Python routines → AL
- IDL routines → PZ, CB
- /cep/lofar/nenufar common directory on nancep
- Collaborative organization to be discussed

Data use policy

- Management plan, exploitation phases, ... → FC
FLOW proposes a non-standard solution for contributing to LOFAR2.0. This involves making available NenuFAR as an ILT station – which has indeed been a long-standing aspiration – and making available a new LBA design – profiling from the available NenuFAR designs and expertise. It is here recommended to defer a future decision by the ILT Board on these topics until further careful assessments have taken place. A few demonstration experiments with NenuFAR as an ILT station can then be used for some test observations to probe the performance of NenuFAR (e.g. internal calibration, sensitivity, polarisation, spectral response, beam shape), and its suitability for use in the standard ILT network. A test plan will be developed, with a few targets with appropriate compactness/structure, carefully selected with the aim to obtain publishable results in short order.

**Memo on the performance of NenuFAR for ILT observations**

While fringe may initially be achieved even with imperfectly calibrated data, this experimental setup will then be used for some test observations to probe the performance of NenuFAR (e.g., internal calibration, sensitivity, polarisation, spectral response, beam shape), and its suitability for use in the standard ILT network. A test plan will be developed, with a few targets with appropriate compactness/structure, carefully selected with the aim to obtain publishable results in short order.

**Memo to update NenuFAR-ILT future science cases**

While the potential science cases for the use of NenuFAR as an ILT element were composed at the time when NenuFAR was proposed, it is timely to update these. In the coming months, the assessment of the science potential can specifically be informed by real data (e.g. w.r.t. sensitivity, bandpass, beamshape) from the demonstration observations as described above. J. McKean has agreed to initiate this effort, particularly since it relates very closely to the long-baseline topics within the overall compilation of LOFAR2.0 science cases (coordinated J. Hessels and J. Broderick).

**Calibration of the NenuFAR array**

While Calibrator is an ILT element, calibration is also of importance to LOFAR2.0. The current status of calibration is as follows:

- **LOFAR Super Station mode**
  - Tests in progress → CT, JG
  - Exploitation via LOFAR (ILT plan 23/9/2018, need ASTRON manpower for full integration)

- **Integration in LOFAR 2.0 in discussion**
Timeline

- 2008 : Initial idea & workshop :
- 2009-2013 : Design study
- 2014-2019 : Construction (75%)
- 2016-2019 : Tests, Qualification, Commissioning
- 2019/03 : 1st Users Workshop
- 2019/9/17 - 2019/10/03 ⊇ Inauguration of NenuFAR
- 2019-2021 : Early science, end of construction (ERC, ...)?
Construction

72 core MA + 4 remote funded, 56 MA core built & operational (1064 antennas)
+ 1 remote MA built & monitored

LOFAR FR606 to be built in 2019
Construction

Going from 72 to 96 MA: beam, pointing accuracy?
Further steps  (see details on Astronomers page)

• Preparation of observations
  - Smart SB selection / RFI occupancy statistics
  - VOevents for GW follow-up observations

• Data analysis
  - Integrate LOFAR/NenuFAR subtables in MS (v.1) (MA tile definition, beam modelling, …)
  - Development of the NenuFAR pre-processing pipeline: Flagging, rebinning, demixing/DDD subtraction, …
  - Development of the NenuFAR Calibration & Imaging pipeline: DDFacet/KillMS for DI and DD calibration (A-team subtraction, beam model, wide-field imaging, polarization…)
  - Data management: XST/MS code acceleration, Hi-res Vis "direct-to-disk" …
    → NenuFAR TV (Near Real-time "all-sky" imager in I and |V|)

• Hardware
  - Choice and implementation of correlator
  - End of core construction (~1 M€), of imager (2 remote MA + correlator ~200 k€)
• ...
Web site

  - Art project: "Le Dôme de NenuFAR"

  - Identified features
  - "Contact NenuFAR team" form for feedback / questions

- [https://confluence2.obs-nancay.fr/display/NEN/Wiki+NenuFAR](https://confluence2.obs-nancay.fr/display/NEN/Wiki+NenuFAR) (restricted access)
The team

- **PI**: P. Zarka, M. Tagger  
  **Project Manager**: L. Denis

- **Comité Scientifique NenuFAR**: the above 3 + F. Casoli, S. Corbel, G. Theureau

- **Commissioning team**: J. Girard, L. Denis, P. Zarka, A. Loh, L. Bondonneau, M. Pommier, J.-M. Grießmeier, C. Tasse, C. Briand, E. Bonnassieux, C. Viou, B. Censier
  
  → support for Early Science observations

- **Development team**:
  
    
  
  - Other: D. Charrier, J. Girard, A. Loh, L. Bondonneau, I. Cognard, B. Cecconi, P. Zarka


- **Artist**: C. Courte
Publications

Published / in press : NenuFAR

- NenuFAR-France collaboration (80 co-authors), NenuFAR : instrument description and science case, 6/2014.

Published / in press : Methods


In preparation :

- Charrier et al., NenuFAR antenna and preamplifier
- Girard & Zarka, Optimization of a small 2D phased array layout synthesizing a wide-beam antenna pattern, A&A
- NenuFAR collaboration, The LF radiotelescope NenuFAR, Exp. Ast.
- NenuFAR collaboration, NenuFAR science case, Exp. Ast.

Theses, report :

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Le projet dans les temps