# Radioastronomy with Lofar

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Mots clés: LOFAR, radioastronomie basse fréquence
Keywords: LOFAR, low frequency radioastronomy

## Abstract

LOFAR is the first radiotelescope of a new generation, which can be described as "software telescopes". Observing between 10 and 250 MHz, the main complexity of LOFAR does not lie in the receivers (crossed, active dipoles), but in the hierarchical organisation of a large number of antennae (almost 50 000) and in the analysis of the incoming data in a large computing facility. Rather than mechanically steering the telescope, pointing occurs fully numerical, and all observations are pre-reduced on the fly to obtain a reasonable data volume. LOFAR will be 10 to 100 times more sensitive than the current instruments in the same frequency range. It will achieve sub-arcsecond resolution, which is 10 to 100 times better than the resolution of existing low-frequency instruments. It is also one of the most flexible instruments, making it interesting for a large number of scientific fields.

## Introduction

The International LOFAR Telescope (ILT) integrates all LOFAR radio astronomy resources (in the Netherlands and in the partner countries) with the aim of maximising the scientific return. LOFAR consists of a total of 48 stations, 40 of which are located in the Netherlands. Of these, 22 "core stations" form a dense core of approximately 2 km diameter in the province of Drenthe, the Netherlands, and 18 are "remote" stations with distances of up to approximately 100 km relative to the core. The remaining 8 stations are "international stations". 5 of them are located in Germany (in Effelsberg, Tautenburg, Garching-Unterweilenbach, Potsdam-Bornim, and Jülich), one is located in the UK (at Chilbolton), one in Sweden (Onsala), and one in France (Nançay), at a distance of 700 km from the LOFAR core. A few more international stations might become available shortly, depending on funding decisions in different countries.
The international stations play an important role: Not only do they increase the total effective area of the telescope, allowing for more sensitive observations of faint objects, but they also provide the long baselines which are required to resolve small sources. The addition of these long baselines to the LOFAR telescope improves the angular resolution by one order of magnitude, giving access to sub-arcsecond resolution in the metric radio domain (Section 1.4).
Each station is connected to the Center for Information Technology of the University of Groningen via a fibre network with a datarate >3 GBit/s. With all 48 stations, the BlueGene/P supercomputer receives close to 150 Gbit of data every second. This data flow has to be calibrated, reduced, and analysed in real time.

LOFAR will allow both imaging as well as spectral studies, and records two linear polarisations, from which all Stokes parameters can be constructed. With its capacity of multi-frequency and wide-field multi-beam observations (Section 1.1), with its high time-and-frequency resolution (Section 1.3), its high angular resolution (Section 1.4) and its high sensitivity (Section 1.5), LOFAR will be the first versatile general purpose low-frequency radiotelescope, making it interesting for a large number of scientific fields (Section 2).

## 1. Parameters

### 1.1. Multibeam observations

The connection of every LOFAR station via a >3 GBit/s fibre network link allows to continuously stream 244 subbands of 195.3125 kHz bandwidth from every LOFAR station. These subbands can be freely selected within the boundaries of the observation mode selected (see section 1.2), and they can each be pointed independently at a different position in the sky. This allows to monitor a relatively large fraction of the sky if required. If all subbands are selected to be adjacent to each other, this amounts to ~48 MHz bandwidth per station.

### 1.2. Observable frequency range

LOFAR observes in the frequency range 15-250 MHz. To cover such a large frequency range, two different types of antennae are used, the Low Band Antennae (LBA, optimized for 15 MHz-80 MHz) and the High Band Antennae (HBA, optimized for 120 MHz-240 MHz). This leaves a gap between 80 MHz-110 MHz, the FM band, which is difficult to exploit scientifically. A LOFAR station can be set to either use the LBA or the HBA, but not both simultaneously (however, it is possible to use a subset of the LOFAR stations in HBA mode while the other stations are using the LBAs, and vice versa). Also, observations have to avoid the sampling frequency of the clock. As the clock can be set to a sampling frequency of either 160 MHz or a 200 MHz, each single LOFAR station can be operated in any of the following observation modes:

- 10-90 MHz (LBA, 200 MHz clock)
- 10-70 MHz (LBA, 160 MHz clock)
- 30-90 MHz (LBA, 200 MHz clock, with a highpass filter at 30 MHz)
- 30-70 MHz (LBA, 160 MHz clock, with a highpass filter at 30 MHz)
- 110-190 MHz (HBA, 200 MHz clock)
- 170-230 MHz (HBA, 160 MHz clock)
- 210-250 MHz (HBA, 200 MHz clock)

Additional flexibility can be gained by setting different LOFAR stations in different observation modes (either creating several sub-arrays or using the data from the stations individually). This is useful when a wide spectral coverage is required, and will be used, e.g. for solar observations.

### 1.3. Time and frequency resolution

Although data are sampled at either 200 MHz or 160 MHz (resulting in a native time resolution of 5 ns and 6.25 ns, respectively), these data are usually not exploited (but snapshots of approximately one second of data with this resolution can be obtained via the Transient Buffer Boards). Rather, the data are passed through a polyphase filter, which generates so-called subbands of width 195.3125 kHz at a time resolution of 5.12 μs (or subbands of width 156.250 kHz at a time resolution of 6.4 1μs for the 160 MHz clock).
In a second step, the subbands can be further subdivided into $2^n$ channels, with n between 0 and 12. Typically, n=8 is used. During this operation, the time resolution element increases at the same rate as the frequency resolution element decreases. The typical frequency resolution obtained in this way (i.e. for n=8) is 763 Hz at a time resolution of 1.3 ms (or 610 Hz at a time resolution of 1.6 ms for the 160 Mhz clock). The optimal choice of n depends strongly on the scientific case, as different astronomical objects are variable sources on timescales ranging from ns to Myr (see Section 2 for examples).

### 1.4. Angular resolution

The angular resolution *R* of LOFAR is given by [6]

$$R = \alpha * \lambda / L. \quad (1)$$

The value of $\alpha$ depends on the array configuration and the weighting scheme that is used during imaging. For illustrative porposes, we will use $\alpha = 0.8$ (the value used for the WSRT with standard tapering). L denotes the longest baseline. Table 1 gives the resolution of LOFAR for three different maximum baselines. L=2 km corresponds to the LOFAR core (combination of the 22 core stations only). L=80 km corresponds to the conbination of all Dutch LOFAR stations. L=700 km is achieved by combining all stations of the ILT, including the international stations. It can be seen that the inclusion of the international stations increases the angular resolution by a factor of 10.

| *frequency* | $\lambda$ | *R (for L=2 km)* | *R (for L=80 km)* | *R (for L=700 km)* |
|---|---|---|---|---|
| [MHz] | [m] | [arcsec] | [arcsec] | [arcsec] |
| 15 | 20.00 | 1650 | 41.3 | 4.71 |
| 30 | 10.00 | 825 | 20.6 | 2.36 |
| 45 | 6.67 | 550 | 13.8 | 1.57 |
| 60 | 5.00 | 413 | 10.3 | 1.18 |
| 75 | 4.00 | 330 | 8.25 | 0.94 |
| 120 | 2.50 | 206 | 5.16 | 0.59 |
| 150 | 2.00 | 165 | 4.13 | 0.47 |
| 180 | 1.67 | 138 | 3.44 | 0.39 |
| 210 | 1.43 | 118 | 2.95 | 0.34 |
| 240 | 1.25 | 103 | 2.58 | 0.29 |

***Table 1:*** *Maximum resolution achievable for different maximum baselines.*

### 1.5. Sensitivity

The single polarisation System Equivalent Flux Density (SEFD) $S_{sys}$ of a single LOFAR station is determined by the telescope's efficiency, the system noise temperature, and its collecting area. Once this value is known, the (single station) sensitivity of a given observation $\Delta S$ can be calculated as follows:

$$\Delta S = S_{sys} / \mathrm{sqrt}(2\delta\nu\delta\tau) \quad (2)$$

where $\delta\nu$ is the frequency bandwidth and $\delta\tau$ is the integration time of the observation. Table 2 contains the values of $S_{sys}$ for the three different types of LOFAR stations: Dutch Core stations, Dutch Remote stations (which differ only for the HBA), and International stations (which have twice as many antenna elements in both LBA and HBA). It can be seen that the LBAs are most sensitive at 60 MHz and the HBAs are most sensitive at 150 MHz. For an observation with known bandwidth and integration time, it is possible to calculate the sensitivity using Table 2 and Eq. (2). Conversely, this can also be used to calculate the integration time required to reach a specified sensitivity limit.

| *frequency* | $\lambda$ | $\Delta S_{NL\text{-}Core\text{-}station}$ | $\Delta S_{NL\text{-}Remote\text{-}station}$ | $\Delta S_{INTL\text{-}station}$ |
|---|---|---|---|---|
| [MHz] | [m] | kJy | kJy | kJy |
| 15 | 20.00 | 483 | 483 | 519 |
| 30 | 10.00 | 89 | 89 | 41 |
| 45 | 6.67 | 48 | 48 | 19 |
| 60 | 5.00 | 32 | 32 | 15 |
| 75 | 4.00 | 51 | 51 | 25 |
| 120 | 2.50 | 3.6 | 1.8 | 0.89 |
| 150 | 2.00 | 2.8 | 1.4 | 0.71 |
| 180 | 1.67 | 3.2 | 1.6 | 0.81 |
| 210 | 1.43 | 3.7 | 1.8 | 0.92 |
| 240 | 1.25 | 4.1 | 2.0 | 1.0 |

***Table 2:*** *Single polarisation System Equivalent Flux Density (SEFD) $S_{sys}$ for single LOFAR stations [6, 10]. Three different types of LOFAR stations are shown, see text.,*

## 2. The Key Science Projects

It has already been mentioned that LOFAR is a highly versatile multi-purpose instrument. This is also reflected by the number and by the broad range of scientific fields that have already identified interesting applications of LOFAR. The main science cases of LOFAR, denoted as « Key Science Projects », are the following:

1. **Observation of the Epoch of Reionisation (EoR):** After the dense and hot early phase which is today reflected in the Cosmic Microwave Background (CMB), the Universe went through a cold and neutral phase (the "dark ages"). A few hundred million years later, the first stars and quasars started to form. This period, in which the Universe went from completely neutral to mostly ionised, is called the Epoch or Reionisation (EoR). The EoR project will measure the fraction of neutral hydrogen in the Universe as a function of redshift (cosmological age) through the hydrogen hyperfine spin-flip 21 cm line. This emission allows to trace structure formation in the early universe, which will pose important constraints on cosmological models. Despite its importance for cosmological models, the EoR has not yet been observed, and the detection of the signature of the EoR is one of LOFAR's main objectives.
2. An important goal of LOFAR is to explore the low-frequency radio sky through a series of **large-scale surveys**. Low-frequency radio telescopes, and LOFAR in particular, are ideally suited for large-scale surveys, because of their large instantaneous fields of view. The large field of view also means that traditional approaches for calibration are no longer sufficient [e.g. 9]. Three large surveys which will contribute to fundamental questions of astrophysics are planned: Formation of massive galaxies, clusters and black holes using $z \geq 6$ radio galaxies as probes, Intercluster magnetic fields using diffuse radio emission in galaxy clusters as probes, Star formation processes in the early Universe using starburst galaxies as probes.
3. While many radioastronomical observations look at a source with a constant flux, there is a large number of **transient and variable sources**. Exploding stellar giants, accreting supermassive black holes and rapidly rotating superdense neutron stars can all release huge amounts of energy into their surrounding environments on very short timescales. Such events and phenomena usually have associated radio emission, so by observing in the radio band one can understand where and how often such events occur, and gauge their combined impact on the ambient environment. On a smaller scale, radio observations of flare stars and of radioemission from planets teach us about the local environment of these objects. Finally, with its wide field of view and its multibeam-capacity, LOFAR is also very well adapted to search for currently unknown transient radio sources. LOFAR will be the first instrument to monitor a large fraction of the sky on a regular basis. This "Radio Sky Monitor" will allow for an accurate census of transient and variable sources. Many objects discovered in this way will lead to follow-up observations, either by LOFAR itself, or by other instruments.
4. **The study of magnetic fields in the Universe:** Magnetic fields are present in many places in the Universe. They play an important role for the evolution of galaxies and galaxy clusters, contribute to the total pressure of interstellar gas, they are essential for star formation, and they control the density and distribution of cosmic rays in the interstellar medium. They are, however, not easily observable, and thus the origin, evolution, and structure of magnetic fields are still not understood. Low frequency radioastronomy offers unique tools to measure not only the field strength, but also its orientation. First, synchrotron emission (which contains information on the magnetic field orientation in the plane of the sky) is usually most intense at low frequencies. Also, synchrotron sources are more extended at low frequencies; this is caused by the longer lifetime of charged particles with low energy, whereas the more energetic particles visible at higher frequencies lose their energy already after a short distance. The second important tool to measure cosmic magnetic fields is the effect of Faraday rotation, which is proportional to the magnetic field along the line of sight. Because Faraday rotation is also proportional to the inverse square of the observation frequency, weak fields can only be measured at low frequencies. LOFAR will thus open a new window to study cosmic magnetic fields.
5. **The study of the Sun and its influence on Space Weather:** The sun has long been known as a radio source, and once even served to define a relative flux scale (the Solar Flux Unit). The solar radio emission consists of a number of different contributions, of which only the quiet sun background is relatively constant. Sporadic and violent radio bursts are connected to flares, Coronal Mass Ejections (CMEs) and accelerated particles. The study of the spatial and spectral variations of this emission can be used to study these processes. Flares and CMEs can also influence Earth and the terrestrial environment. In some cases, such Space Weather effects can lead to disturbances of our technical civilisation: Flares are accompanied with an enhanced emission of X-rays and enhanced fluxes of energetic particles, while CMEs also produce highly energetic particles and cause geomagnetic storms if they impact on Earth's magnetosphere. LOFAR offers a combination of high spatial and spectral resolution, which makes it ideally suited for radio observations and monitoring of the solar upper corona.
6. **The study of ultra-high energy cosmic rays:** When cosmic ray particles of sufficiently high energy penetrate into the Earth's atmosphere, they generate a shower of secondary particles. These particles create an intense, but extremely brief radio pulse, which can be detected by LOFAR. This allows to study the origin of high-energy and ultra-high-energy cosmic rays (HECRs and UHECRs) at energies between $10^{15}$ and $10^{20.5}$ eV, which is currently not well understood.

In addition to the observations planned by the Key Science Projects, additional observation proposals are welcome, and some have already been submitted during the last call for proposals. A new call for proposals is under preparation. All observing proposals will be evaluated by the LOFAR Time Allocation Committee. The "open-skies" fraction of the total observing time is going to increase over time, starting at 10%, and will reach over 50% within 4-5 years.

## 3. Current Status

The construction and rollout of LOFAR are almost terminated. Observations have begun, and the telescope was inaugurated in June 2010. At the same time, software development is ongoing. The different observation modes are gradually made available, and the data format to be used by LOFAR are being defined. Different data formats are going to be used for different cases, including Radio Sky Images, Transient Time Series data, Beam-Formed data, Dynamic Spectra, UV Visibility, Rotation Measure Synthesis, Near-field Imaging [1, 5]. Even though the ILT instrument is still in its commissionning phase (which will continue through 2011), first scientific observations have already been performed, and scientific publications of first results are in preparation [e.g. 7].

## 4. LOFAR in France

### 4.1. Scientific interest

Since the start of the LOFAR project, French scientists have been interested in this instrument. At a meeting in Meudon in 2006, a large number of astronomical fields were represented, ranging from planetology to cosmology, and not all participants were specialists in radioastronomy. Shortly thereafter, the newly formed FLOW consortium wrote a science case for a French participation in LOFAR [8], which allowed to structure the French community and eventually led to the installation of a LOFAR station in Nançay. French scientists are represented in almost all KSPs, and they participate actively in the first observations which allow to commission the instrument.

### 4.2. A French LOFAR station at Nançay

The French LOFAR station, FR606, was installed in 2009/2010. After first tests and validation, the station was officially accepted on 30.11.2010. It has been tested and used both as a stand alone instrument as well as part of the ILT.

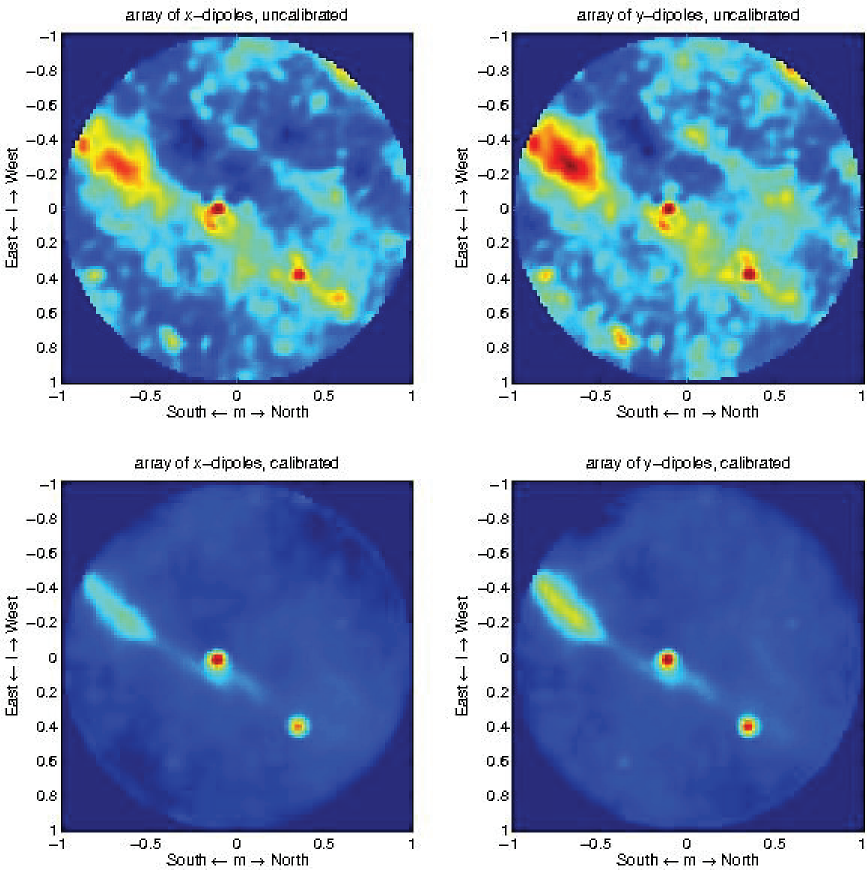


Figure 1 shows the first sky image obtained with LOFAR station FR606. The observation was taken at a frequency of 60 MHz, with a bandwidth of only 195.3125 kHz (1 subband). The integration time was 20 seconds. The comparison of the upper (uncalibrated) and lower panels (calibrated) also shows that good calibration is essential. The calibration scheme is described in [11]. Three radiosources are clearly visible:

- The milky way (upper left).
- The bright radiogalaxy Cygnus A (middle).
- The supernova remnant Cassiopeia A (lower right). Cas A is one of the brightest radiosources in the sky.

***Figure 1:*** *The first full sky observation using the Nançay LOFAR station (29 November 2010). The observation was taken at a frequency of 60 MHz with a bandwidth of 195.3125 kHz, and with an integration time of 20 seconds. Left panels: x-dipoles. Right panels: y-dipoles. Upper panels: uncalibrated images. Lower panels: calibrated images.*

### 4.3. The French Superstation project (LSS)

The Nançay radio astronomy observatory and associated laboratories are also working on the concept of a LOFAR "Super Station" (LSS). The idea is to extend the French LOFAR station at Nançay by adding a third type of antennae in addition to the existing LBA and HBA fields. Each of these new antennas will consist of an analog-phased mini-phased-array of 10–20 antennas, thus increasing the sensitivity of the LOFAR station by at least one order of magnitude for a moderate cost. In addition to the increased sensitivity, the LSS will increase the number of high sensitivity long baselines, provide short baselines and a second core (useful when the primary core is occupied with a project requiring only short baselines, e.g. EoR observations). It will also give access to frequencies below those of the standard LBAs, and will represent a large standalone instrument (with a somewhat reduced field of view when compared to the existing international station). Currently, the LSS is in the prototype study phase, with the aim to present a detailed concept by the end of 2011. The LSS project and first design studies are described in more detail in [2,3]. A full science case for the LSS is in preparation [12], and contributions are welcome.

## 5. Conclusions

While LOFAR is still being commissioned, it is already clear that it has a huge potential for a large number of fields within astronomy. It is an extremely versatile and flexible instrument, allowing for a large number of choices by the user. Both its spatial resolution and its sensitivity will surpass those of existing instruments by one to two orders of magnitude. Current information about LOFAR can be found at www.astron.nl and at www.lofar.org. Information on the French LOFAR station and on French LOFAR activities can be obtained at http://www.obs-nancay.fr/lofar/.

**Acknowledgments**

LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy.

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