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SIGNAL PROCESSING ASPECTS OF THE LOW FREQUENCY ARRAY

André W. Gunst and Mark J. Bentum
[gunst/bentum]@astron.nl
ASTRON, P.O. Box 2, 7990 AA Dwingeloo, The Netherlands

ABSTRACT

In the Northern part of the Netherlands ASTRON is building the largest radio telescope in the world for low frequencies. The telescope is based on phased array principals and is known as the LOw Frequency ARray (LOFAR). 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 fifty stations will be build, mainly within a circle of 150 kilometres in diameter but also internationally. The signals of all the stations are distributed to the central processor facility, where all the station signals are correlated with each other. In this paper the signal processing aspects on system level will be presented mainly for the astronomical application.

Index Terms— radio astronomy, phased array, digital processing, data transport, correlator.

1. INTRODUCTION

LOFAR (Low Frequency Array) will be a wide-area sensor network for astronomy, geophysics and precision agriculture [1,3,4]. The LOFAR infrastructure will consist of a collection of sensor fields (also referred to as “stations”). Up to thirty-two 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 (see Figure 1). A dedicated supercomputer, called 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 [5]. 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. The first step in the realization of LOFAR was the construction of a Research and Development Core Station (referred to as “CS1”) to be used as part of the final end-to-end functional validation.

2. LOFAR SYSTEM ARCHITECTURE

The LOFAR architecture for the astronomical applications consists of the following main architectural blocks (see Figure 2. for the relationships):

Figure 1. Geometrical overview of LOFAR. All the red dots are stations.

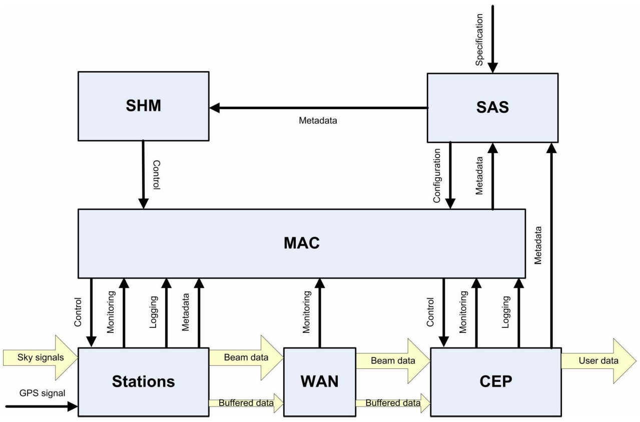

Figure 2.LOFAR system architecture.

1. Stations. A station selects the sky signals of interest for a particular observation out of the total sky. This process results in one or multiple beams onto the sky.
2. Wide Area Network (WAN). The WAN is responsible to transparently transport all the beam data (the beam signals on the sky) from the stations to the central processor.
3. Central processor (CEP). The central processor is responsible to process and combine the beam data from all stations in such a way, that user data is generated as was specified by the user.
4. Scheduling And Specification (SAS). Given the specification, the main responsibility of SAS is to schedule and configure the system in

the right mode. Additionally SAS facilitates the possibility to store metadata of the system for a long term and make that information accessible for the user.

5. Monitoring And Control (MAC). The main responsibility of MAC is to (real-time) control the system based upon the actual configuration of that moment. Additionally MAC facilitates the (real-time) monitoring of the present state of the system.
6. System Health Management (SHM)[1]. SHM is identified as an autonomous block to predict and act on failures of the hardware before it actually fails. Ideally it even should pin point which system component is the cause of a failure. The reason to identify this block is because of the scale of the system and the percentage of time the system should be effectively operational.

The remote stations will differ from the core stations by more data reduction obtained by producing only one beam in the remote stations instead of multiple beams in the core stations. This is chosen because the remote stations are further away from the central computer so data transport is more expensive.

3. THE SENSORS

For the astronomical application each LOFAR station will contain 96 Low Band Antennas (LBAs) and 96 High Band Antenna (HBA) tiles to cover the whole frequency range with sufficient sensitivity. The LBAs will cover the spectrum from 30 to 80 MHz and the HBA tiles will cover the spectrum from 120 to 240 MHz. Each HBA tile consists of a 4x4 array of antenna elements. Connectivity will be provided for a second type of low band antenna as well which will cover the lower part from the low band spectrum (above 10 MHz).

For the geophysical application remote stations will be equipped with vibration sensors (geophone). For infrasound detection remote stations will contain several micro barometers. In selected stations additional sensors for agricultural applications are included. The stations will provide connectivity for other sensor systems as well. The sensor systems within the LOFAR station are independent. The common components are:

- The WAN (Wide Area Network) interface will take care of the data and control streams between the different sensor systems and the LOFAR central processor
- The control and sync system provides an accurate timing and synchronization signal to the different sensor systems and performs monitoring tasks

4. THE STATION ARCHITECTURE

A more detailed block diagram of the station is depicted in Figure 3. Within a station the electromagnetic signals received are converted into electrical signals by antennas. After transport to the receiver via coaxial cables the electrical signals are amplified, filtered and converted to the digital domain within the receiver block.

Subsequently, in the digital domain the data is reduced by:

➔ filtering and selecting specific subbands
➔ combining the data of all antennas for selected subbands (beam forming)

Finally the digital data is merged with the control data and data from the non-astronomical sensor networks, converted to the optical domain and transported via a WAN. The data path of a station is controlled and synchronized with other stations by a control and synchronization unit that is disciplined by GPS signals as reference.

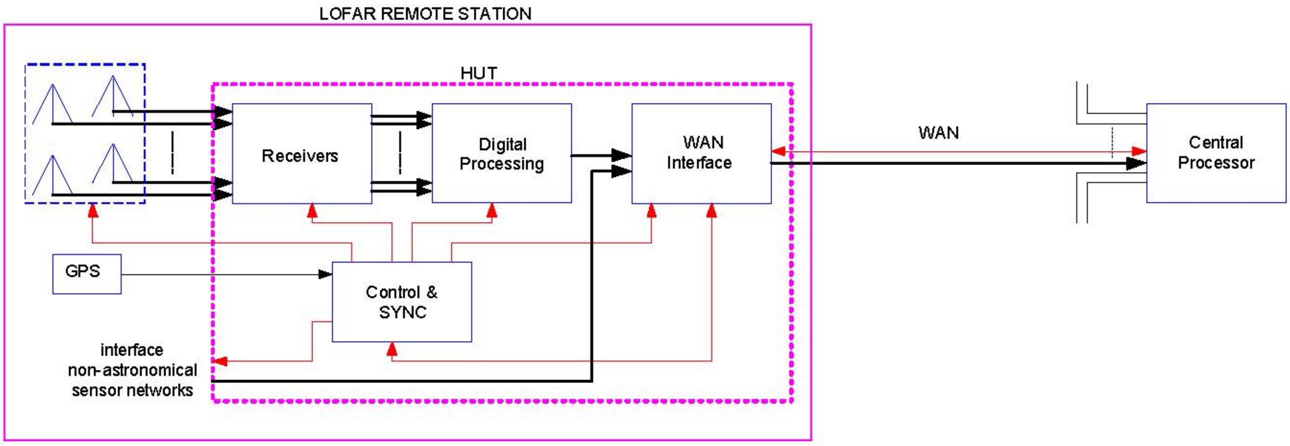

Figure 3. Block diagram of a LOFAR station.

[1] This subsystem is developed by Science & Technology (Delft, the Netherlands)

Description	*Value*	*Unity*
Number of low band antennas	96	
Number of high band antennas	96	
Number of polarizations	2	
LBA frequency range	30-80	MHz
HBA frequency range	120-240	MHz
Number of subbands	512	
Max. number of beams	8	
Min. number of beams	1	
A/D converter resolution	12	Bit
Sample frequency	200/160	MHz
Aggregate output bandwidth	32	MHz

Table 1. Key parameters for the remote station (all parameters are given for one polarization).

5. THE RECEIVER SYSTEM

The receiver unit selects one out of two antennas. An extra interface at the input of the receiver is provided to cope with future extensions with a third antenna. After selecting an antenna, the signal is filtered with one of the four integrated filters. These filters split the input band in four parts. After filtering, the signal is amplified and filtered again to reduce the out of band noise contribution.

For the receiver a wideband direct digital conversion architecture is adopted. This reduces the number of analogue devices used in the signal path. The A/D converter converts the analogue signal into a 12 bit digital signal at a maximum sampling rate of 200 MHz. To fill the gaps in between the Nyquist zones a sample frequency of 160 MHz can be chosen as well. This results in the observation modes depicted in Figure 4. The area around 100 MHz is not used because the FM radio signals are present in that band.

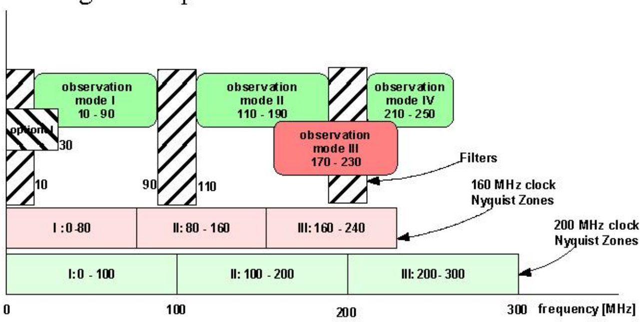

Figure 4. Observation modes in the station receiver.

6. THE DIGITAL PROCESSING SYSTEM

After A/D conversion, the band is split into 512 equidistant subbands using a polyphase filterbank. The negative part of the original spectrum is omitted, i.e. the real input signal is from here on represented by complex signals. Each subband signal is decimated with a factor of 1024 after filtering. Hence, the clock rate after filtering is reduced to 195 kHz and 156 kHz respectively, for a 200 MHz and 160 MHz input sampling rate. After filtering, specific subbands can be selected. The selection is controlled centrally at the station. The selected subbands have a maximum total effective bandwidth of 32 MHz per polarization. This bandwidth is matched to the current capacity of the CEntral Processor (CEP) [5].

To form beams, the antenna signals are combined. This is done with independent beam-formers for each subband. The weights necessary for the beam-former are calculated in the Local Control Unit (LCU) and are sent to the beam-formers each second in order to follow sources while the earth rotates. Additionally statistical measurements are performed at the station. This monitor information is forwarded to the Monitoring And Control (MAC) subsystem.

In parallel with the beam-forming a full cross correlation of all the antenna signals for one subband can be done as well. This is done to accommodate for online calibration of all signal paths for gain and phase differences. Furthermore this information will be used as well for RFI (Radio Frequency Interference) detection.

The raw antenna data or subband data can be stored in a transient buffer as well. Freezing of the buffer content can be controlled by internal or external triggers. The stored data or selections thereof can be sent to CEP for further processing.

7. CENTRAL PROCESSOR FACILITY

The Central Processor hardware (CEP) system will be used to process the data from the stations. Currently a maximum data flow of ~4x3 Gbps can be received and processed in prototypes of the on-line processing pipelines, including usage of IBM's BlueGene/L (BG/L) [6]. Storage is available for temporary storage of raw data files until these are processed off-line and products are exported to users. Additional storage is available for (limited) archiving of end-products (see Figure 5).

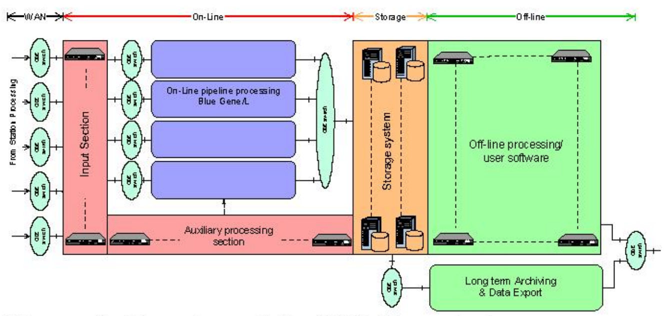

Figure 5. Overview of the LOFAR central processor hardware consisting of 4 different clusters integrated with the Blue Gene/L computer.

A streaming processing application has been developed for the entire pipeline converting the raw station data streams into correlation products. In the first step of this pipeline the 12 Gbps of data is received, validated and synchronized. Also, additional delay is applied in order to correct for the rotation of the earth. The next step of the pipeline is a polyphase filter bank to split the subbands data into 256 frequency channels. This results in channels of approximately 1 kHz. From each channel, the correlation matrix for all stations is calculated. The filter bank and correlator operations are implemented on the Blue Gene/L computer. The correlator is extremely efficient and achieves 98.1 percent of the theoretical peak performance [7].

The output of the correlator is stored until completion of the observation. The remainder of the processing operates off-line on these datasets containing the coherent data from a complete observation. The basic tasks to be performed are typically flagging of bad samples, calibration and transformation to the image plane, resulting in an image of the sky.

8. FIRST RESULTS

CS1 (core station 1) is the first LOFAR station put in the field. CS1 is currently operational and already produced lots of useful measurement sets [8]. Although the name suggest CS1 is physically one station, in practice CS1 is grouped in four clusters.

Using this setup, it is possible to emulate LOFAR as it were 24 (micro) stations. Currently 16 (micro) stations are operational. The end to end processing pipeline is validated with known sources on the sky and led to the first deep wide field image [8]. Furthermore full sky images are made with the 48 dipoles cluster by using the on-line cross correlation functionality of the stations [9]. In Figure 6 an autocorrelation spectrum of the antennas in CS1 is given. The spikes in the spectrum are RFI.

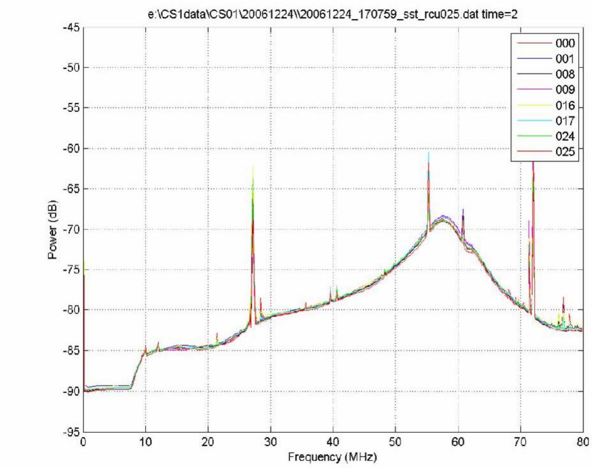

Figure 6: Typical autocorrelation spectrum of the CS1 antennas retrieved from the subband statistics recorded for each low band antenna (8 antennas displayed).

9. FUTURE WORK

Building the first LOFAR station is only the beginning of LOFAR. CS1 is the first full station of LOFAR with which we have tested the complete pipeline from reception of the Electromagnetic waves to the signal processing in the supercomputer. The rollout of the rest of LOFAR will start with the rollout of the core stations in the first half of 2008 and thereafter the remote stations and international stations in 2008, 2009.

10. ACKNOWLEDGEMENTS

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