

LOFAR: THE LOW FREQUENCY ARRAY

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ABSTRACT

LOFAR is a major new instrument being developed for astronomical research in the 10-240 MHz frequency range. It features a large collecting area distributed over a physical extent of 400 km, promising a 100-fold improvement in both angular resolution and sensitivity compared to current instruments. To realize this potential, ionospheric signal propagation effects must be accurately measured and removed. LOFAR builds on powerful self-calibration techniques developed for radio astronomy, whose byproduct is information about the plasma above the array at an extraordinary level of detail. This presentation describes LOFAR, with particular emphasis on its potential for ionospheric measurements.

INTRODUCTION

The LOFAR project is a collaboration between the ASTRON institute in Dwingeloo, Netherlands, the Naval Research Lab Remote Sensing Division in Washington DC, and the Massachusetts Institute of Technology. The principal motivation is to exploit the opportunity, offered by modern signal transport and processing technologies, to dramatically improve the resolution and sensitivity of radio astronomy in the 10-240 MHz frequency range, with the expectation of accompanying scientific breakthroughs.

Although radio astronomy began at low frequencies, and the construction of large physical collecting areas is easy and cheap at meter wavelengths and longer, this waveband has remained largely unexplored. The principal reasons for this are the need for long baselines to achieve useful angular resolutions, and the severe signal distortions introduced by propagation through the ionosphere, which destroy interferometric coherence on all but the shortest baselines. Combined with the deleterious effects of astronomical source confusion at multi-arcminute resolutions, radio astronomy at 200 MHz and below has been shackled both by poor resolution and poor sensitivity. In recent years, vastly improved computational resources combined with the development of improved algorithms for ionospheric compensation have started to open up the low frequency regime to improved performance. The Very Large Array (VLA) in New Mexico has been equipped with 74MHz receiving systems, and routine utilization of baselines up to 35km is now possible.

The VLA, however, is far from an ideal platform for low frequency radio astronomy. The 25-meter dishes are inefficient at 4-meter wavelength, and yield poor performance. Calibration strategies, of paramount importance in this work, are hampered by low SNR. Achievable dynamic ranges are relatively low. Also, the antennas must be mechanically pointed, which is slow and cumbersome. The LOFAR concept, by contrast, is based on large numbers of fixed dipole receptors, each of which sees most of the sky above the horizon. The antennas are grouped into stations, each of which is equipped with an electronic beamforming system capable of placing multiple simultaneous full-sensitivity beams at widely separated positions on the sky. These beams are highly agile in both pointing and frequency, and each station is sufficiently sensitive that sophisticated calibration algorithms can be employed, using astronomical radio sources themselves as beacons. By early digitization of signals from each individual antenna, not only does LOFAR retain maximum data processing flexibility, it also benefits to the fullest possible extent from rapid commercially driven advances in digital hardware and accompanying software.

The signal propagation delay caused by the ionosphere above LOFAR is proportional to the square of the wavelength. These delays must be measured to a precision corresponding to a small fraction of a degree of interferometric phase, in many different directions simultaneously, for of order 100 separate stations spread out over a 400km region. Therefore, in order to calibrate LOFAR, we must characterize the ionosphere above the array with a precision and spatial resolution far beyond anything available today. LOFAR is being designed specifically to be able to achieve this calibration accuracy, using distant astronomical radio sources as calibration beacons. The end result will be a 3-dimensional tomographic movie of the ionosphere with a time resolution of a few seconds.

In addition to this calibration system byproduct, LOFAR will be a powerful standalone ionospheric and space weather observatory. Measurement of CMEs via interplanetary scintillation, and ionospheric research using the passive radar technique, both promise to be revolutionized by LOFAR.

DESCRIPTION OF LOFAR

In order to cover the full 10-240 MHz frequency range, LOFAR will employ at least two different antenna systems, one covering 10-90 MHz, below the FM band, and one for 110-240 MHz, above the FM band. Fixed crossed dipoles with active impedance-matching circuitry will be used, in order to achieve useful performance at wavelengths for which the dipoles will be electrically short. This approach is attractive for LOFAR due to the properties of diffuse radio emission from the Milky Way galaxy. Despite the effective increase in receiver noise temperature caused by the poor response of a short dipole, sky noise remains the dominant contribution to the overall system temperature across the entire frequency range, and effective noise performance from the short dipoles is thus indistinguishable from that obtainable from a resonant dipole. However, (depending on certain definitions) the effective collecting area of the dipoles goes as λ^2 , which results in unacceptably low sensitivity above the FM band. Therefore, a second antenna system is being designed, based on a 4x4 grid of fat dipoles, with an integrated beamformer, in order to boost effective collecting area by at least an order of magnitude above 110 MHz.

The baseline design calls for 13,000 antennas of each type, organized into ~100 “stations”, each of roughly 150 meters diameter. Signals from the ~130 antennas in each station are combined in digital beamformer, and the station output data streams are then cross-correlated in a special-purpose central processing facility to generate ~5000 baselines, resulting in a dataset suitable for processing into an image. Amplified analog signals from each antenna are mixed and filtered to produce a 32 MHz baseband, which is immediately digitized, with 14 bits of dynamic range in order to accommodate strong RFI signals while retaining astronomical information in the low-order bits. The data streams are transformed into the frequency domain, where additional filtering and initial spectral RFI excision is performed.

The station beamformer receives signals from each of ~130 antennas, which contain information from the full field of view of each antenna. In the case of the low frequency antennas, this consists of the entire sky above roughly 30 degrees elevation, while for the high frequency 4x4 antenna arrays, it consists of a roughly 20 degree beam which can be electronically steered anywhere on the sky down to 30 degrees elevation. Within these antenna system fields of view, the station beamformer generates up to 8 independent phased-array beams, of angular size ranging from roughly 1-10 degrees. Adaptive nulling algorithms implemented within the beamforming system provide a second layer of RFI mitigation, which is expected to be effective against stationary or slowly moving sources of RFI. The fully digital implementation of beamforming, combined with the almost omnidirectional antenna systems, gives LOFAR a unique and powerful ability to look in many directions at once, with full sensitivity, and to react swiftly to changing circumstances.



Figure 1. Artists impression of a single LOFAR station in a generic landscape. Note that only the low frequency antenna systems are shown

The stations are distributed over ~400km, in a configuration optimized for astronomical imaging. This leads to a centrally condensed layout, with 75% of the collecting area within a 75km diameter, and 25% within a 2km diameter. For stations outside the 2km central “core” region, data streams for each of up to 8 beams are transmitted via high bandwidth fiber to the central processing facility for correlation. Within the central core, all antenna signals are

transported to the central facility, at an aggregate data rate of ~6 Tbit/sec, yielding options for a variety of special processing steps which treat the inner array as an independent entity.

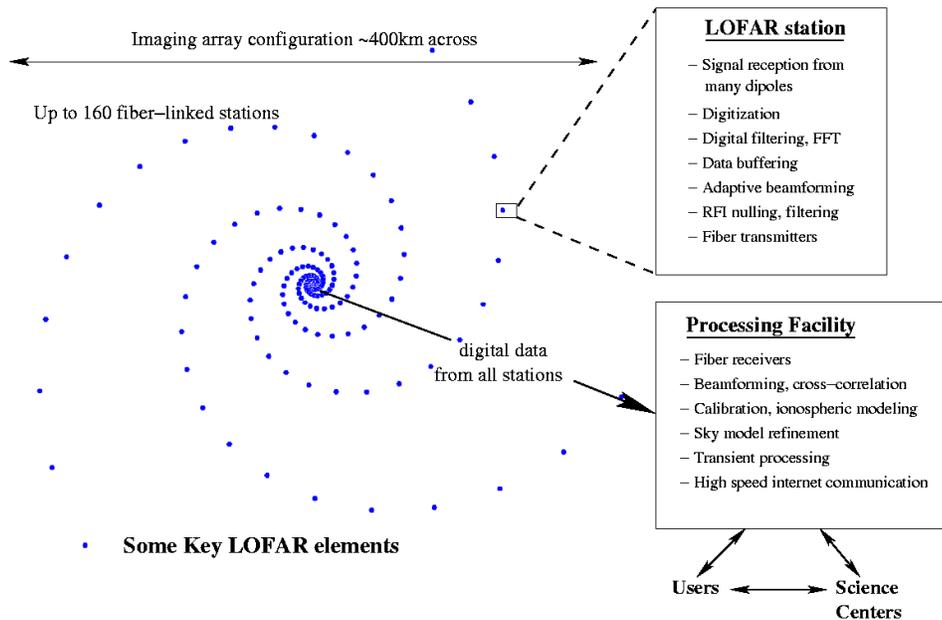


Figure 2. Major functional elements of LOFAR

Correlations between stations, for each beam, are performed at the central facility, and a complex and sophisticated calibration system removes the worst effects of ionospheric and station performance fluctuations in real time. The primary goal of the online calibration system is to permit time and frequency averaging of the data, to reduce data rates to manageable levels without significant degradation of the final image fidelity. More details of the calibration system, which lies at the heart of LOFAR, are given in the next section. LOFAR also features remote operation with complete control of all main functions across the internet. Figure 2 illustrates some of the main components of LOFAR.

CALIBRATION SCHEME

In the late 1970's, a radio astronomical technique known as self-calibration was developed. This technique makes use of the fact that radio interferometer arrays generate many more independent measurements, on baselines, than the number of calibration parameters required for the array. This is because the number of baselines is $N(N-1)/2$, while the number of calibration parameters is generally only a few times N , where N is the number of stations in the array. A complication is that the sky brightness distribution is unknown, and must be simultaneously solved for. However, iterative schemes were developed with good convergence properties, and self-calibration is currently the gold standard in modern astronomical radio interferometry. The fundamental requirement is that one or more sources be present within the field of view, such that a SNR of several is achieved on each baseline, within the characteristic timescale for station-based gain or delay fluctuations.

For LOFAR, the situation is more complex. The amplitude and size scale of ionospheric irregularities is such that at low frequencies, a single ionospheric delay per station is no longer adequate for precision calibration. Instead, many separate delays are needed, for many different directions within the station beam. In addition, gain fluctuations and other influences at individual antennas lead to short-term variability in the shape of the station beam. Other effects peculiar to low frequencies further complicate the self-calibration technique. These problems are soluble, using a more sophisticated implementation of self-calibration (referred to within the LOFAR project as generalized selfcal). However, these algorithms require more information to work with than is typically available at shorter wavelengths. Each field of view must contain at least 20 astronomical sources of sufficient brightness, and extensive prior knowledge of the sky is required, in the form of a global sky model (GSM).

The most difficult circumstance to arrange is sufficient SNR on at least 20 sources within a beam that is only 1-10 degrees across. This has led to a scheme in which the inner core of the array, comprising 25% of the total collecting

area, is phased up to form a single “super-station” with much higher sensitivity, and a much narrower beam. By cross-correlating central core beams with stations from the outer regions of the array, not only is SNR improved on target sources, but the narrow beam effectively isolates individual sources, instead of seeing several at once, thus greatly simplifying the task of solving for ionospheric delay and station gain in the source direction. This so-called “station-core selfcal” acts as a jump-start for subsequent generalized self calibration.

A byproduct of core-station selfcal is high precision measurement of ionospheric phase delay toward each bright radio source, within each station beam, for each station, and for each solution interval. For reasonable LOFAR parameters, this amounts to of order 20,000 independent measurements of ionospheric phase delay distributed throughout the space above LOFAR every few seconds, constituting an extraordinarily rich database. An example of the type of information to be harvested is shown in figure 3, which shows the ionospheric phase delay versus time for three VLA telescopes at 74 MHz. The LOFAR calibration system will exploit spatial and temporal continuity properties of a physical ionosphere to optimize removal of phase errors from the astronomical dataset, but high temporal and spatial resolution ionospheric tomography is an obvious and attractive additional use of the data.

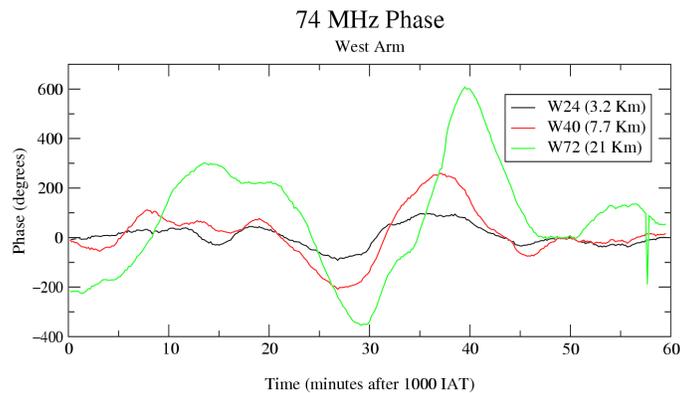


Figure 3. Phase delay versus time for 3 antennas of the VLA at 74 MHz. The measurement precision is much better than 1 degree, which corresponds to 2×10^{-4} TEC units. (Courtesy: R. Perley, NRAO)

For imaging, known sources in the GSM will be corrected for the ionospheric and station gain models, and subtracted from the data. Refinements to the GSM will then be made from residual imaging, as a byproduct of the specific scientific results from the observation. In this way, the GSM will gradually improve, and LOFAR calibration will gradually become more precise.

PROJECT STATUS

The LOFAR project is currently in a development phase, with preliminary design review scheduled for January 2003, and critical design review scheduled for spring 2004. All partners in the project are fully funded through critical design review. The construction phase begins in 2004, and an initial operating capability is anticipated in 2006, with full capability expected two years later. Three potential sites for LOFAR are under consideration, namely the Netherlands and northern Germany, the southwest U.S. (Texas and New Mexico), and western Australia. Selection of the site is planned to coincide with the preliminary design review in early 2003. Many details about the project can be found on the LOFAR web pages, at www.lofar.org.