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The low-frequency radio telescope NenuFAR

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Abstract

NenuFAR is a new, large low-frequency radio telescope, in construction and commissioning at the Nançay Radioastronomy Observatory, that starts to provide high sensitivity observations in the 10-85 MHz range. NenuFAR's 1938 dual polarization antennas are connected to a suite of receivers allowing the instrument to operate, simultaneously if needed, in 4 distinct modes : as a standalone beamformer, a standalone imager, a waveform snapshots recorder, and a giant low-frequency station of the LOFAR array. We provide here an overview of the antennas, receivers, data products, operation and scientific context of the instrument.

1 Introduction

Besides the very successful LOFAR observations in the high frequency band (110-250 MHz) [1], there is need for a very sensitive radio telescope operating in the range 10-85 MHz, between the Earth's ionospheric cutoff and the FM band. NenuFAR, initially conceived as a giant extension of LOFAR in its low-frequency band, has evolved during its design study (2009-2013) as a large standalone radio telescope, aimed at fulfilling this need.

2 Antennas and distribution

NenuFAR elementary antennas are crossed inverted-V dipoles (Figure 1), with a quasi-isotropic response at elevations ≥20°, oriented at 45° from the meridian like LOFAR dipoles [2]. The radiators are those developed for the LWA [3]. They are coupled to a custom-designed low noise preamplifier (developed in SUBATECH and USN) that ensures a relatively flat response across the entire 10-85 MHz band with a level of sky background several dB above the preamplifier noise at all frequencies. The sensitivity, displayed in Figure 2, is thus sky-limited.

Figure 1. NenuFAR antenna field in Nançay. Each LWA-like antenna is mounted above a 3m × 3m metal grid (ground plane). The custom-made preamplifier is in the white box at the top of each antenna.

NenuFAR antennas are hierarchically distributed [4,5]. They are grouped in hexagonal tiles of 19 crossed-dipoles (Mini-Arrays, hereafter MA, ∅=25 m, cf. Fig. 2 of [5]) that are analog-phased using achromatic delay lines to produce a broad beam of (700/f)° with f in MHz smoothly steerable from horizons to zenith. 96 such MA are densely distributed with a 400 m diameter core, whereas 6 additional MA are distributed at distances up to ~3 km. The core has a near perfectly Gaussian coverage of the *uv* plane, whereas the distant MA provide a sparse instantaneous coverage, that becomes fairly continuous when combined with Earth rotation and multi-frequency synthesis. NenuFAR core provides an angular resolution of (43/f)°, and the whole NenuFAR can reach ~(6/f)°. Effective areas at zenith and angular resolutions are listed in Table 1.

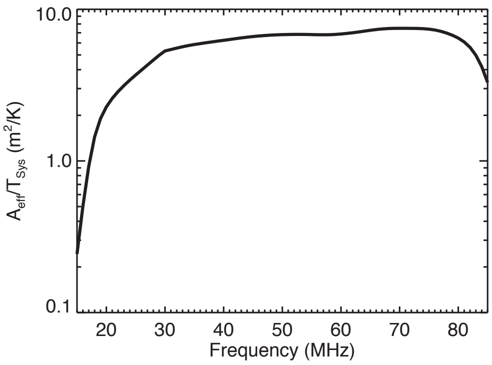

Figure 2. NenuFAR sensitivity in the 15-85 MHz range. With a value ~6-8 m^2/K, it is 1.6 to 8 times larger that that of the LOFAR core [2], and larger than that of the full LOFAR out of the range 50-65 MHz.

MA are rotated with respect to each other by angles multiple of 10°, in order to reduce the contribution of the side (and grating) lobes in beamformed (phased array) mode. Antennas are back-rotated by the same angle to remain aligned throughout NenuFAR. All distant MA have a rotation angle of 0°.

Table 1. Effective areas (top), field of views and resolutions (bottom) as a function of the frequency f and wavelength λ.

f (MHz)	λ (m)	A_{dipole} (m^2)	A_{MA} (m^2)	A_{core} (m^2)	A_{all} (m^2)
15	20.	133	864	83001	88189
27	11.1	41	568	54612	58025
48	6.2	13	247	23750	25234
85	3.5	4	78	7574	8047

f (MHz)	λ (m)	θ_{MA} (°)	FoV_{MA} ($°^2$)	θ_{core} (°)	θ_{all} (’)
15	20.	46	1650	2.9	23
27	11.1	26	509	1.6	13
48	6.2	15	161	0.9	8
85	3.5	8	51	0.5	4

3 Receivers and data products

The 96 × 2 polarizations analog signals from the core MA are split in order to feed simultaneously the LOFAR FR606 station backend (via its LBL inputs [2]) as well as the main NenuFAR standalone receiver *LANewBa* (LOFAR-like Advanced New Backend). These receivers digitize (at 200 MHz), channelize (in 195 kHz bands) and digitally (multi-)beamform the signals. Beamforming is a coherent summation of MA signals with adequate phase shifts. It produces 195 kHz-wide (×2 polarizations) beamlets defined by their central frequency f_c and the angles (θ,φ) defining the center of phase in the sky. Beamlet signals are streams of 195k-complex pairs, allowing for further channelization and computation of the 4 Stokes parameters of the incident waves.

LOFAR FR606 can then send 244 16-bit beamlets (~48 MHz instantaneous bandwidth) of these “super station” signals to the LOFAR central correlator, for enhancing LOFAR’s low-frequency imaging capabilities.

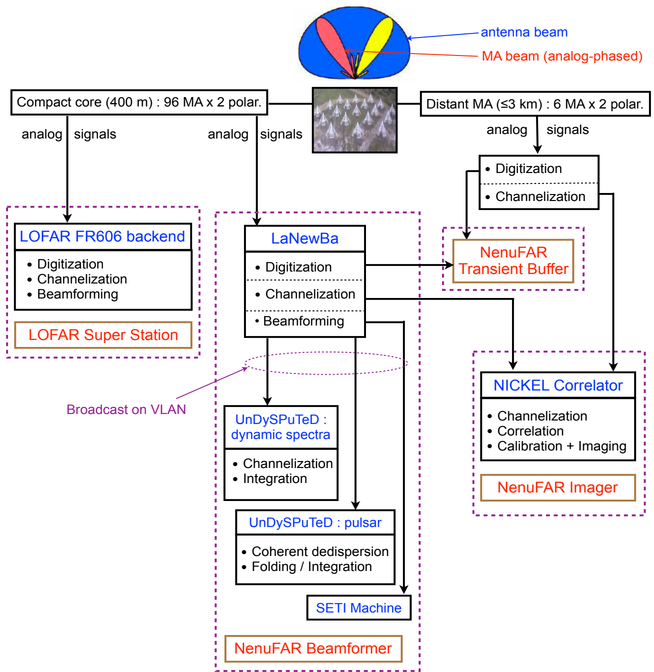

Figure 3. Synoptic view of NenuFAR receivers and signals/data distribution.

LANewBa can process up to 768 16-bit beamlets at any time (630 Gb/s, 24/7), equivalent of 150 MHz of instantaneous bandwidth, i.e. 2 beams each with the full 10-85 MHz band, or 10 beams of 15 MHz bandwidth, etc. Each beamlet is defined independently without any practical constraint other that being included in the MA analog beam. *LANewBa* products are broadcasted on a local network that feeds in parallel several calculators: two identical *UnDySPuTeD* (Unified Dynamic Spectrum, Pulsar and Time Domain) machines [6] compute full Stokes Dynamic Spectra, standard Pulsar products, or waveform (Time Domain) series of samples. A calculator

procured together with the Berkeley Breakthrough Listen laboratory will produce high spectral resolution dynamic spectra for SETI studies, mostly in piggyback mode thanks to the flexibility of *LANewBa* broadcasting on a local network.
In parallel, *LANewBa* produces low-rate statistics measurements (Spectral, Beamformed, and Cross-Correlations) in FITS format, and feeds a circular Transient Buffer per MA with the 200 MHz signals, allowing up to 5 s of high-rate waveform capture and dump-to-disk (similar to LOFAR's Transient Buffer Boards). Finally *LANewBa* feeds the standalone correlator with the channelized signals per MA and per polarization, together with digitized signals from the distant MA. The correlator is a clone of the new LOFAR Colbalt-2 correlator, adapted and tuned for NenuFAR use and thus named *NICKEL* (NenuFAR Imager Correlation Kluster Elaborated from LOFAR's). It will deliver standard Measurement Sets (MS) that can be processed for standalone imaging, or simultaneous to LOFAR MS on the same fields to provide information on short baselines (down to 25 m).

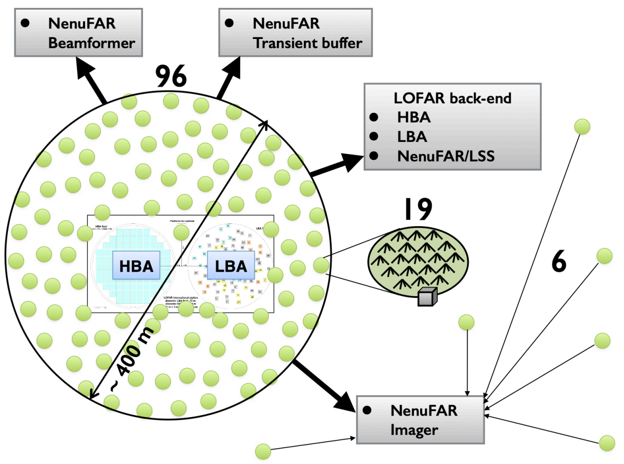

Figure 4. Sketch of the instrument concept. The LOFAR station FR606 is surrounded by NenuFAR's core. Green dots are NenuFAR MA of 19 antennas (96 in the core + 6 up to 3 km). Receivers are sketched by the grey boxes.

Figure 3 provides a synoptic view of the receivers, that can be used nearly all in parallel, while Figure 4 summarizes the full instrument concept.

4 Status and operation

1083 antennas out of 1938 are operational as of 1/1/2020, with 56 core MA being routinely acquired and 1 distant MA being monitored, waiting for *NICKEL* availability. Available funding will allow us to reach a total of 1596 operational antennas in 2020 (80 core + 4 distant MA). End of funding and construction is expected for 2021.

The *UnDySPuTeD* machines and Transient Buffers are operational, the NICKEL correlator is being installed and will be available – as well as the SETI receiver – for the 2nd semester of 2020. Tests of the *LOFAR super station* mode have been performed, but it is not yet operational.

The beamformed mode has been phase-calibrated (to ensure truly coherent summation) by using cross-correlation statistics to build a calibration table. Analog pointing, using the 7-bit MA delay lines, is performed by discrete steps, on a 128×128 grid finer than 1° for elevations ≥20° [7]. It is designed to ensure relative gain variations ≤1% (0.1 dB) between consecutive pointings. Digital pointing within the analog MA beams is done at round multiples of 10 seconds. Pointing accuracy is affected by the LWA antenna response [8], but an empirical on-the-fly correction results in an effective accuracy ~5'-10', much smaller that the NenuFAR digital beam width at the highest frequency (Table 1). In imaging mode, the calibration ensures a much better positioning accuracy.

In order to pilot easily the relatively complex instrument that NenuFAR is, a *VCR* (Virtual Control Room) has been developed. It is a web interface that allows one to fully manage and control the telescope and its receivers, from observations scheduling, preparation and programming, real-time display of low-rate statistics, and data access and download, to real-time health monitoring down to every antenna preamplifier and maintenance management.

For helping the interpretation of the beamformed observations, a beam model has been computed for individual MA and for the entire telescope. When convolved with a GSM such as [9], it allows to simulate the expected beamformed response with a few % accuracy and compare it with the observations. Low-frequency observations are affected by various radio frequency interference (RFI), that we monitor in order to eliminate their sources or mitigate them in the data. Pipelines are in preparation for the standard processing of beamformed and imaging data (including demixing of strong sources, RFI mitigation, calibration, transients detection…). Imaging pipelines will be based on the kMS/DDf software developed at Observatoire de Paris [10]. A near-real-time calibration+imaging scheme, inspired by the LWA-TV (http://www.phys.unm.edu/~lwa/lwatv.html), is in preparation for broadcasting a NenuFAR-TV live.

5 Scientific exploitation

With the availability of the Dynamic Spectra, Pulsar and waveforms products (that will be soon followed by the imaging products), the NenuFAR scientific committee (nenufarcsn@obs-nancay.fr) has launched an Early Science phase (that will run in parallel with the end of construction and commissioning) of 5 semesters from 1/7/2019 to 31/12/2021. The French community and European LOFAR collaborators were invited to propose Key Programs for this Early Science phase. 15 programs have been proposed (*Cosmic Dawn, Exoplanets & Stars, Pulsars, Transients, Fast Radio Bursts, Planetary*

Lightning, Jupiter, Galaxy clusters & AGNs, Filaments & Cosmic Magnetism, Radio recombination lines, Sun, Gamma-ray showers, SETI, Cas A monitoring, Large Scale Background Survey), gathering some 140 scientist from France and Europe. Semester calls for observation proposals from these Key Programs result, after validation by the NenuFAR scientific committee, in a schedule in tabular format. When exported in *csv* format, this schedule is automatically translated by the *VCR* into time block reservations, the setup of which can then be programmed by the end users (with adequate access rights management), limiting the required human support and the risk of errors. The amount of technically successful observations during the first semester is close to 100% (without presuming the data quality, that depends on RFI, ionospheric conditions, etc.), demonstrating the robustness of the entire system.

Raw – Level 0 – NenuFAR data (several PB/year) will be (pre-)processed on the Nançay data center. Reduced – Level 1 – data products (≤1 PB/year) will be transferred to a long-term archive (in preparation) adjacent to a cloud computing center managing dynamically post-processing machines pre-equipped with the required pipelines (based on the technique of containers).

NenuFAR was officially inaugurated on 3/10/2019 (https://www.obspm.fr/inauguration-de-nenufar-un.html). On 1/1/2022, it will open to the international community and start its nominal exploitation phase. Time allocation will then be managed in the standard way by an international Program Committee. Within 5–10 years, the fraction of open time will gradually increase to 100% whereas KP time will decrease to 0.

5 Conclusion

Selected as an official SKA pathfinder since 2015, NenuFAR is a new, large 4-in-1 low-frequency radio telescope performing simultaneously (1) standalone beamforming, (2) capture of waveform snapshots from selected antenna signals, (3) standalone imaging, and (4) as a giant low-frequency LOFAR station. Additionally, it will perform piggyback SETI searches. The only observational constraint on simultaneous use of several modes is the necessary restriction to the portion of the sky targeted by the analog MA beams. NenuFAR should be the most sensitive instrument in its frequency range, until the advent of SKA that will bring a tenfold increase in sensitivity above 50 MHz (in the southern hemisphere).

Detailed information can be found on the telescope's web page dedicated to astronomers: https://nenufar.obs-nancay.fr/en/astronomer/

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