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The next generation radiotelescopes / Les radiotélescopes du futur

Radioastronomy with LOFAR

La radioastronomie avec LOFAR

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ABSTRACT

LOFAR is the first radiotelescope of a new generation, which can be described as "software telescopes". Observing between 15 and 240 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 numerically, and all observations are pre-processed 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.

RÉSUMÉ

LOFAR est le premier radiotélescope d'une nouvelle génération d'instruments dit « télescopes numériques ». Observant entre 15 et 240 MHz, la complexité de LOFAR ne repose pas dans les capteurs (dipôles croisés), mais dans l'organisation hiérarchique d'un grand nombre d'antennes (près de 50 000) et du traitement des données dans un grand centre de calcul. Le pointage est entièrement numérique, et toutes les observations sont pré-traitées en direct pour parvenir à un débit gérable. LOFAR aura une sensibilité 10 à 100 fois supérieure à celle des instruments existants dans cette gamme de fréquences. Sa résolution angulaire sera proche d'une seconde d'arc, 10 à 100 fois plus élevée que la résolution disponible jusqu'à maintenant. LOFAR est également l'un des instruments les plus flexibles, ce qui le rend intéressant pour un grand nombre de domaines scientifiques.

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1. Introduction

As the name indicates, LOFAR (the **Lo**w **F**requency **Ar**ray) was conceived and built with the aim to study the low frequency radio domain. For this, a distributed approach was chosen: The **I**nternational **L**OFAR **T**elescope (ILT) 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 these are located in Germany, one is located in the UK, one in Sweden and one in France (Nançay, see Section 4), 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 long baselines, and improve the angular resolution by one order of magnitude, thus giving access to sub-arcsecond resolution in the metric radio domain (Section 2.3).

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/s of data. This data flow has to be calibrated, reduced, and analysed in real time.

LOFAR will allow imaging as well as spectral studies, and record two linear polarisations from which all Stokes parameters can be constructed. With its capacity of multi-frequency and wide-field multi-beam observations (Section 2.1), with its high time-and-frequency resolution (Section 2.2), its high angular resolution and its high sensitivity (Section 2.3), LOFAR will be the first general purpose low-frequency radiotelescope, making it interesting for a large number of scientific fields (Section 3). The current status of LOFAR in general and the situation of LOFAR in France are described in Section 4, and Section 5 closes with a few concluding remarks.

2. Parameters

2.1. Multibeam observations and observable frequency range

The connection of every LOFAR station via a 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, 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 all subbands are selected to be adjacent to each other in frequency, this amounts to a bandwidth of 48 MHz per station.

LOFAR can observe in the frequency range 15–240 MHz. To cover such a large frequency range, two different types of antennae are used, the Low Band Antennae (LBA, optimised for 30–80 MHz) and the High Band Antennae (HBA, optimised for 110–240 MHz). This leaves a gap between 80 and 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 different frequency ranges can be selected for different stations when a wide spectral coverage is required (e.g. for solar observations).

2.2. 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 (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 µs 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. 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. The optimal choice of n strongly depends on the scientific case.

2.3. Angular resolution and sensitivity

The angular resolution R of LOFAR is given as $R = \alpha\lambda/L$ [1]. The value of α depends on the array configuration and the weighting scheme that is used during imaging. For illustrative purposes, we will use $\alpha = 0.8$, the value used for the WSRT (the **W**esterbork **S**ynthesis **R**adio **T**elescope) 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). $L = 80$ km corresponds to the combination 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 adding the international stations increases the angular resolution by a factor of 10.

Table 1
Columns 3–5: Maximum resolution achievable for different maximum baselines. Column 6: Single polarisation System Equivalent Flux Density (SEFD) for a single LOFAR remote station [1–3].

Frequency [MHz]	λ [m]	R (for $L = 2$ km) [arcsec]	R (for $L = 80$ km) [arcsec]	R (for $L = 700$ km) [arcsec]	SEFD (remote station) [kJy]
15	20.00	1650	41.3	4.71	483
30	10.00	825	20.6	2.36	89
45	6.67	550	13.8	1.57	48
60	5.00	413	10.3	1.18	32
75	4.00	330	8.25	0.94	51
120	2.50	206	5.16	0.59	1.8
150	2.00	165	4.13	0.47	1.4
180	1.67	138	3.44	0.39	1.6
210	1.43	118	2.95	0.34	1.8
240	1.25	103	2.58	0.29	2.0

The single polarisation System Equivalent Flux Density (SEFD) of a single LOFAR station is determined by the telescope's efficiency, the system noise temperature, and its collecting area. From the SEFD, the sensitivity can be calculated using the bandwidth of the observation and the integration time. Conversely, the SEFD can also be used to calculate the integration time required to reach a specified sensitivity limit. Table 1 contains the values of the SEFD for one of the 18 Dutch remote stations. As mentioned above, LOFAR uses three types of stations. An international station (such as FR606, see Section 4) has twice as many antenna elements, and thus is approximately twice as sensitive. Thus, for an international station, the value of the SEFD is divided by a factor 2 (except at the lower end of the frequency range of the LBAs, where the effective areas of the individual dipoles partially overlap). Table 1 also shows that the LBAs are most sensitive at 60 MHz and the HBAs are most sensitive at 150 MHz.

3. The Key Science Projects

The fact that LOFAR is a highly versatile multi-purpose instrument is reflected by the number and by the broad range of scientific fields that have identified interesting applications of LOFAR. The main science cases of LOFAR, denoted as "Key Science Projects", are the following:

(i) 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 formed. This period, in which the Universe went from completely neutral to mostly ionised, is called the **Epoch of 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.

(ii) An important goal of LOFAR is to explore the low-frequency radio sky through a series of **large-scale surveys**, making use of LOFAR's large instantaneous field of view. The large field of view also means that traditional approaches for calibration are no longer sufficient [4]. Three large surveys which will contribute to fundamental questions of astrophysics are planned: (1) formation of massive galaxies, clusters and black holes using radiogalaxies with $z \geqslant 6$ as probes; (2) intercluster magnetic fields using diffuse radio emission in galaxy clusters as probes; (3) star formation processes in the early Universe using starburst galaxies as probes.

(iii) While many radioastronomical observations look at sources 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 radio emission from planets teach us about the local environment of these objects. LOFAR is also very well adapted to search for currently unknown transient radio sources, and the so-called "Radio Sky Monitor" will allow for an accurate census of transient and variable sources.

(iv) **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 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 the field strength and its orientation. First, synchrotron emission (containing 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 (the lifetime of low energy charged particles is longer). The second tool is the effect of Faraday rotation, which is proportional to the magnetic field along the line of sight. Faraday rotation is also proportional to the inverse square of the observation frequency, so that weak fields can only be measured at low frequencies.

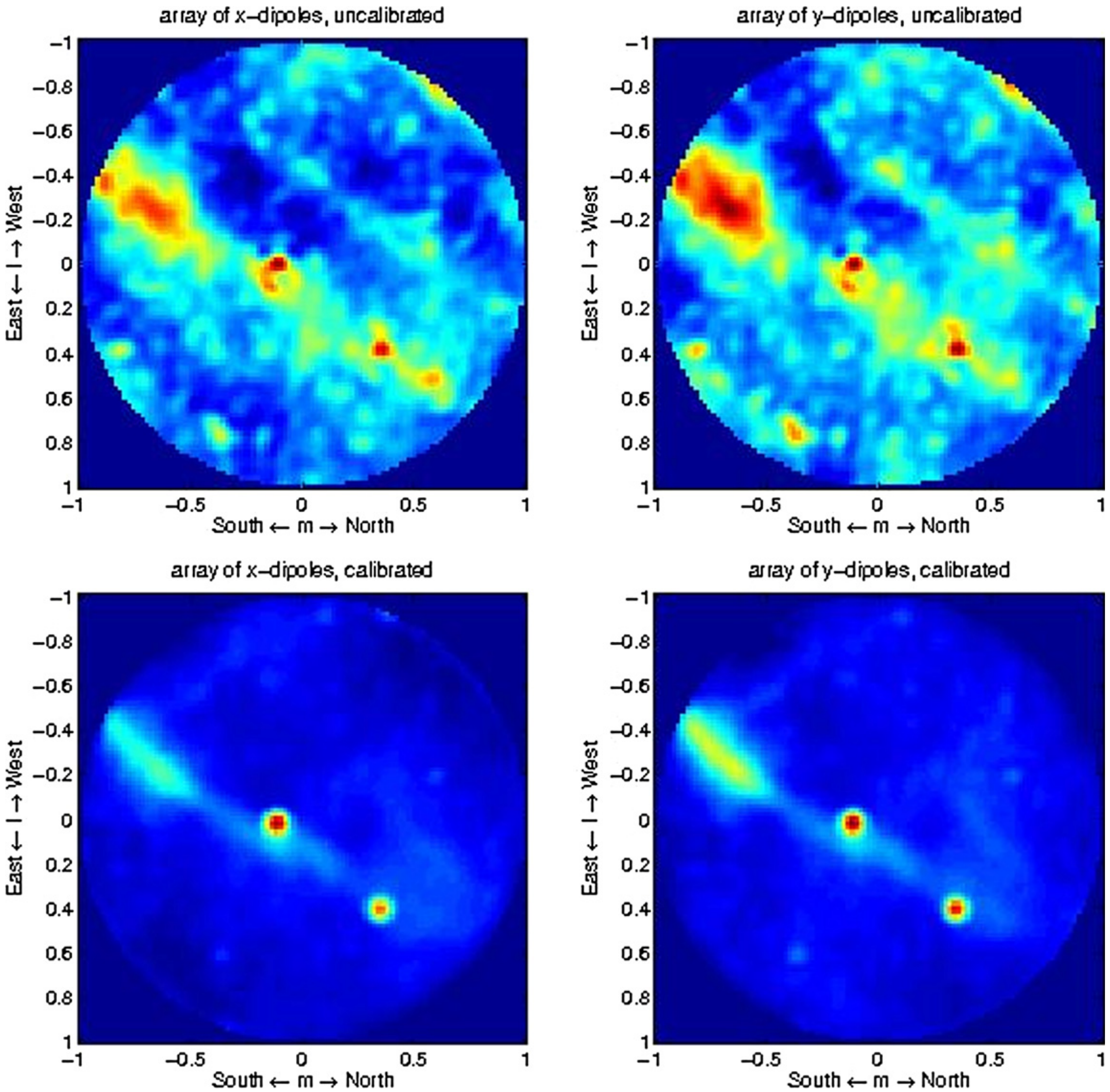

Fig. 1. The first full sky observation using the Nançay LOFAR station (29 November 2010). The observation was taken at a frequency of 60 MHz with a bandwidth of 195.3125 kHz, and with an integration time of 20 s. Axes: (l, m) are directional cosines such that positive l is pointing East and positive m is pointing North. Left panels: x-dipoles. Right panels: y-dipoles. Upper panels: uncalibrated images. Lower panels: calibrated images.

(v) The study of **the Sun and its influence on Space Weather**. The solar radio emission consists of a number of different contributions. 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 can produce highly energetic particles and cause geomagnetic storms. LOFAR offers a combination of high spatial and spectral resolution, which makes it well suited for radio observations and monitoring of the solar upper corona.

(vi) When high energy cosmic ray particles 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 currently unknown origin of **high-energy and ultra-high-energy cosmic rays** (i.e. with energies between 10^{15} and $10^{20.5}$ eV).

In addition to the observations planned by the Key Science Projects, additional observation proposals are welcome, and some have already been submitted. 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.

4. Current status & LOFAR in France

The construction of LOFAR is almost terminated. Observations have begun, and the telescope has been inaugurated in June 2010. At the same time, software development is ongoing. The different observation modes are gradually made available, and the data formats to be used by LOFAR are being defined. Even though LOFAR is still in its commissioning phase (which will continue through 2011), scientific observations are ongoing, and first results have already been published, see e.g. [5].

The French LOFAR station, FR606, was installed in 2009/2010. After first tests and validation, the station was officially accepted on 30.11.2010 and inaugurated on 20.5.2011. It has been tested and used both as a stand alone instrument as well as part of the ILT. Fig. 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 s. As for the axes, $l = \cos(el)\sin(az)$, and $m = \cos(el)\cos(az)$. The comparison of the upper (uncalibrated) and lower panels (calibrated) shows that good calibration is essential. The calibration scheme is described in [6]. Three radio sources are clearly visible: The Milky Way in the upper left part, the bright radiogalaxy Cygnus A in the middle and the supernova remnant Cassiopeia A on the lower right. Considering that the instantaneous bandwidth can be chosen up to 244 times larger and that (depending on the scientific objective) much larger integration times can be used, Fig. 1 just gives a first hint at the capabilities of even a single LOFAR station. Images with the full array (48 stations, and with baselines four orders of magnitude larger than within one station) will surpass everything done in this frequency range to date.

The Nançay radioastronomy observatory and associated laboratories are also working on the concept of a LOFAR "Super Station" (LSS). The LSS project and first design studies are described in [7,8].

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/.

Acknowledgements

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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