LOFAR, a new low frequency radio telescope

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Abstract

LOFAR, the Low Frequency Array, is a large radio telescope consisting of approximately 100 soccer-field sized antenna stations spread over a region of 400 km in diameter. It will operate at frequencies from \(\sim 10\) to 240 MHz, with a resolution at 240 MHz of better than an arcsecond. Its superb sensitivity will allow for studies of a broad range of astrophysical topics, including reionisation, transient radio sources and cosmic rays, distant galaxies and AGNs. In this contribution a status rapport of the LOFAR project and an overview of the science case is presented.

Key words: Galaxies: high-redshift; Radio continuum: galaxies; Instrumentation: interferometers

1 LOFAR, the telescope

The mission of LOFAR is to survey the Universe at frequencies in the range 10 - 240 MHz (corresponding to wavelengths of 1.5 – 30 m). Until now this portion of the spectrum has been virtually neglected. This is mainly because at these low radio frequencies the natural image quality is set by “radio seeing”, i.e. severe image blurring due to the ionosphere. Recent work with the VLA at 74 MHz nicely illustrates the problem of “radio seeing”, with the apparent position of objects being shifted by more than an arcminute on timescales of tens of minutes (Cohen, Röttgering, Kassim et al. 2003). Recently Cotton and Condon (2002) developed an algorithm to correct for these diffraction effects. The basic idea is that on short regular timescales the wandering of positions of a number of bright sources within the primary beam is measured. This timescale is chosen as a compromise between being long enough so that a sufficient number of sources are visible, and short enough so that changes in the ionosphere can be smoothly tracked. For observations at 74 MHz, typically for 5-10 sources, shifts are measured on timescales of 1-2 minutes. A Zernike polynomial is then fitted to the source shifts and the resulting fit is used to correct for the ionospheric phase fluctuation.
2.1.3 Development of a research infrastructure

The third component of our program, the essential binding element that allows us to bring our communities together effectively in order to achieve cross-disciplinary added value, is the provision of a unique, advanced research infrastructure, which for convenience we refer to simply as LOFAR. This facility is to be located by preference in the northern Netherlands (extending into Lower Saxony), and will consist of a high capacity, wide area, scalable optical network capable of managing a very large lti-sensor array and its embedded and high performance processing needs. A schematic representation of how this network might look is shown in Figure 2.2.

The rationale for this infrastructure is threefold:

- It will provide a significant increment in capability beyond current networking active (e.g., well beyond even that provided by GigaPort Next Generation Network), thereby enabling innovative, large-scale sensor-based applications.
- Its design and development will ensure that our research on large-scale, wide-area adaptive sensor networks is firmly grounded in technological reality as well as guided by the world of applications.
- The prospective availability of this unique infrastructure will promote intimate involvement of application groups, thereby guaranteeing that the insights and capabilities achieved are firmly embedded in several research communities, both inside and beyond the ICT sector.

LOFAR’s design is such that a similar scheme will work even under the severe ionospheric conditions present at these low frequencies. Each of the LOFAR stations will form a baseline with the very sensitive central core, which comprises 25% of the collecting area. The sensitivity of each of those baselines is such that, within the coherence time of the ionosphere and within the primary beam of each station, enough sources are visible to perform the needed calibration.

LOFAR will have 2 antenna systems, one for the 10-90 MHz range, and one for the 110-240 MHz range. These antennas will be placed in soccer-field sized stations yielding, for each station, effective aperture sizes that will range from 50 m to 150 m, depending on frequency. The signals from each antenna are digitised and fed into the station beamformer. The beamformer can produce up to eight coherent “station-beams” within the primary power pattern of the antenna element in use. In total of the order of 100 stations will make up the array. These stations will be distributed over an area with a diameter of about 400 km. For a sketch of a possible layout if LOFAR is built in the Netherlands, see Figure 1.

An overview of the resulting resolutions and sensitivities is given in Table 1.
There is an interesting trade-off between sensitivity and number of beams. If observations are carried out with 8 different beams, then the maximum bandwidth available for each beam is 4 MHz. It is also possible to observe with only one beam and use the full 32 MHz bandwidth, thus obtaining greater instantaneous sensitivity.

Table 1
An overview of the resolutions and sensitivities of LOFAR for a number of fiducial frequencies. The sensitivity are for a single polarisation.

| Frequency (MHz) | Wavelength (meter) | resolution (arcsec) | Sensitivity (mJy $\left(\frac{\text{bandwidth}}{4\text{MHz}}\right)^{-1/2}$) |
|----------------|--------------------|---------------------|-------------------------------------------------|
| 10             | 30                 | 15                  | 3                                               |
| 30             | 10                 | 5                   | 1.6                                             |
| 75             | 4                  | 2                   | 1.0                                             |
| 120            | 2.5                | 1.3                 | 0.13                                            |
| 200            | 1.5                | 0.8                 | 0.03                                            |

2 Science case

The science case for LOFAR is broad; there are important application of LOFAR not only for astrophysics, but also for studies of the Earth’s ionosphere and the physical properties of the solar wind. Here we will briefly sketch the general astrophysical science case and subsequently those applications that are most relevant for this workshop.

As a direct result of the calibration scheme that measures phase fluctuation of the ionosphere, LOFAR will map its dynamic structure and variability over a wide range of scale sizes. Emission of a longwavelength radar directed at the sun would be scattered back by Solar Coronal mass ejections (CMEs). The Doppler shifts introduced by different parts of an outward moving CME will result in a characteristic frequency and time dependent signature. This not only enables studies of the CMEs, but would also lead to accurate predictions for occurrences of geomagnetic storms.

An interesting application of LOFAR is its use as a detector for high-energy cosmic rays (HECRs). The existence of HECRs at energies between $10^{15} - 10^{20.5}$ eV is an outstanding challenge for particle astrophysics. Both the sites and processes for accelerating these particles are unknown. A primary CR induces a particle cascade in the atmosphere which emits coherent radio emission in the terrestrial magnetosphere (Falcke and Gorham 2003). From the arrival times and intensities of the radio pulse at various antennas of LOFAR,
the poorly understood development of the electromagnetic part of the cascade can be studied. Furthermore, the direction of the primary particle can then be determined to an accuracy of 1 degree, potentially revealing the origin of the cosmic rays.

LOFARs large instantaneous beam allows for the first time a sensitive unbiased survey for radio transients on a variety of time scales, ranging from a few tenths of seconds to many days. Rapid follow up with LOFAR at high resolution will give the accurate positions required for optical and X-ray identifications. There are numerous classes of sources that are variable or expected to be variable at low frequencies and these include radio supernovae, Gamma-ray burst afterglows, Galactic black-hole/neutron-stars, exo-planets and radio flare stars.

One of the most exciting goals of LOFAR will be to chart the end of the Dark Ages when the first stars and AGNs started to ionise the neutral baryonic gas pervading the Universe. LOFAR will study at which redshift range the bulk of the HI became ionised. Through studies of the spatial distribution of both the heated and still cold IGM, it will be possible to determine which objects or processes are responsible for re-ionising the Universe.

*Radio loud AGN*

One of the main goals of LOFAR will be to survey the whole accessible sky at a number of the lower frequencies (e.g. 15, 30, 75 MHz) down to the confusion limit. These surveys will be complimented by surveys at higher frequencies (e.g. 120 and 200 MHz) with the aim of (i) obtaining good positional information, essential for optical identification and (ii) determining the higher frequency part of the radio spectrum.

Due to the low observing frequencies, LOFAR surveys will yield large numbers of radio galaxies with very steep radio spectra. Using the empirical correlation between radio spectral steepness and distance, (e.g. de Breuck et al. 2000), LOFAR surveys will be used to efficiently pick out very distant \((z > 5)\) radio galaxies. As discussed in many contributions to this workshop, study of these distant radio galaxies at other wavelengths will provide information about the formation of massive galaxies, AGN and proto-clusters.

It is possible that some of these radio galaxies are located at an epoch before reionisation has completely occurred. This would open up the possibility of studying the epoch of reionisation through observations of the absorbing neutral gas against these very distant radio galaxies (Carilli et al. 2002)
Starforming galaxies

With its unprecedented sensitivity to non-thermal radio emission from star formation, LOFAR will detect large numbers of star-forming galaxies at an epoch at which the bulk of galaxy formation is believed to occur. Observing at 200 MHz, LOFAR should be able to detect the nearby star-forming galaxies, such as M82 and the “ultra-luminous infrared galaxy” Arp 220 (z=0.018), out to redshifts of respectively $z = 1.1$ and out to $z = 3.3$ (e.g. Garrett 2002). Since the ratio of radio flux to sub-mm flux is a sensitive redshift indicator (Carilli and Yun 1999), LOFAR surveys, in combination with data from new far-IR and millimeter facilities such as SIRTF, ALMA, and JWST, will therefore provide distances and thus allow for a complete census of the cosmic star-formation history, unhindered by the effects of dust obscuration.

Cluster radio halos

Due to their large extent, low surface brightness, and steep-spectra, diffuse cluster sources are difficult to detect with conventional facilities, such as Westerbork and the VLA. However, their properties are well matched to LOFAR’s observational capabilities. The number of cluster halos that could potentially be detected with LOFAR has been estimated using a simple model (Enßlin and Röttgering 2002). This model takes into account the locally observed fraction of cluster radio halos, the observed relation between radio and X-ray luminosity, and a Press-Schechter description of the merging rate of massive clusters as a function of redshift. A LOFAR survey at 120 MHz covering half the sky to a 5-sigma flux limit of 0.1 mJy (1 hour per pointing) is feasible on the timescale of one year and could detect of the order of 1000 halos at the 10 sigma level, of which 25 % are expected to be at redshifts larger than $z \sim 0.3$.

The XMM X-ray telescope, the Planck satellite and the Sloan Digital Sky Survey should catalogue as many as 500,000 new clusters (Barthelmann and White 2002). LOFAR has sufficient sensitivity to detect existing radio halos in all such clusters. This will be very relevant for (i) understanding the dynamics of the cluster gas, (ii) determining the origin of their magnetic field content, and (iii) constraining physical models for the origin of these sources.

3 The Project

ASTRON (Dwingeloo, the Netherlands), M.I.T. (Cambridge, USA) and Naval Research Lab (Washington, USA) are responsible for the design, construction,
operation and software of the LOFAR telescopes. The agreed timescale is ambitious and has the aim of full operations in 2008. Important milestones towards this goal are (i) a first test station with 100 antennas in 2003, (ii) the LOFAR core operational in 2005, and (iii) operations of the central core plus first outer stations in 2006.

A site characterisation committee is presently obtaining data needed to assess the suitability of LOFAR siting in the Netherlands, south-west Australia and the southern USA (Texas and New Mexico). A decision on the location for LOFAR is expected to be made in 2003.

The international project is supervised by an International Steering Committee (ISC), consisting of directors of the participating institutes. An Engineering Consortium (EC) is responsible for the design and implementation of the instrument. The Science Consortium Board (SCB) is responsible for developing the science case for LOFAR in close collaboration with the community and gives scientific input to the EC.

The Science Consortium Board very much welcomes suggestions for improving or optimising the design of the instrument for general or very specific applications. For further information, visit: www.LOFAR.org

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