LOFAR2.0 compared to LOFAR: a short summary

2023-05-30

LOFAR2.0, see also the LOFAR2.0 White Paper, is a major upgrade to the LOw-Frequency ARray (LOFAR), offering simultaneous low- and high-band observing, increased field-of-view, and various other improvements to the sensitivity and operation of the telescope. A set of staged LOFAR2.0 test stations are helping to commission the new hardware and software, with a full system roll-out expected in 2024 – 2025, followed by early shared-risk observations and full operations thereafter. LOFAR2.0 will continue to be unique and world-leading, with an angular resolution $> 10\times$ higher than that of the planned Square Kilometre Array low-frequency component (SKA-Low), and also accessing the largely unexplored spectral window below 50 MHz.

Figure 1: International LOFAR Telescope.

The International LOFAR Telescope (ILT), see Figure 1, has previously been described in a general overview paper[1] and a paper specifically presenting beam-formed modes[2]. The goal of this short document is to summarise what new capabilities and improvements are offered by LOFAR2.0 compared to the previous system.

Telescope array

LOFAR is the world's largest and most sensitive low-frequency radio telescope (Figure 1). It stretches across Europe, from Ireland to Latvia, with a dense 'Core' and 38 stations distributed throughout the Netherlands, as well as 14 larger-collecting-area stations located in the 10 partner countries that have joined the project since its inception. The pan-European infrastructure (stations, data processors, archive nodes) is jointly exploited in the International LOFAR Telescope (ILT), soon to become LOFAR ERIC. LOFAR employs two types of antennas: the low-band antennas (LBAs) are sensitive between 10 − 90 MHz, whereas the high-band antennas (HBAs) are sensitive from 110 − 240 MHz (Figure 2).

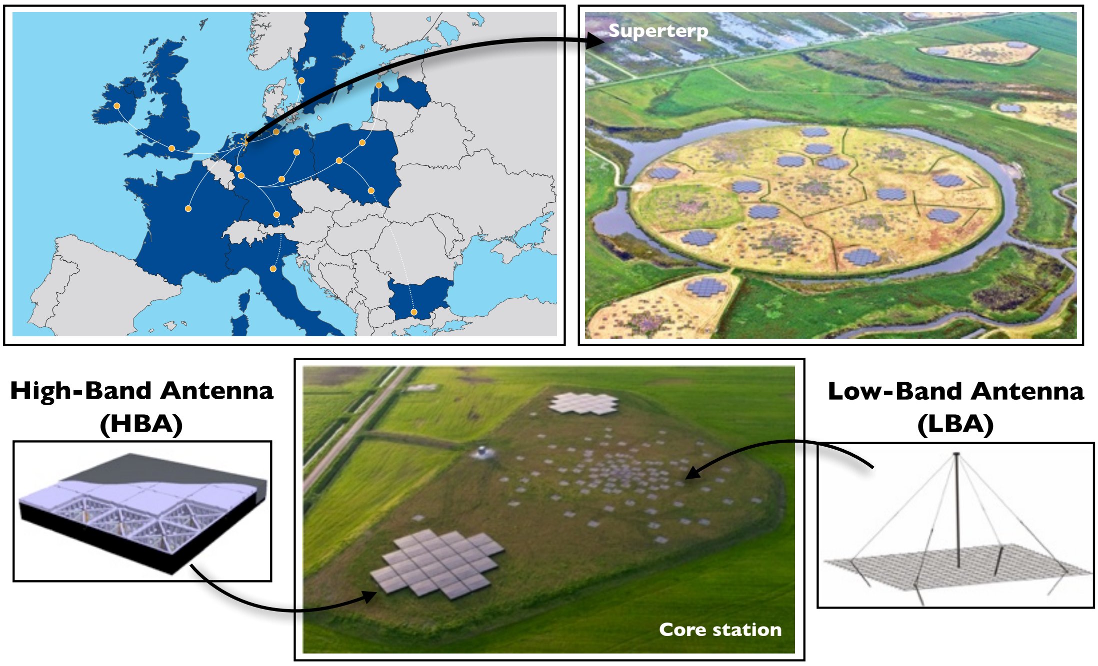

Figure 2: The International LOFAR Telescope (ILT) and the two antenna types, LBAs and HBAs.

In the LOFAR2.0 era, international stations in Italy (at Medicina) and Bulgaria (at Rozhen) will be built, significantly enhancing the north-south extent and long-baseline *uv*-coverage of the array. Furthermore, the 'New Extension in Nançay Upgrading LOFAR', NenuFAR, will be connected to the LOFAR network, thereby providing an additional 'superstation' baseline with comparable sensitivity to the LOFAR LBA Core for low-band observations.

Station processing

Each Dutch LOFAR station contains 96 LBAs and 48 HBAs; the international LOFAR stations contain 96 LBAs and 96 HBAs. All antennas are dual (linear) polarization. Due to limitations in the electronics capacity at each station, it was previously only possible to use 48 (Dutch stations) or 96 (international stations) antennas in any single LOFAR observation. LOFAR2.0 will greatly increase the computational capacity of the LOFAR stations and allow all antennas to be used simultaneously. This major upgrade is being realised via a project called the Digital Upgrade for

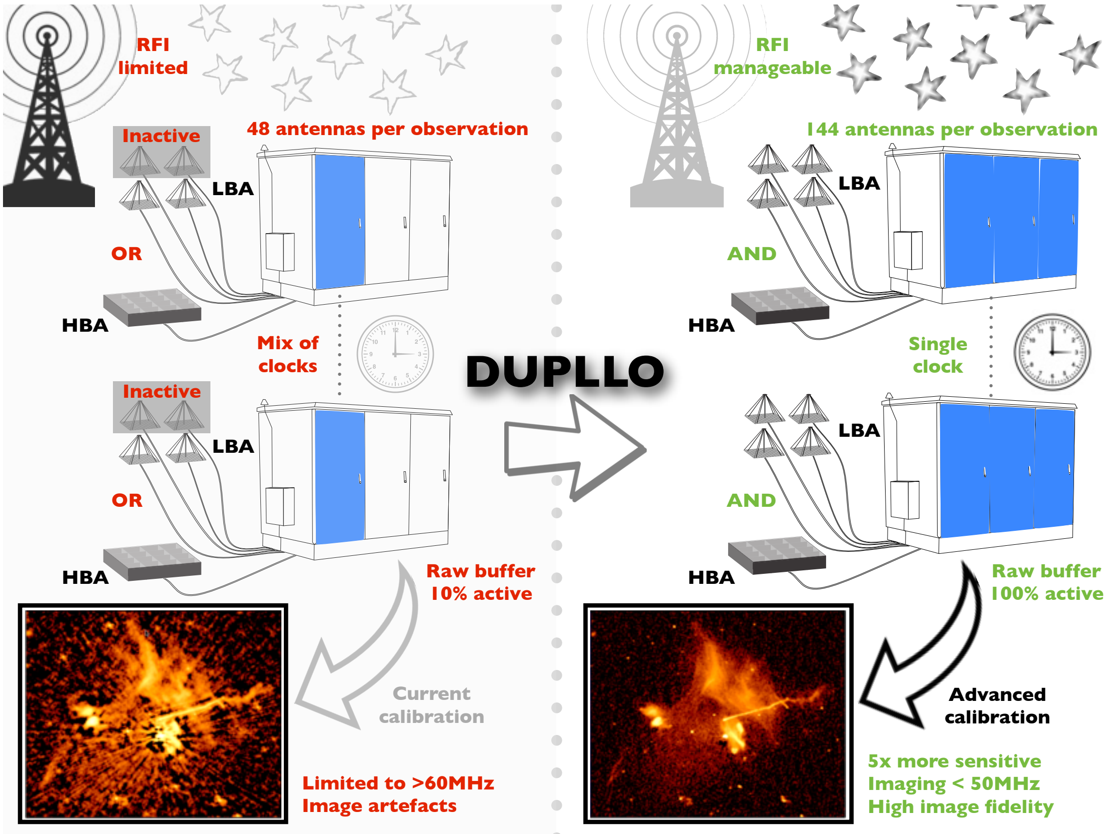

Figure 3: Schematic of the DUPLLO upgrade project, part of LOFAR2.0.

Premier LOFAR Low-band Observing (DUPLLO; see Figure 3). This enables two complementary approaches that provide major advances in the achievable low-band sensitivity: 1) with 2× as many active LBA elements, one has ∼ 2× as many sources bright enough to characterize and correct ionospheric distortions (low-risk approach) and 2) with simultaneous LBA+HBA information, one can apply the ionospheric corrections derived from the HBA array, where more calibrator sources are available, to the LBA data (this is an innovative but riskier, unproven, approach).

Furthermore, LOFAR2.0 will enable the distribution of a single-clock signal to all Dutch LOFAR stations, which greatly increases the robustness and precision of ionospheric calibration by separating these effects from clock errors. Using this three-pronged approach, LOFAR2.0 will provide a step function in the 10 − 90 MHz range (Figure 3): At ∼ 60 MHz, we aim for sensitivities of better than 1 mJy/beam rms noise (in an 8-hr integration, and even during non-ideal ionospheric conditions), and at ∼ 30 MHz, we aim for 5 mJy/beam rms noise or better. For most fields, this will improve the sensitivity by a factor of roughly five compared to the current system. Just as importantly, the greatly enhanced calibration will enormously improve the fidelity of the images, which presently suffer from ionosphere-induced artifacts.

As a significant bonus, LOFAR2.0 will also provide a 24/7 system for cosmic-ray, lightning and transient triggering; currently that is only possible in dedicated observations, but with the new system it will be possible to continuously feed the LOFAR transient buffers with raw antenna data from both the LBAs and HBAs. Nonetheless, the exact functionality of the transient buffers depends on the available firmware modes, which are currently limited in scope and are being focused to the needs of lightning and cosmic-ray observations.

Additionally, the increased computational capacity at the stations can also be used to form more beams on sky — though at the expense of running both LBA and HBA simultaneously, since the data transfer rate from each station to CEP is limited to 10 Gbit/s. It is possible to transfer 2×96 MHz of bandwidth (976 subbands). This can be used to double the survey speed and provide matching between the field-of-view of Dutch and international stations.

Previously, LOFAR has had both a 200-MHz and 160-MHz clock to provide observing in different spectral windows (Nyquist zones). LOFAR2.0 has a hardware implementation of both clock modes, but additional work is needed to provide full software and control support for the 160-MHz mode. Thus, observations from $160 - 240$ MHz are not possible at the start of LOFAR2.0, while $110 - 190$ MHz and $210 - 250$ MHz are supported. Note also that LOFAR2.0 implements a new optional filter to block the $170 - 190$-MHz band, which is strongly corrupted by digital audio broadcast (DAB) signals. This is to remove inter-modulation products in the $110 - 170$-MHz band, and thereby improve the quality of deep imaging observations.

Central processing

The LOFAR stations are linked to a central computing infrastructure in Groningen, the Netherlands, via a high-bandwidth fibre network. Here a CPU/GPU computing cluster called the Correlator and Beam-former for the LOFAR Telescope (COBALT) acts as the central 'brain' of LOFAR. The upgraded COBALT2.0 is already running and provides an order-of-magnitude increase in computational capacity compared to its predecessor. Extensions to the correlator/beam-former code allow much more flexible options for parallel observations, which can use different station sets and provide imaging and high-time-resolution beam-formed data in parallel. This will allow LOFAR to use more of the information that is already arriving from the stations at COBALT2.0 and to run multiple science cases commensally.

The achievable transfer speed from COBALT to the Central Processing cluster (CEP) will be 100 Gbit/s, and this can accommodate the wider-bandwidth, simultaneous imaging plus beam-formed observing possibilities. A wide range of time and frequency resolutions, station combinations, and imaging+beam-formed setups, are possible, but the overall data rate is constrained by the transfer speed between COBALT and CEP.

Furthermore, the Telescope Manager Specification System (TMSS; replacing the previous MoM system) is a brand-new software application for the specification, administration, and scheduling of LOFAR observations. Its realisation is crucial, as it enables the required support for LOFAR2.0 use cases, while also streamlining LOFAR operations and improving the adaptability and maintainability of software for future extensions. The system will control all aspects of observation execution and system monitoring.

Archiving & Analysis pipelines

Please also consult the document 'Data Management Capabilities & Policies'.

The ILT anticipates that (final) science data products, generated through standard pipelines (such as image cubes) can be kept available indefinitely (under open access policies), but that raw/intermediate products may only be retained for further processing within a restricted dwell time. As an indicative example: processing of visibility data to image cubes may have to be carried out within an average timespan of one to two years, thus significantly restricting achievable combinations of final image cube field size, spanned bandwidth, spatial and spectral resolution, given available compute clusters to handle a sustained observing rate. Allocation of data storage dwell times and other parameters may be tailored to specific science projects. Additional resources contributed by a project team will be of significant benefit, especially where these can be incorporated into the production data flow for the project. Composition of the LOFAR2.0 Large Programme Portfolio will take into account, among other factors, the potential to realize (afford) the resources necessary to achieve overall science excellence and high impact for the community.

Summary

LOFAR2.0 offers:

- All 96 LBA antennas in Dutch stations can be used, compared to 48 LBA antennas previously.
- Simultaneous LBA and HBA observing using all stations.
- 2×96-MHz (976 subbands) total observing bandwidth, compared to half of this previously. Either 96 MHz for each of the LBA and HBA arrays, or 2×96 MHz in one array at a time. This bandwidth can be divided across a flexible number of station beams (trade bandwidth for field-of-view).
- Robustness to DAB-induced inter-modulation products when the $170 - 190$-MHz filter is used. This will benefit deep integrations in the $110 - 170$-MHz band.
- Integration of NenuFAR as a LOFAR low-band superstation.
- Two new International stations in Italy and Bulgaria, increasing the long-baseline *uv*-coverage.
- A maximum data rate of 100 Gbit/s from COBALT to CEP.
- A more powerful and flexible COBALT for simultaneous imaging and beam-formed observations.
- A 24/7 transient buffer offering access to data from at least half of the Dutch LBA and HBA antennas.
- The new TMSS monitoring and control system, including a dynamic scheduler.
- Open access reduction pipelines for imaging data, via LINC and Rapthor.

The configurability of LOFAR is incredibly flexible in terms of the possible trade-offs between time and frequency resolution as well as sensitivity/bandwidth and field-of-view[1, 2]. Here we outline only some of the possibilities, to give an overall impression.

LOFAR2.0 imaging can reach 30 μJy/beam (HBA) and < 1 mJy/beam (LBA) sensitivity in 8-hr synthesis observations that use the full EU array, with corresponding angular resolution of $0.2''$ (HBA) and $0.5''$ (LBA) and corresponding field-of-view of ~ 12 deg^2. The standard imaging data products provide full Stokes parameters with 1-s integrations and 3-kHz channels, but higher time/frequency resolution is possible within the constraints of the total maximum output data rate from COBALT2.0. For example, visibilities with 10-ms integration time are achievable for up to a dozen stations, and sub-kHz channels can be synthesized given a longer integration time.

LOFAR beam-formed modes provide voltage tied-array beam data (with 5.12 μs and 195.3-kHz resolution) for up to a dozen beams, or up to hundreds of tied-array beams if the time/frequency resolution is downgraded and only Stokes I is stored. With COBALT2.0 the flexibility in forming sub-arrays and running in parallel to imaging observations is significantly increased. Standard tied-array observations combine either the 6 Superterp or 24 Core stations to provide 0.5° or $3'$ (FWHM) beams, respectively. In a 1-hr integration, a full-Core tied-array beam can reach an rms noise level of 0.1 mJy (HBA) and 1 mJy (LBA). Sub-arrays and 'fly's eye' mode allow one to also record multiple station subsets simultaneously; e.g., the full complement of international stations, each pointing in a different direction. With online re-digitization of the data to 8-bit samples, the field-of-view or time/frequency resolution can also be increased in general.

Additional technical details can also be found in the following tables and figures An overview of the LOFAR stations and antennas is given in Table 1. The LOFAR LBA and HBA sensitivities, for a variety of central frequencies, are quoted in Table 2.

Table 1
Overview of stations and antennas

Station Configurations	# of Stations	LBA dipoles	HBA tiles	Max. baseline (km)
Superterp	6	96	2×24	0.24
NL Core Stations	24	96	2×24	3.5
NL Remote Stations	14	96	48	121.0
International Stations	14(+2)	96	96	$\sim$ 2000

Two additional International stations are planned for construction in Italy and Bulgaria. The 6 stations comprising the central Superterp are a subset of the total 24 Core stations. Note that the tabulated baseline lengths represent unprojected values. Both the LBA dipoles and the HBA tiles are dual (linear) polarization.

Table 2
LOFAR sensitivities

Freq. (MHz)	λ (m)	Superterp (mJy)	Sensitivity NL Core (mJy)	Full NL (mJy)	Full EU (mJy)
15	20.0	...	...	...	...
30	10.0	36	9.0	5.7	3.8
45	6.67	29	7.4	4.7	3.1
60	5.00	25	6.2	3.9	2.6
75	4.00	44	10.8	6.8	4.5
120	2.50	1.5	0.38	0.30	0.20
150	2.00	1.3	0.31	0.24	0.16
180	1.67	1.5	0.38	0.30	0.20
200	1.50	(2.5)	(0.62)	(0.48)	(0.32)
210	1.43	(2.5)	(0.62)	(0.48)	(0.32)
240	1.25	(5.6)	(1.4)	(1.1)	(0.73)

The quoted sensitivities are for image noise calculated assuming 8 hours of integration and an effective bandwidth of 3.66 MHz (20 subbands). The sensitivities are based on the zenith SEFDs derived from 3C295 in the Galactic halo[1]. These values assume a factor of 1.3 loss in sensitivity due to time-variable station projection losses for a declination of 30 degrees, as well as a factor 1.5 to take into account losses for 'robust' weighting of the visibilities, as compared to natural weighting. Values for 15 MHz have not yet been determined awaiting a good station calibration. Similarly values at 200, 210, and 240 MHz should be viewed as preliminary and are expected to improve as the station calibration is improved. The procedure for determining these values along with associated caveats are discussed in more detail in van Haarlem et al. (2013)[1].

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