Chapter 9
Low Frequency Array (LOFAR)
Potential and Challenges

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ABSTRACT
The Low Frequency Array (LOFAR) is a large radio telescope based on phased array principles, distributed over several European countries with its central core in the Northern part of the Netherlands. LOFAR is optimized for detecting astronomical signals in the 30-80 MHz and 120-240 MHz frequency window. LOFAR detects the incoming radio signals by using an array of simple omni-directional antennas. The antennas are grouped in so called stations mainly to reduce the amount of data generated. More than forty stations will be built, mainly within a circle of 150 kilometres in diameter. But LOFAR stations will also be built in other European countries. The signals of all the stations are transported to the central processor facility, where all the station signals are correlated with each other, prior to imaging. In this chapter, the signal processing aspects on system level will be presented. Methods to image the sky will be given and the mapping of these concepts to the LOFAR phase array radio telescope will be presented. Challenges will be addressed, and potentials for further research will be presented.

INTRODUCTION
Astronomy is one of the oldest sciences in the world. In the early days, astronomers performed methodical observations by looking at the sky. It was the Dutch invention of the telescope in 1609, used by Galileo Galilei, which brought astronomy into modern science. Observational astronomy was purely optical until the serendipitous discovery of radio emission from the center of our Galaxy by Karl Jansky in 1932 (Jansky, 1932). He built an antenna, designed to receive terrestrial radio waves at a frequency of 20.5 MHz. After recording signals from all directions, Jansky categorized...
them into three types of signals: static from nearby thunderstorms, static from distant thunderstorms, and a faint steady signal of unknown origin. This was the discovery of extra-terrestrial radio signals and in fact the start of radio astronomy science. It took some time before these results were taken seriously and before radio astronomy started to build new instruments.

After World-War-2 new radio-astronomical instruments were built all over the world. To improve important properties such as sensitivity and spatial resolution, telescopes became larger. Since resolution is linear with respect to wavelength, new telescopes also operated at much higher frequencies. Another reason for observing at higher frequencies is the occurrence of spectral lines, such as the Hydrogen emissions line at 1420.4 MHz predicted by van de Hulst in 1944, and detected shortly after. After the development of earth-rotating synthesis techniques in the sixties large telescope arrays were deployed, such as the Westerbork Synthesis Radio Telescope in Westerbork, The Netherlands and the Very Large Array in Socorro, New Mexico, Unites States of America.

Since the nineties, extension of observing frequencies has been an important aspect of radio astronomy. At high frequencies new observatories have been developed and built, such as the eSMA in Hawaii (Bentum, 2006). Currently the Atacama Large Millimeter Array (ALMA) is being constructed consisting of fifty parabolic reflectors for the frequency range of 31 to 950 GHz (Wootten 2005). Research at low frequencies is one of the major topics at this moment in radio astronomy and several Earth-based radio telescopes are constructed at this moment. It is considered as one of the last unexplored frequency ranges (Weiler, 2000). A number of major new facilities for low frequency operation are being developed or under construction, such as the Giant Metre wave Radio Telescope (GMRT, Swarup et al., 1991), Long-Wavelength Array (LWA, Kassim et al., 2005), Murchison Widefield Array (MWA, formerly known as the Mileura Widefield Array, Morales, 2006), the 21 Centimeter Array (21CMA5 ; formerly called Primeval Structure Telescope, PAST 6, Peterson et al., 2005), Precision Array to Probe the Epoch of Reionization (PAPER, Bradley et al., 2005), and the Square-Kilometre Array (SKA, Schilizzi, 2004). For frequencies below ~50 MHz, space-based instruments must be considered due to the ionosphere (Bentum et al, 2009 and Jester et al, 2009).

Our approach is LOFAR, the Low Frequency Array. LOFAR will be a wide-area sensor network for astronomy, geophysics and precision agriculture (Gunst et al 2007, 2008, Bregman 2000). The LOFAR infrastructure will consist of a collection of over thirty-six sensor fields, also referred to as “stations”. At least eighteen sensor fields will be concentrated in a central area, further referred to as core stations. The rest of the stations (remote stations) will be distributed over a larger area of about 150 kilometers in diameter. The stations will cover the spectrum from 30 to 240 MHz. A dedicated supercomputer, the Central Processor, will combine and process the sensor data. Data will be transported over optical fiber connections from the sensor fields to the Central Processor. The total digitized data rate from the sensors is about 0.5 Tb/s at each sensor field. Station level processing reduces this rate to roughly 2 Gb/s by combining data from multiple sensors into phased array beams. LOFAR is fully based on phased array principles. This gives LOFAR the ability to operate in multiple directions simultaneously. LOFAR is one of the first radio telescopes in which RFI mitigation techniques are an integral part of the system design, which will be presented in this chapter as well as some practical issues.

A signal processing view of the instrument should starts with a description of the signal. In radio astronomy we are interested in signals from cosmic sources very far away. A fundamental property of the radio waves emitted by these cosmic sources is that they are stochastic in nature. The signal strength of these signals is very small.
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