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LOFAR Station

Architectural Design Document

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Table of contents:

1 Introduction

1.1 Purpose of this document

This document describes the top-level architecture of the station hardware for the astronomical applications in LOFAR and discusses important choices made. The user requirements defined in [1] are in this document translated into an architecture. Since, this document serves as an overview; references are given to more detailed documents.

1.2 Applicable documents

Figure 1 positions the station ADD (Architectural Design Document) in the main document baseline for system CDR (Critical Design Review). This document motivates the mapping of the station requirements onto available technologies, frameworks and algorithms.

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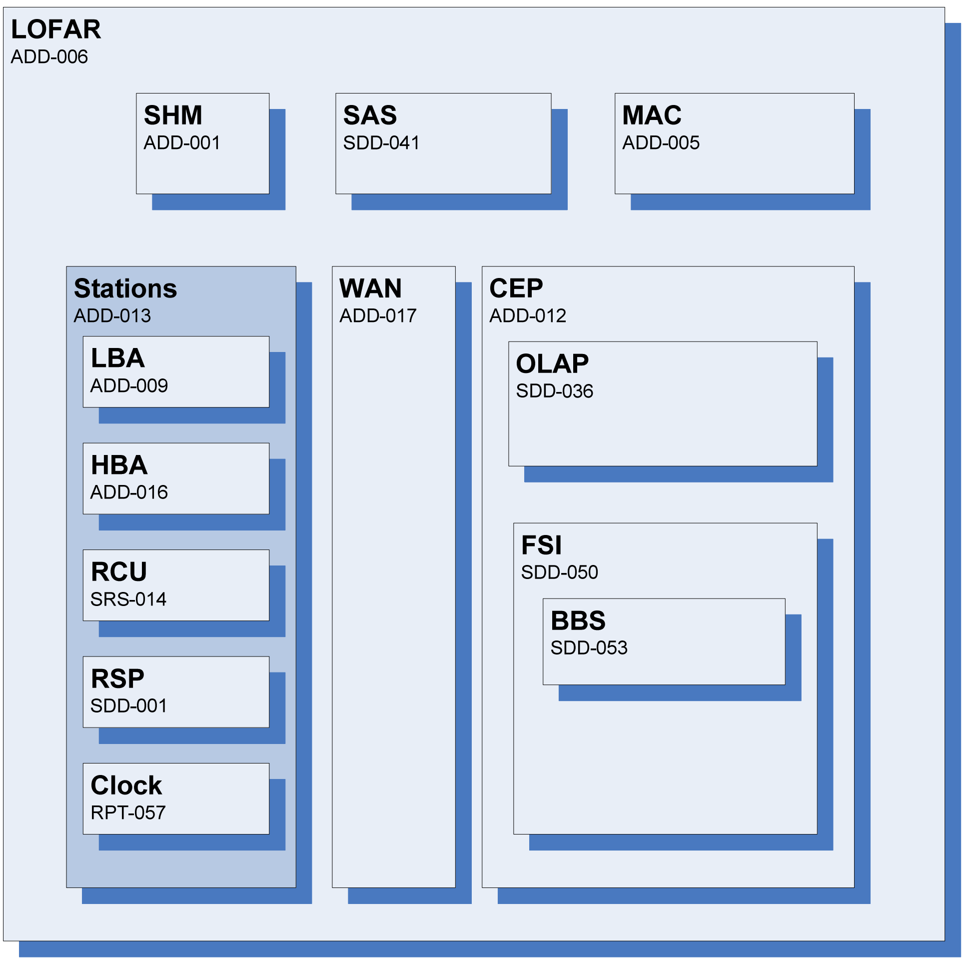

Figure 1 *Dependency relations between this ADD and other documents available for the LOFAR system.*

1.3 List of Terms and Abbreviations

ACM	Auto Correlation Matrix
ADD	Architectural Design Document
Beamlet	beamformed subband
BBS	BlackBoard SelfCal
CDR	Critical Design Review
CEP	CEntral Processor
ECB	Embedded test Controller Board
EMI	Electro Magnetic Interference
FOV	Field Of View
FSI	Flagger, Selfcal and Imager
GPS	Global Positioning System
HBA	High Band Antenna
ITS	Initial Test Station
JTB	Jtag Test Board
KSP	Key Science Project
LBA	Low Band Antenna
LBH	Low Band High antenna
LBL	Low Band Low antenna
LCU	Local Control Unit
MAC	Monitoring and Control
MCB	Modular Circuit Breaker
OLAP	On-Line Applications and Processing
PCB	Printed Circuit Board
PPS	Pulse Per Second
Rb	Rubidium
RCU	ReCeiver Unit
RFI	Radio Frequency Interference
RSP	Remote Station Processing board
SAS	Specification, Administration & Scheduling
SHM	System Health Management
SPU	Subrack Power Unit
SRS	System Requirements Specification
Subband	Narrow frequency band
TDS	Time Distribution board Subrack
TBB	Transient Buffer Board
USG	User Software Group
UTP	Unshielded Twisted Pair
WAN	Wide Area Network

2 Station requirements

In this chapter the requirements in [1] and [2] relevant for the stations at station system level are listed and broken up if applicable over the station subsystems. Requirements relevant for subsystems are mentioned in the detailed documents available for those subsystems. The numbers refer to the numbering system in [1].

2.1 Functional requirements

From the astronomers (general):

- LOFAR shall be able to measure electromagnetic radiation in a frequency range from 10 – 240 MHz and be optimized for a frequency range from 30-80 MHz and from 120 - 240 MHz (LO-3.01.1-01 and LO-3.01.1-02).
- It shall be possible to define up to four groups of antenna elements in a station (LO-3.01.2-02 and LO-3.01.2-03).
- Simultaneous use of low frequency and high frequency antenna elements shall be possible by using groups of antenna elements (LO-3.01.5.2-02).
- LOFAR shall have sufficient digital signal paths to process either all low frequency or all high frequency antenna signals, but not both of them simultaneously (LO-3.01.5.2-01).
- LOFAR's sensitivity shall be based on achieving the response of a fixed number of matched dual-polarization dipoles (LO-3.04.1-03):
    - * 7700 low band antennas
    - * 7700 4 x 4 high band antenna tiles

*From the astronomers (*signal quality)

- The LOFAR station shall have a spectral dynamic range in all signal paths that is not limited by continuously present RFI sources with a strength up to 40 dB on top of the whitened integrated sky noise power in at least 32 MHz (continuous presence being defined as present for at least 80% of the time). This requirement implies that the signals of such sources are not clipped (LO-3.01.4-01).
- The LOFAR station shall be able to apply spatial suppression of static interferers by means of deterministic nulling.
- The LOFAR station shall be able to detect local static interferers.
- LOFAR shall be calibratable for at least 50% (TBC) of the time at all optimized frequencies (LO-3.04.1-02).
- It shall be possible to position each LOFAR beam (as described above) with sufficient flexibility such that any position above the horizon can be included in the main lobe of the beam (LO-3.05.2-04).
- The phase relations between the subbands and channels within a beam shall be known to such a level that wider bands and corresponding time series can be reconstructed from subbands and/or channels (LO-3.01.2.2-05).

From the astronomers (performance)

- LOFAR shall have a maximum instantaneous bandwidth of 32 MHz per polarization positioned anywhere within the operating frequency range (LO-3.01.2-01).
- The LOFAR station shall produce 1 up to 8 beams, with a combined total bandwidth of at least 32 MHz (note this means 1 beam of 32 MHz or 2 beams of 16 MHz to a maximum of 8 beams of 4 MHz) (LO-3.05.2-01).
- The LOFAR station shall support beam directions updates at least once every second.
- The LOFAR station shall support changing of operation mode within 1 second in case of scheduled switching sequences (LO-3.01.5-01).
- The LOFAR station shall support changing of operation mode within 3 seconds in case of scheduled trigger responses (LO-3.01.5-02)..

From the astronomer (transient detection):

- The LOFAR station shall be able to take a snapshot of 1 second of all raw antenna data around an event (transient). The station shall be able to detect events.
- The LOFAR station shall support a triggered readout of the signal buffer.
- Filling and emptying the transient buffer shall be possible in parallel to the other station functions.

Miscellaneous:

- The LOFAR remote station shall provide continuous statistical information from each subband with an update rate of 1 second (health management).
- The LOFAR station shall have a cold startup time of < 24 hours (LO-4.04-02).
- The LOFAR station shall have a warm startup time of < 4 hours.
- The LOFAR station shall be compliant with the LOFAR EMC standard (LO-3.09.3.1-01).

2.2 Noise requirements

According to the System Requirements Specification (SRS) the noise budget for LOFAR is set to be sky noise dominated (LO-3.04.1-01): “LOFAR shall be designed such that the sky noise dominates the antenna noise over 30 - 80 MHz and 120 - 240 MHz.”

Since, the sky noise decreases with frequency the requirement is harder to meet for the high end of the band. Hence, the requirement for the stations is split into a low band requirement and a high band requirement.

For the 30-80 MHz frequency range the total system noise contribution is set to be less than 20% of the sky noise. Half of this is assigned to the antenna and the other half is assigned to the receiver. A further split up of the noise contributors between antenna, cable and receiver is detailed in [14].

The high band requirement is relaxed in such a way so that the system noise contribution is equal to the sky noise. The antenna may contribute 90%, while the receiver should contribute not more than 10% of the sky noise [14].

The digital hardware shall be designed in such a way that the additional noise that is introduced by using a finite number of bits shall be less than the quantization noise of the A/D converter.

2.3 Linearity requirement

In [25] the intermodulation analysis for LOFAR is given. A so called hard spurious requirement and soft spurious requirement was defined. In [26] was decided to design the station system given the soft spurious requirement in order to design a system against realistic costs. The requirement is formulated as: the integrated power of all spurious in the selected band should remain 10 dB below the integrated noise power of the selected frequency band after whitening the sky noise [25].

2.4 Selectivity requirements

Filtering of the subbands shall be such that the strength of an aliased interferer in the stopband (outside the transition band) shall be at least smaller than the astronomical source 'Cassiopeia A' (LO-3.01.6-02). The neighboring subband will be considered as transition band.

From this the requirements of the analog and digital filters in the LOFAR system are derived in [27]. The requirements are:

- Transition region is maximal the subband width (only applicable for digital filters)
- Stopband attenuation: > 80 dB (required), 91 dB (nice to have)
- Ripple: < 0.5 dB

The ripple of 0.5 dB is hard to meet for the analog filters given the significant stop band attenuation which must be achieved in a limited band. Hence, the ripple for the analog filters is relaxed to 2 dB. Furthermore, in [14] the analog filters are specified in more detail.

2.5 Clock accuracy

The clock noise increases the system noise of the receiver due to the sampling process [13]. The noise contribution is worst case for input signals with the highest frequency and with maximal amplitude. This circumstance would lead into a jitter requirement of preferably 0.5ps rms. It is expected that RFI in the high band is less than in the low band, this reduces the effects of jitter. Therefore this requirement is relaxed to 1ps rms to achieve an implementation for reasonable costs.

The clock difference between two stations shall be smaller than the average ionospheric changes. This means that the clock between two stations shall not drift more than 80ps over 10s. During a meeting with the astronomers, later on a maximal clock change of 75ps over 20s was communicated.

3 Top level architecture

3.1 Introduction

The main function of the stations is to receive sky signals and select from those the specific signals of interest in time, frequency and spatial domain. This results in a reduction of data which was originally received by the station system.

Figure 2 shows the station system and the interfaces. At the left hand side the sky signals are received by the station and processed in such a way that it results in beams of a certain selection on the sky and within a given frequency range as controlled by the Monitoring And Control (MAC) interface. Monitor signals are returned to the MAC interface, so that an operator can instantly check the status of the hardware within a station. Furthermore a station is able to store the individual antenna signals. The output data is send via the Wide Area Network (WAN) to the central processor.

Each station is synchronized with the other stations by using the time of the GPS signal.

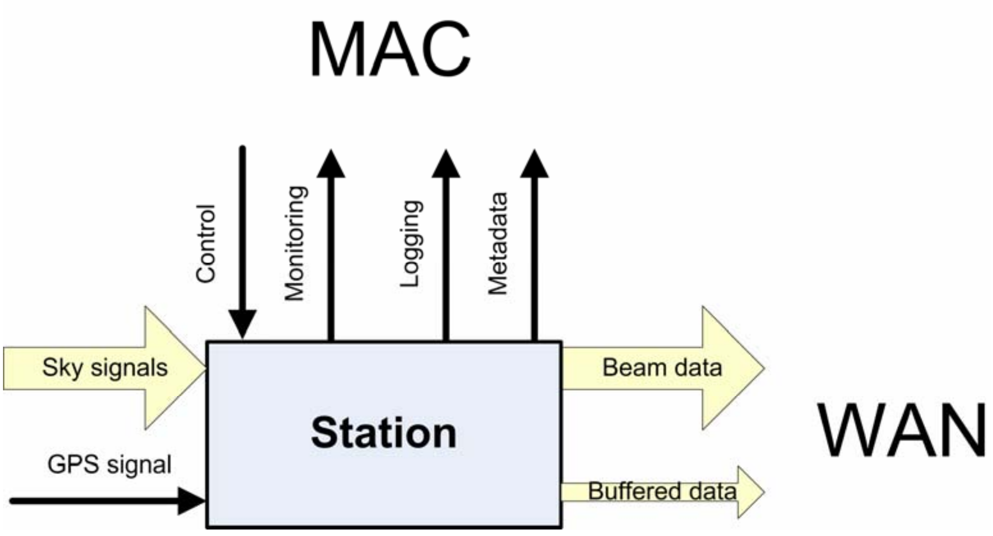

Figure 2 *Station system with its interfaces*

The station has the following interfaces:

- Sky signals: these are the sky signals received by the station, including man made interference signals.
- GPS signal: this is a signal transmitted by satellites and is used for the synchronization of the stations
- Beam data: this is a particular selection of the sky signals (or multiple selections) and contains the scientific information of interest. The beam data is a continuous real-time data stream.
- Buffered data: this is either raw or subband data from the antennas, which is stored at the stations to serve specific astronomical applications. Since this data is stored and on request send to the Central Processor, the data rates involved are much lower than the beam data stream.
- Control: MAC configures the station by this interface to set the station in the right mode.
- Monitoring: via this interface station hardware status information is send to MAC
- Logging: this information is sent to MAC and contains logging information of the station software. Examples of logging information are warnings or errors which do occur.

- Metadata: via this channel metadata can be sent to MAC which contains information about the data itself or information about the circumstances the environment is in. Examples are outside temperatures or statistical information of the antenna signals.

3.2 Functional decomposition of the system

In this section the station system breakdown is motivated from a functional point of view.

The signal block diagram of the station, as discussed in the LOFAR system ADD [3], is shown in Figure 3. The signals flow from left to right, starting with the antenna. In this block the electromagnetic signals are received and converted to electrical currents. The receiver selects a frequency band and conditions the signal prior for sampling and digitization, included in the receiver as well. After this a filterbank divides the band in subbands. For each subband a beamformer is used to make the spatial selectivity of a station, which leads to a significant data rate reduction at station level.

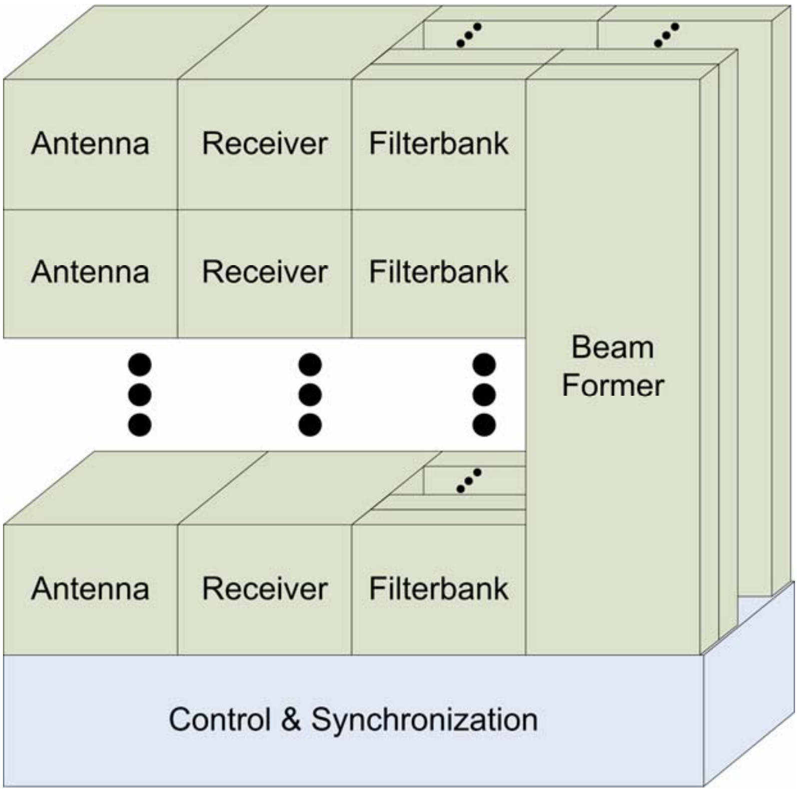

Figure 3 *Functional signal block diagram of the station. The third dimension represents the frequency domain to indicate that the total band is split up in subbands and can be processed further independently.*

3.2.1 Antennas

To achieve an effective area of order 1000 square meters, the antennas within a station are spread over a field of about 100 meter in diameter. All those antenna signals must be brought together in the beamformer to create a phased array. To reduce Electro Magnetic Interference (EMI) the choice was made not to do the sampling and digitization of the antenna signals near the antenna. Hence, the A/D conversion will take place in a central housing near the station for all antennas. The analog antenna signals will be transported via coax cables to the housing. So, the antennas are localized throughout the field, while the rest of the station hardware is localized at a central place for each station field.

The operating frequency range of LOFAR is from 10 MHz to 240 MHz, while the antennas should be optimized for the range 30-80 MHz and 120-240 MHz according to [1]. Since, the optimized bandwidth of the operating frequency range spans 8 octaves at least two types of antennas are necessary in order to fulfill the sensitivity requirement in [1]. Therefore, two types of antennas are developed: the Low Band Antenna (LBA) and the High Band Antenna (HBA). To accommodate science below 30 MHz an extra provision is made for a third antenna, also referred to as the Low Band Low (LBL) antenna. In that context the LBA is also referred to as Low Band High (LBH) antenna.

Since there are no requirements set to observe in the low band mode and in the high band mode instantaneously, all three antennas share the same receiver. In the receiver a switch is made between the antennas.

The number of antennas in a station is set to about 100 to yield in an effective area of about 1000 m^2 over the frequency range (the effective area is also dependent on the antenna configuration). For practical reasons in total 96 antennas are actually placed, see section 5.1.

3.2.2 Receiver

In the receiver the antenna signals must be converted to base band, amplified, filtered and converted to the digital domain. Among a variety of receiver architectures which can be used, a sub-sampling architecture is chosen because:

1. no mixers are required (mixers suffer from reciprocal mixing [11] which is degrading the receiver sensitivity if strong interferers are present)
2. no extra Local Oscillator signal distribution is required

The counterpart of the advantages is that

1. the A/D converter must have a higher analog bandwidth
2. multiple bandpass filters should be implemented to select the frequency band

The required bandwidth is 32 MHz [1], while the LBA band runs from 30 – 80 MHz. Selecting a band from the LBA band requires a cut off region for the filters as well and therefore it is chosen to convert the whole LBA band at once. Then, after digital filtering a band of 32 MHz can be selected. Since observing in the FM band is useless a sample frequency of 200 MHz is chosen, which results in a Nyquist edge almost in the centre of the FM band. Furthermore three usable Nyquist zones can be used in this way, as depicted in Figure 4.

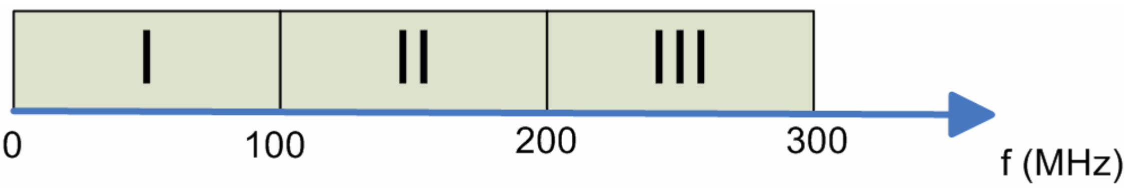

Figure 4 *Nyquist zones for a sample frequency of 200 MHz*

At the edges of the Nyquist zones aliasing will occur due to the cut of region of the analog filters. Hence, the areas around the edges of the Nyquist zones suffer from loss in sensitivity. For that reason an alternative sampling frequency of 160 MHz will be accommodated. That results in the Nyquist zones shown in Figure 5.

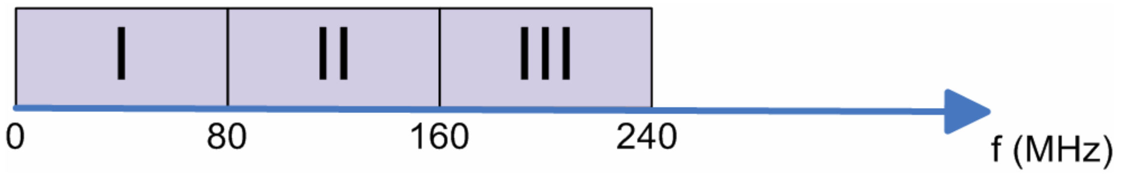

Figure 5 *Nyquist zones for a sample frequency of 160 MHz*

The frequencies around 200 MHz can be observed with the 160 MHz sampling frequency. The previous discussion is of importance at station system level since it has impact on the digital processing and the clock distribution system.

3.2.3 Filterbank

As is explained in [3] the function of the filterbank is to make the spectral resolution for the correlator. This spectral resolution can be used for the beamformer as well to apply phase shifts instead of true time delays for all the antenna signals. By approximating the true time delays by phase shifts in a limited frequency band an error is made since only one phase can be set per subband. This causes decorrelation at the subband edges. From this perspective the subbands must be as small as possible. However, from a cost perspective the total number of subbands should be limited. In the final design the complete sampled band is split in 512 subbands resulting in a maximal subband width of about 195 kHz which gives about 1.5 % decorrelation for a centre frequency of 10 MHz and an elevation of 30 degrees [8]. The effects of this on the LOFAR calibration are discussed in [9].

The reason for splitting up the whole band in subbands instead of prefiltering resulting in only 216 subbands, is because it costs about the same amount of hardware resources, assuming that the filterbank is designed as a poly phase filterbank. With a selector in between the filterbank and beamformer a maximum of 216 subbands, making up in total 32 MHz of bandwidth, can be selected randomly.

3.2.4 Beamformer

The beamformer in a station will phase up the antenna signals for a certain direction and tracks a source. The update rate of the beamformer is set to 1 second, so a standard computer can be used to calculate the beamformer weights and send that to the hardware. A 1 second update rate causes about 0.3% gain variation considering a 3 degree beam.

3.2.5 Buffering

To enable the science cases for the cosmic rays and transients, a transient buffer is included in the station design. With this buffer 1 second of raw data can be recorded in a circular buffer for all antenna inputs of a station. This means that the full Nyquist band is stored. The storage time can be increased by exchanging bandwidth for storage time and/or antennas for storage time. Also facilities are required to detect nanosecond effects like cosmic rays and lightning. For these applications a detection algorithm [6] will be implemented in front of the buffering. This detection algorithm will act on the raw antenna data. If an event is detected a message will be send to MAC. There a decision will be made depending on how many events were detected by the individual dipoles to freeze the circular buffer. After the detection the stored data can be sent to the central system upon request.

3.2.6 Control & Synchronization

On the stations a local control unit (LCU) will be installed. The station subsystem boundary towards MAC lies in the control unit. The lower level control layers are considered to be part of the station. Among them is the hardware driver software, the beam server (which is responsible for allocating beams) and the calibration server (which is responsible to execute the calibration algorithms) [16]. In Section 4.5 these topics are discussed in more detail.

To synchronize all stations, the GPS signal will be used. Both the time as the clock of the GPS will be used in the stations.

3.3 Architectural decomposition of the system

The top level architecture of the remote station is depicted in Figure 6. In this diagram the choices made in the previous sections are reflected.

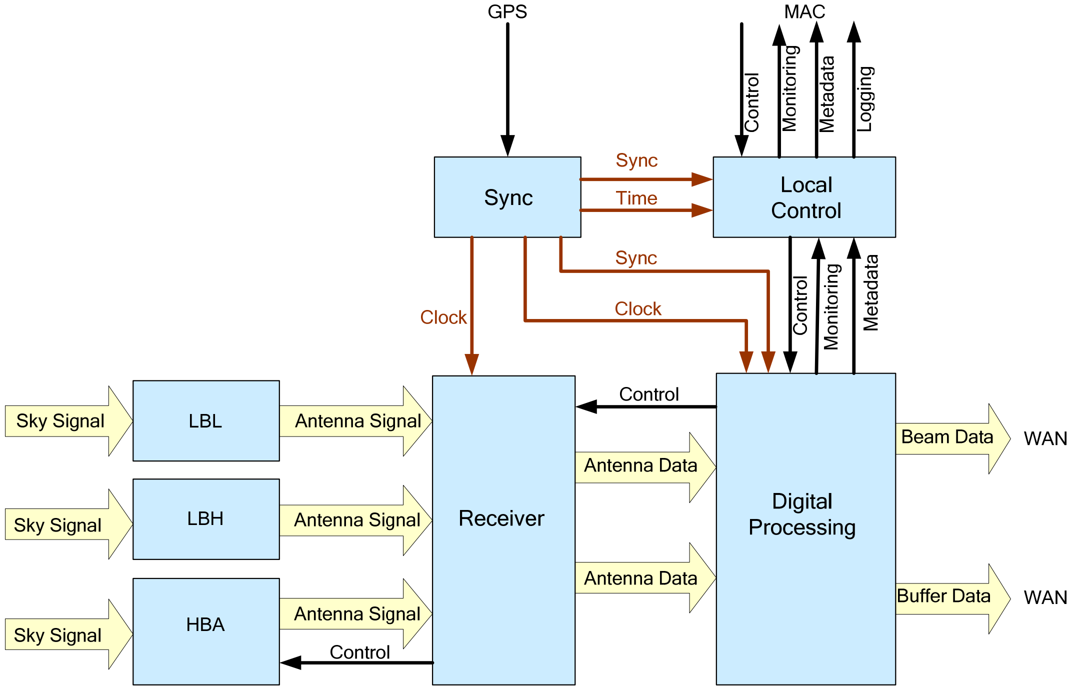

Figure 6 *Station top level architecture*

4 Subsystems description

4.1 The low band antenna

The LBA consists of two perpendicular inverted-V shaped dipole antennas [12], because this antenna type has an almost frequency independent radiation pattern over a wide frequency band. The antenna is optimized for a frequency range of 30-80 MHz.

In the low band antenna design a filter with a strong high-off behavior is used to reject the strong FM signals at the higher end of the band. The signal is amplified with a low noise amplifier in such a way that the noise contribution of the coaxial cable between the antenna and receiver can be neglected [14]. The power for the low noise amplifier of the antenna is delivered by the same coaxial cable which transports the signal in the reverse direction. To save on costs, studies have been done to use different coaxial cable lengths. However, loss and length compensations must be done to compensate for the different lengths. The impact of this is discussed in [19].

The electronics of the LBA are integrated on one Printed Circuit Board (PCB) for both polarizations. This PCB is potted to withstand the environment for 15 years. The antenna is kept up right by the use of guy wires [12].

4.2 The high band antenna

The HBA is optimized for a frequency range from 120-240 MHz. To achieve an effective area of about 1000m^2 for a complete station 16 times more antenna elements are needed compared with the LBA. The 16 antenna elements are integrated into a 4x4 array, to use the same signal paths as for the LBA elements.

The antenna concept chosen for the HBA antenna elements is the bowtie antenna with holes in it to save costs. After investigating different dipole structures this element type has been chosen because of the input impedance is lowest for this structure [5]. Two dipoles will be used to accommodate two polarizations.

To achieve sufficient signal to noise ratio the antenna signals are amplified close to the antenna. Each individual antenna signal can be delayed in 32 different steps in order to coherently add the signals for a certain direction on the sky. All antenna signals are summed together in the summator. A functional diagram of one polarization of the HBA is depicted in Figure 7 [4].

To save cost the HBA delays are controlled by control signals via the Y polarized signal cable [43]. The power of the array will be delivered via the X polarized signal cable, just like the LBA. A higher voltage than required is used to save on energy loss within the cable.

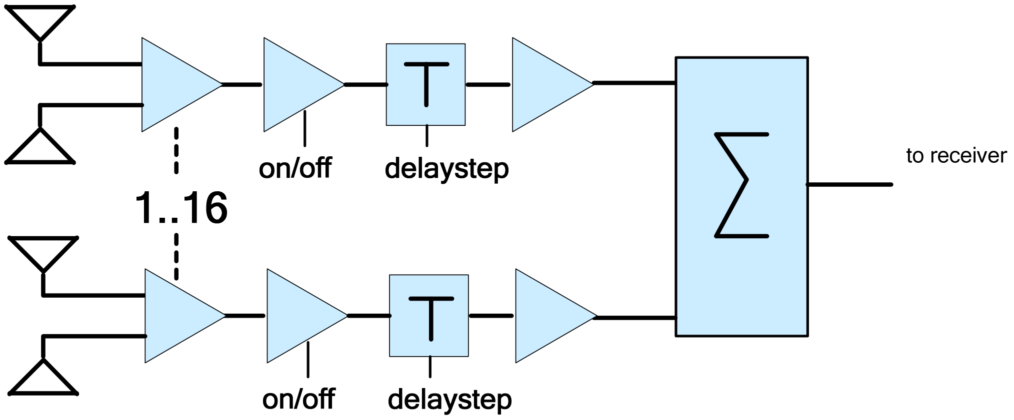

Figure 7 *Architecture of the HBA (only one polarization is shown)*

4.3 Receiver architecture

The receiver is able to accommodate three input signals:

- Low Band Low (LBL) for a frequency range of 10-30 MHz
- Low Band High (LBH) for a frequency range of 30-80 MHz (=Low Band Antenna)
- High Band Antenna (HBA) for a frequency range of 120-240 MHz

Two main signal paths can be distinguished on the receiver as depicted in **Figure 8**. The top signal path is shared by the LBL and LBH antenna, here a 10 MHz or 30 MHz high pass filter can be selected to optionally suppress the RFI signals below the 30 MHz. An additional filter is used to select the 10 - 90 MHz band of the antennas. This filter suppresses the out of band signals to reduce the amount of aliasing after sampling. The full low band antenna signals are sampled with a 200 MHz clock signal. This allows for an acceptable transition region of the filter to gain its specified suppression. Amplification is accomplished in multiple stages. The first amplifiers are optimized for noise, while the last amplifiers are optimized for linearity.

The bottom signal path of **Figure 8** shows the high band signal chain. In this chain the antenna signal is first filtered from 120 - 240 MHz and amplified. Since, the full high band frequency range cannot be covered by one Nyquist zone, three filters are used to select between:

- 110 – 190 MHz using a sample frequency of 200 MHz (2nd Nyquist zone)
- 170 – 230 MHz using a sample frequency of 160 MHz (3rd Nyquist zone)
- 210 – 250 MHz using a sample frequency of 200 MHz (3rd Nyquist zone)

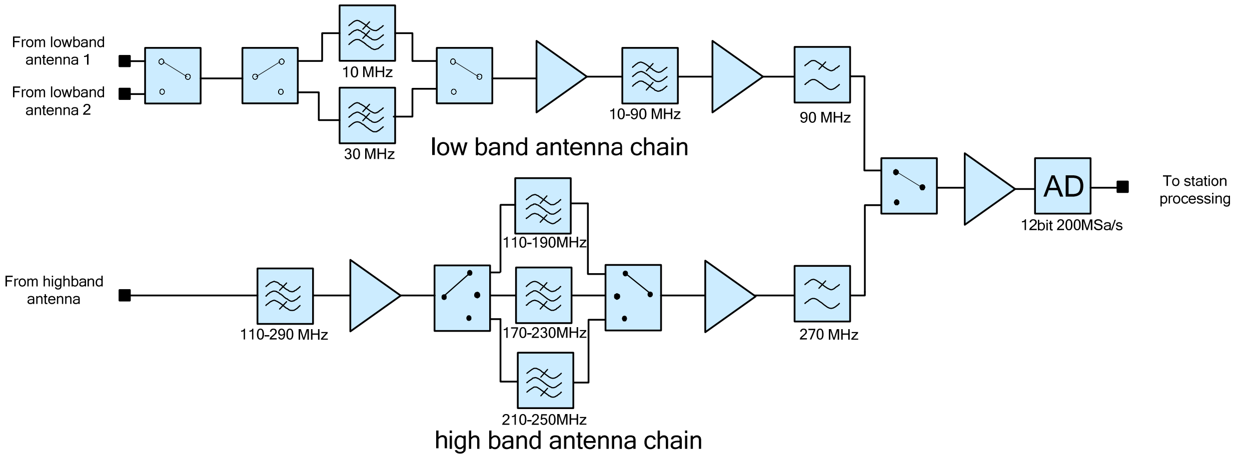

Figure 8 *Architecture of one data path of the receiver*

To cope with RFI signals on top of the sky noise signals, a 12 A/D converter is used. Roughly 3 bits are used to cover the sky noise and the rest for the RFI headroom [44]. Furthermore, the receiver is designed to be sky noise limited as specified in Section 2.2.

4.4 Digital Signal Processing

In Figure 9 a flow diagram of the digital signal processing functions, including part of the control is depicted. In red and orange the real time processing and in cyan the processing with less timing critical requirements and the control is depicted.

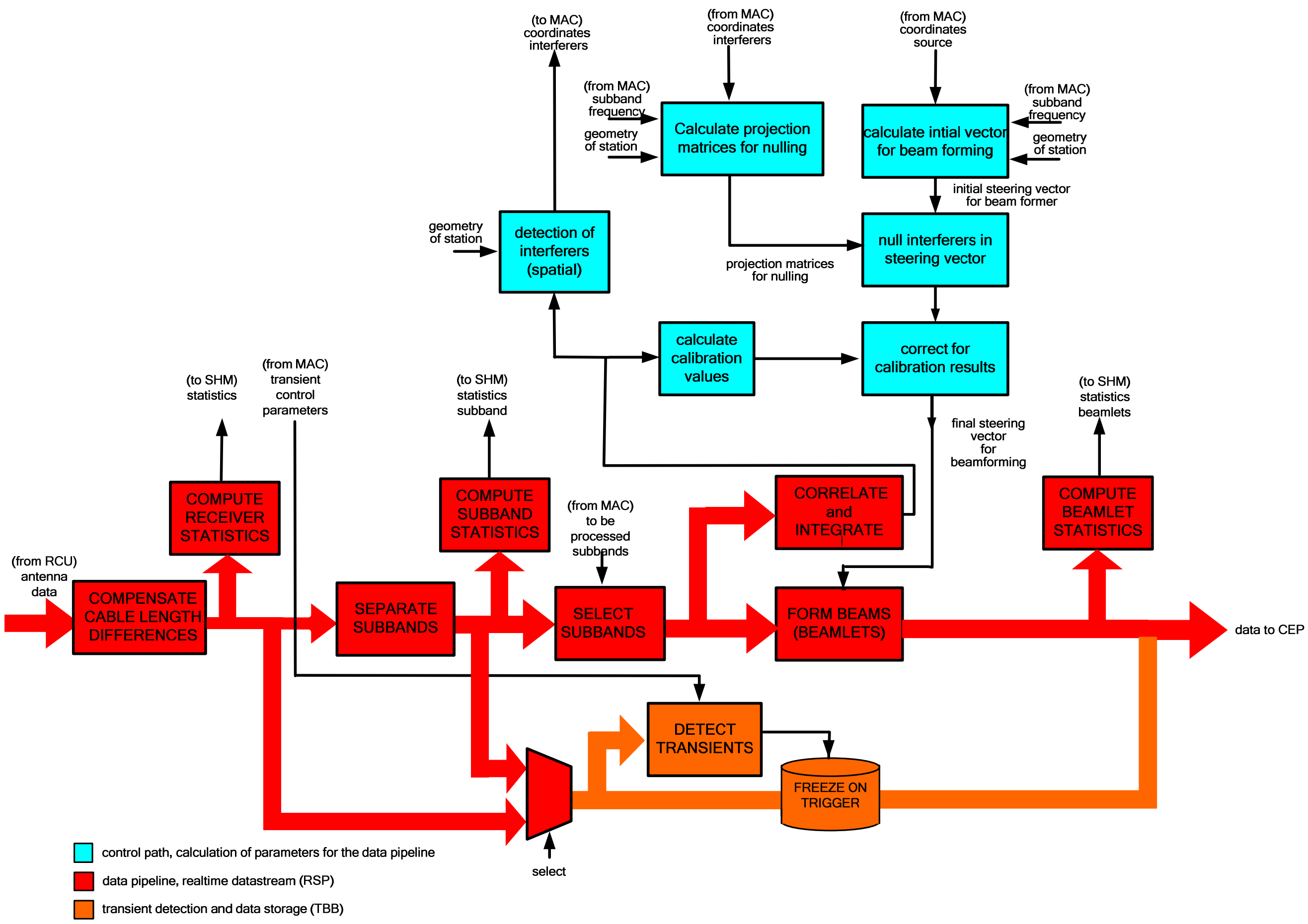

Figure 9 *Flow diagram of the digital signal processing and control*

The main tasks distinguished in the data path (from left to right) are:

- Delay compensation for cable length differences. This is implemented as a true time delay by a FIFO buffer.
- Subband filter to divide the received band into smaller subbands.
- Subband selector to select 32 MHz out of the received band.
- Beamformer to select a part of the sky.
- Transient buffer selector to select raw data or subband data for storage.
- Transient detection algorithm.
- Storage buffer to save either raw data or subband data.
- Cross correlator for calibration and RFI detection.

Additionally the digital processing calculates metadata for System Health Management (SHM). The following metadata is generated:

- Calculation of subband statistics.
- Calculation of beamlet statistics.
- Monitoring the temperature and the supply voltages of the processing boards.
- Monitoring the ReCeiver Unit (RCU) supply voltages on the Subrack Power Unit (SPU).
- Calculate receiver statistics like DC-offset and overflow.

Apart from the processing the control of the RCUs and the clock board is done on the processing boards as well (not shown in Figure 9 for clarity).

In the top of Figure 9, the interface and parts of the control are given related to RFI mitigation and calibration. The calibration of the analog signal paths is necessary because temperature variations of the environment cause gain and phase drifts in the signal paths. These gain and phase drifts should be compensated [7]. Furthermore production tolerances results in static gain and phase differences between the signal paths. The complex beamformer weights applied to each antenna signal and for each subband is an excellent way to be used for the calibration as well.

In order to calibrate all signal paths a full cross correlation matrix can be calculated for one subband integrated over one second. This information is input for the calibration algorithm as shown in Figure 9. A full bandwidth calibration can be done by hopping through the band, taking each second another subband. Approximately 10 minutes are required to go through the full 100 MHz or 80 MHz band.

The cross correlation matrix is also used for the RFI detection algorithm, which localizes possible interferers. This information is send to MAC and can subsequently be sent back to the stations based on decision algorithms fed by the interferer information from all stations including the history. If interferers need to be suppressed from certain directions, the coordinates are fed into the station control system and the projection matrix for nulling is calculated. This results into a steering vector which is applied in the beamformer weight.

The initial beamformer weights are calculated locally from the coordinates which are set by MAC. The coordinate of the source is only set at the start of the observation. For the duration of the observation the weights are calculated based on the J2000 standard epoch. The reason for doing this calculation locally is because the station should be able to operate for one hour autonomously [1].

The main data processing is accomplished on the Remote Station Processing (RSP) boards ([32] [34] [35]) and the transient detection and storage on the Transient Buffer Board (TBB) ([33] [36]). These functions are split into two boards to reduce complexity and to enable cost savings if not all stations have to be equipped with storage. The processing on the RSP and TBB boards are done with FPGAs. With these devices, parallel processing, like the filterbanks and beamforming, can be done on streaming data with timing requirements meeting the specification for an affordable cost. Furthermore, the devices can be updated remotely to allow for future changes.

In the following subsections the design topics of the digital boards are discussed in more detail.

4.4.1 Beamformer and station correlator architecture

The beamforming and correlation are combined operations on data streams coming from different antennas in the LOFAR data path. For these combined operations different architectures are possible. In the LOFAR station the so called ring architecture has been chosen, where the processors which perform the calculations are arranged in a ring structure. The ring will span all 96 processing elements corresponding to the 96 dipoles per polarization in a station.

The ring structure is chosen based on the following arguments

- Uniformity of processing boards. One or more processing elements will be mapped on a processing board. All processing boards acting within the ring can be equal.
- Scalability. It is easy to build stations with less and more antennas by just taking away processing boards or adding processing boards in the ring
- Distributing the interconnection between all boards, instead of one large central board.
- Possibility to perform also correlation on the same processing board

- With multiple data outputs distributed around the ring, the impact of a broken link is reduced. This is further enhanced by the possibility to inverse a part of the ring direction (the ring is actually broken up in four sub rings).

The summation operation of the beamformer is partitioned over all processing boards as depicted in Figure 10. Each processing board adds the result from its neighbor in the ring to its own to create a partial sum. The partial sum is forwarded to the next board. Each board is able to send the final beamforming result to WAN. In total four boards (because of the four sub rings) will be configured to sent out the data to WAN.

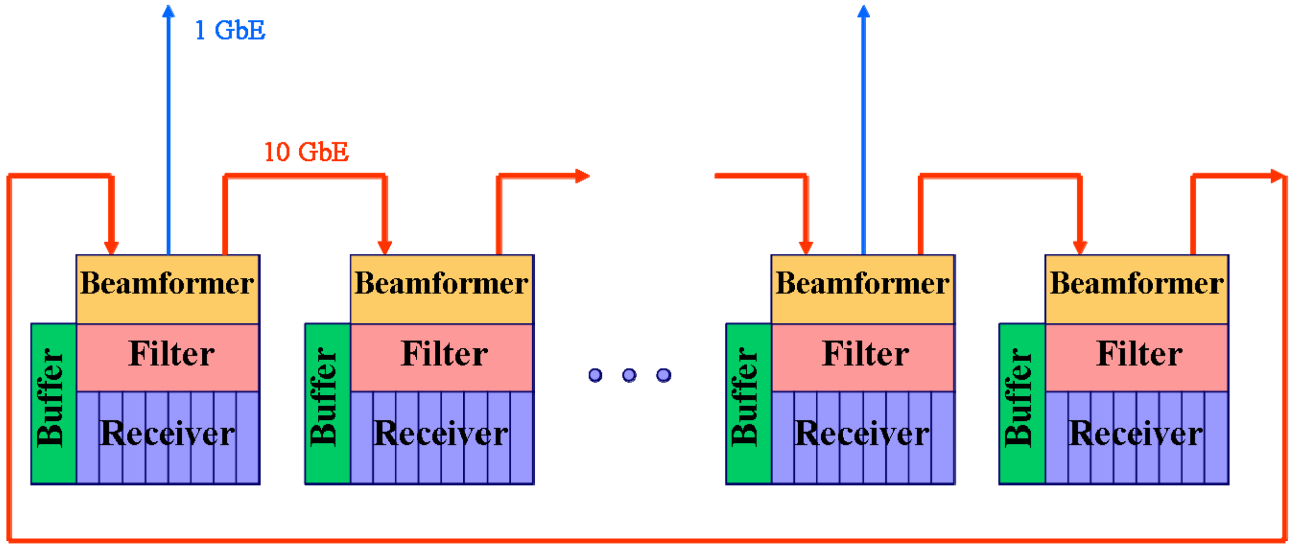

Figure 10 *The ring architecture used to calculate the beamformer products and correlation results*

Each beamformer processing step operates on subband data, resulting in an independent subband beam, also referred to as beamlet. Beams over a wider frequency range will be composed out of multiple beamlets with the same pointing on the sky. The total available bandwidth of 32 MHz can be used in a flexible way by exchanging beams for bandwidth. One beam can be formed with the full 32 MHz bandwidth or at the other extend 8 independent beams can be formed with a bandwidth of 4 MHz. The number of simultaneous beam directions that can be made is limited by the control system, which is responsible to calculate the weights, to 8 independent directions. The hardware puts no limit on the number of beams which can be created till an aggregate of 32 MHz.

The station correlation is implemented via the same ring architecture. For one subband the antenna data from all antennas will be transported via the ring to each board. On each board the correlation products of the antenna data on the ring with the local antenna data are calculated. Hence, the correlation is distributed over all boards.

The correlation works in parallel with the beamforming, which accommodates on-line station calibration and RFI detection.

4.4.2 Station data storage architecture

Since at least two of the major science applications require a storage function in the field, a dedicated Transient Buffer Board (TBB) will be installed. It is possible to either store raw data or subband data. The main reason to store subband data is to exchange storage time for bandwidth.

On the RSP board a selection between raw data and subband data will be accomplished. The data is packed and a header is included with the time stamp and type of the data. From there on the data is send to the TBB.

A transient detection algorithm will be implemented on the TBB and will provide various parameters to experiment with the trigger algorithm [6]. In the trigger algorithm the input data is filtered with a number of notch filters to remove strong RFI signals. This prevents false triggering on RFI. If a trigger is generated a message is sent to the LCU, including additional information about the length, time and power of the triggered signal.

In MAC the trigger is analyzed and if multiple triggers are detected from more antennas in a station or from more stations, a freeze signal can be sent to all or parts of the TBBs in the stations. After freezing the buffers, parts of the storage contents (or completely) can be sent to CEP (the amount of data depends on the application).

The data from four receivers are stored in one memory bank consisting of two memory modules [33]. The four memory banks on the TBB are connected in a ring structure which makes it possible to store one input signal over multiple banks in order to trade antennas for storage time.

For the TBB, DDR2 memory has been chosen. It is expected when roll out of LOFAR starts that these memory modules are the standard PC memory modules. That will make them better available and cheaper. Using standard memory modules makes increasing memory size, and thus storage time possible.

4.5 Station Control

In this section the focus will be on the control initiated by the LCU as described in [16]. In this section the main tasks for the Local Control Unit will be summarized. The LCU has to be able to control the station system with real time requirements, because the weights of the beamformer need to be set on a fixed time tag each second.

In Figure 11 the interaction of the LCU with other subsystems is shown. All subsystems in the station are controlled via the digital processing boards. The receiver passes the control information for the HBA through.

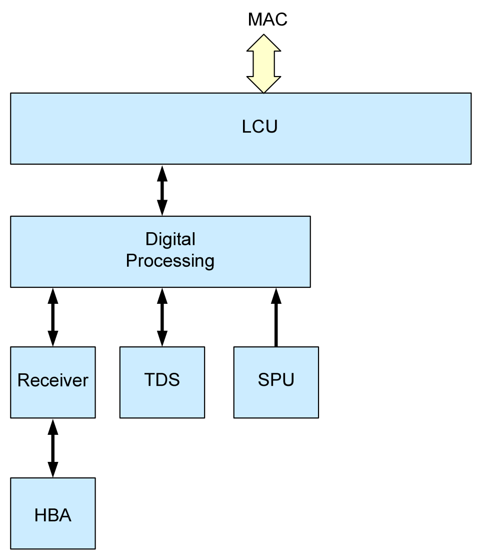

Figure 11 *Overview of station control*

4.5.1 Synchronization

From the clock and time distribution unit the LCU will get the Universal Time (see Figure 6). This time is used to schedule the observations. For time synchronization between the output data streams of multiple stations, the time is sent to the RSP boards which will include a one second time stamp in the data packages towards CEP.

4.5.2 Digital Board Control

The communication with the digital boards is done by raw Ethernet. Raw Ethernet has been chosen to reduce overhead by the TCP/IP stack. The communication is done with a data rate of 100 Mbit. This is sufficient for the update rate of 1 second. Upgrading of this interface to 1 Gbps is possible to accommodate for faster update rates in the future. To prevent collisions the LCU is acting as master. More information about the interface between RSP and LCU can be found in [31].

4.5.3 Calibration

The CEP self-calibration routine requires a reliable initial estimate of the station beam shape. The aim of calibration at station level is to ensure sufficient control over the station beam to fulfill this requirement [17]. For the calibration the antennas are correlated on the RSP boards. Each second a new Auto Correlation Matrix (ACM) for one subband will be calculated. On the LCU this data will be used to calculate the gain and phase differences of the signal paths. The update rate of a full band calibration is 10 minutes. This should be sufficient to compensate for temperature influences. As calibration source an astronomical or a RFI source will be used. More information about the calibration for core stations is discussed in [7].

4.5.4 Beam Server

The various transformations required to go from sky coordinates (Ra,Dec J2000) to beamformer weights are done in the beam server. The beam server is capable of simultaneously calculating beamformer weights for 8 independent beams.

4.5.5 RFI Detection and Mitigation

Given the 10% occupancy of RFI in the LOFAR band [21], RFI detection and mitigation is an important part of the LOFAR system. The ACM information is used to detect interferers. Given the interferer locations the beamformer weights can be modified to null interferers [18].

4.5.6 Monitoring

The LCU receives the monitor information from the digital signal processing. Additionally, cabinet monitoring information is available. The following monitor information will be available:

- A/D converter overflow
- Supply voltages for the receivers
- Supply voltages on the digital boards
- Chip temperatures of the FPGAs
- Temperature in the cabinet

Environmental sensors, like wind speed, temperature and open doors may be added in a later stage as well.

4.6 Clock Distribution

The LOFAR clock distribution is responsible for the distribution of absolute time to the LCU. This time should be known by the LCU in order to apply the beamformer weights calculated for a particular second on the right pulse of the PPS (Pulse Per Second) signal. Furthermore the clock distribution should distribute a stable and equal sampling clock for each A/D converter (in total 192 are necessary). A stable clock is necessary in the long term to prevent decorrelation in between stations and for the short term to achieve the noise requirements of the RCU [22].

Due to the distance in between the stations and noise specifications of the clock and time distribution, a satellite clock/time source has been chosen above equal length copper/optic clock distribution. Because of the availability of GPS satellites and receivers, this clock and time source has been chosen above Galileo [23].

In Figure 12 the generation of the clock and the distribution of the synchronization signal in a station are depicted. The output of the GPS receiver is a time signal for the LCU and a Pulse Per Second (PPS) signal to synchronize the reference clock source and the complete station system. To remove PPS inaccuracies from the GPS (not accurate enough for the short term), a stable clock source is necessary [24]. With a Rubidium (Rb) reference the variance in the GPS-PPS can be reduced to < 4ns rms over 10^5s. The output of the Rb reference is distributed to the time distribution board in a subrack (TDS). Here the reference frequency is converted to the sampling frequency. By using a 10 MHz reference and Phase Locked Loops (PLL) in combination with a Voltage Controlled Crystal Oscillator (VCXO), the jitter of the output clock signals are minimized. Within a subrack all clock distribution is done differentially; this is done to reduce noise picked up by the clock traces and to reduce Electro Magnetic Interference (EMI) by the clock. By tuning the clock traces on the TDS and the backplane for equal line lengths, the simultaneous sampling of the receivers is ensured.

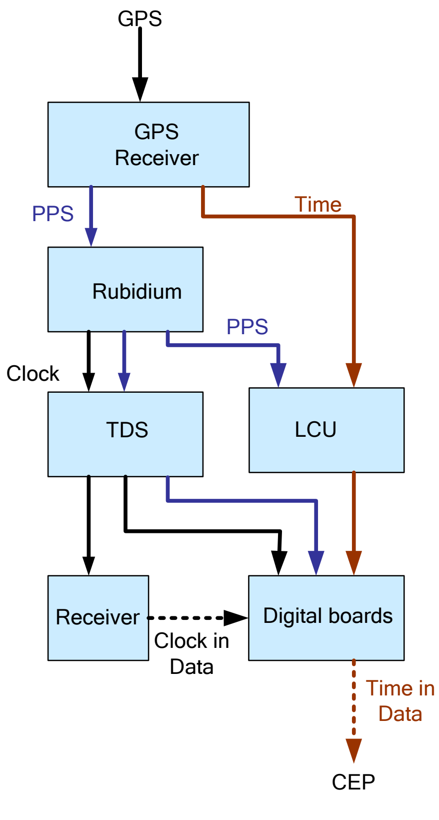

Figure 12 *Station clock and time distribution overview*

5 Station infrastructure

In this section an overview of the station infrastructure is given. More details about the infrastructure can be found in [36].

5.1 Housing

The housing of the subsystems is not only needed for mechanical purposes but it also ensures that inter board disturbances are minimized. For mechanical purposes a 19" system has been chosen. With this system, standard equipment can be used. Although the housing of the subsystems is indoor, special care must be taken with corrosion. Corrosion is caused by a high humidity especially when the cabinet doors are open. This will reduce conductance between the front panels and the racks, which will reduce EMI shielding.

For the electronic requirements of the housing, the EMI performance is the main topic. This includes not only emission to the outside of the rack but also within the rack. Cross talk reduces by applying more distance between current loops. In other words, noisy boards must be separated from sensitive boards to reduce cross talk. In the LOFAR subrack this is done by placing the sensitive receiver on one side of the subrack and the noisy digital boards on the other side. The reduction is further enhanced by grounding the backplane on all sides. By placing additional metal plates between the analog boards cross coupling between receivers is reduced. With special EMI shielding between the front panels coupling on this side is reduced as well. Furthermore, the emission of EMI is reduced by using low volt differential signals (LVDS) for all traces between the digital and analog parts and placing the trace between ground planes as much as possible.

The station hardware (except for the antennas) is housed in an outdoor housing. This housing has the following goals:

- Environmental protection
- Temperature control
- EMC protection for the antennas in the field

In [15] the housing is described in more detail.

5.2 Station board partitioning

The station subsystems as discussed by the previous section are implemented on dedicated hardware because no off the shelf solutions are available to meet the requirements of the station system. To isolate receiver signal paths from each other, one receiver chain is placed on an individual board. A backplane acts as a shield between the analog and digital board. At the digital side the RSP boards are placed. The number of signal paths which can be dealt with on one RSP is in total 8, accommodating 4 antenna signals (dual polarized) per board. This was the maximum number of antenna signals which could be integrated on a board for a 19" system with reasonable complexity and cost.

Since the digital processing complexity of the TBB is much less, 16 signal paths could be integrated on that board. Hence, one TBB is served by 2 RSP boards. This limits the exchange between antenna and storage time to a factor of 16. The backplane can connect 32 RCUs (signal paths), which is a balance between a high density and cross talk. A consequence is that 4 RSP boards and 2 TBB boards are required at the digital side. Furthermore, a Time Distribution Board (TDS) responsible to deliver all clock signals and a Station Power Unit (SPU) is included in a subrack. The SPU delivers the power for all units in the subrack and all the antennas connected (via the RCU). Finally with the JTAG Test Board (JTB) the testability of the subrack is ensured.

In summary the subrack houses 32 receivers, 4 RPS boards, 2 TBB boards a TDS a SPU and a JTB. This means that 16 antennas can be connected to 1 subrack. In other words, an efficient utilization of the subracks would be to use a multiple of 16 antennas in a station (that is why 96 antennas are connected to one station). A schematic picture of the hardware of one subrack is shown in Figure 13.

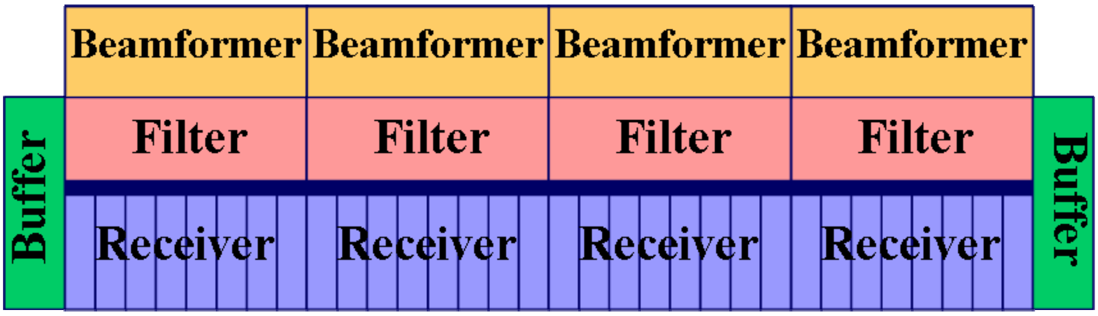

Figure 13 *Schematic picture of the station hardware of one subrack excluding TDS, SPU and JTB*

5.3 Power Supply

The power input of a station consists of 3 phases with a voltage of 400V AC. This input supply is filtered in a line filter and fed to a distribution unit [30]. From this unit the power for the LCU, switches and the AC/DC converter is distributed. The AC/DC converter converts the 3 phases to 48V DC. This voltage is a compromise between safety, and cable loss. Lower voltage will introduce more loss, while a higher voltage will set more constrains on the power supply. The 48V AC/DC converter is a telecom standard power supply. On the power supply over current protection is applied by Modular Circuit Breakers (MCBs).

As can be seen in Figure 14, the 48V power is fed to the Subrack Power Unit (SPU) which will distribute the power in the subrack. On the SPU circuit protection circuits are placed to protect against under and over voltage and over current. The local supplies for the RCU and the LBA are made on the SPU.

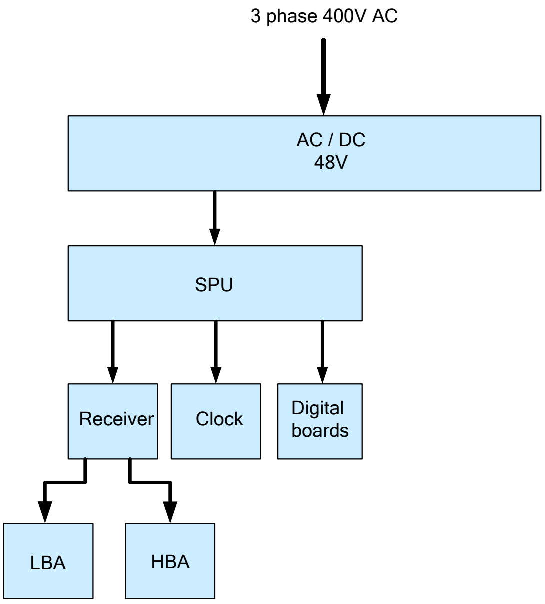

Figure 14 *Station power distribution overview*

5.4 Grounding

The grounding method used for the LOFAR station is mesh grounding. This means that all grounds, signal reference, power ground and earth ground are connected to each other. Furthermore at the entrance of the cabinet the antenna cable is grounded to the chassis of the cabinet. This will not only protect the electronics from lightning but ground loops are kept to a minimum. From here the antenna inputs are connected to the receiver units. On the receiver unit the connector is connected to the front panel and thus to the chassis of the subrack. At the subrack power unit, the power ground of the subrack is connected to the chassis.

To reduce ground loop effects and EMI emission all connections between the boards are done with differential connections. This is done for the ring interface (in between the RSP boards) by using Infiniband cabling and for the data interface with UTP (Unshielded Twisted Pair) cabling.
The cabinets have a ground pin enabling a low impedance path to earth ground; this is needed for lightning protection. For the same reason a lightning conductor is placed on the highest point of the cabinet [37].

5.5 Temperature Control

For the temperature control in the cabinets, heat exchangers have been chosen above air conditioning. Air conditioning has the benefit of a constant temperature independent of the outside temperature. However air conditioning has a typical efficiency of 40%, meaning that using an air conditioner to cool the cabinet will increase the power consumption with 40%.
The temperature analysis of the station hardware can be found in [38]. From this document is concluded that the maximum ambient temperature is 31ºC. With higher temperatures the power consumption of the cabinets must be reduced. This can be done by using for example the modes in which the A/D converter samples at 160 MHz. For that case observations can continue to approximately 35ºC. With even higher temperatures the station or part of the station has to be shutdown to prevent significant lifetime reduction.

5.6 Testability

The testability of the station has been taken into account from the start of the design [29]. All digital interconnections on the boards, but also between the data interfaces between the RCUs and the RSP and between the RSPs and the TBB are testable at low speed with boundary scan and at high speed with test patterns. These tests can be done during roll out but also remotely during operation. For this purpose a JTAG distribution board (JTB) is placed in the subrack. On this board an Embedded test Controller Board (ECB) from JTAG Technologies can be plugged. This board will have an Ethernet connection to the LCU. With special software the location of the errors can be found. The tests which can be done with the RSP firmware are described in [20].

6 Core Station Architecture

The stations in the central core will have additional hardware in order to cover a larger part of the FOV with digital beams. Instead of delivering 1 beam with a bandwidth of 32 MHz the core stations will deliver 24 beams each 32 MHz wide. For the hardware in the core station the hardware for the remote station can be used with an addition of extra hardware to create the extra beams. This means that for observations with remote stations the stations in the central core can be used as if they are remote stations (delivering each one beam with a bandwidth of 32 MHz). In contrary observing in the core stations mode will disable the remote stations.

Normally the system is able to transport at most a single 32 MHz beam from 77 stations to the central systems. The 24 beams mode will re-distribute the total I/O and CEP processing capacity so that it is fully used by the 32 core stations. In order to accommodate the 24 beams, a factor 4 reduction in data-rate will be achieved by bit-reduction: the 16 bit complex words will be replaced by 4 bit versions. This should be preferably done by selecting only the RFI free channels, however, since the second filterbank (which provides the ~1 kHz spectral resolution) is currently implemented in the CEP subsystem in Groningen, further modifications will be required.

Two options are possible:

- implement the channel filter bank in the core stations (note that the number of channel filter banks for the 24 beams mode is 24 fold the required number of channel filter banks in the standard mode)
- implement the bit reduction at the stations after the subband filter bank

Although the architecture of the core station hardware is not fixed, some general remarks can be made. Instead of beamforming on the RSP the data is transmitted to a Core Station Processing (CSP) board. For this transmission the ring interface is used and re-routed to CSP boards. On the CSP boards all 24 beams are formed for a part of the bandwidth. With minor modifications the bandwidth can be split into a factor of four because the ring was implemented by using sub rings. When the total data rate to the CSP boars is to high than a further split up is necessary [28].

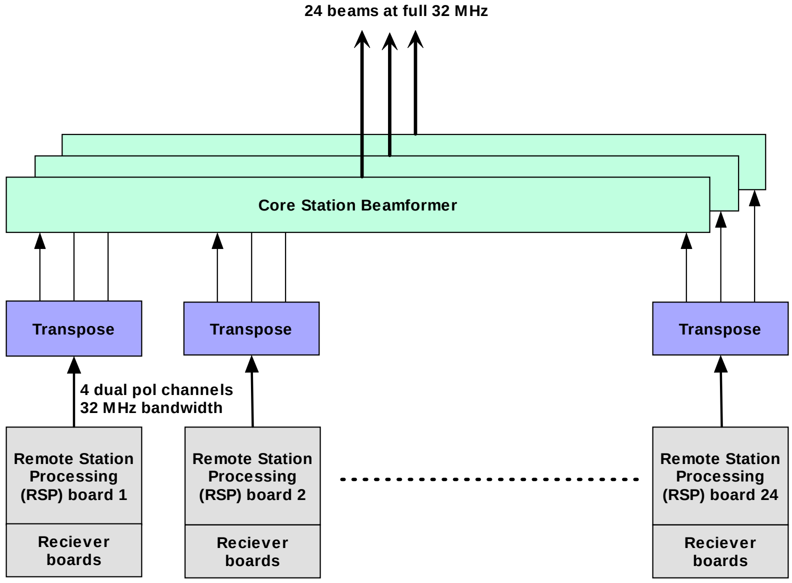

Figure 15 Architecture of a Core station.

7 Compliance

In this section the station compliance compared with the requirements is discussed.

7.1 Functional

7.1.1 General

LOFAR is able to measure electromagnetic radiation from 10-240 MHz and is optimized in the bands 30-80 MHz and 120-240 MHz. Also above 240 MHz to about 270 MHz can be observed with loss of sensitivity.

A station can be split up in so called subarrays. Those subarrays are a subset of the total number of antennas and can operate in different modes. The only exception to this is that the sample rate for all antennas must be set to the same value.

The number of signal paths used in a station is 96, which equals the number of antennas available. The total number of antennas within LOFAR depends on the number of stations which will be installed.

7.1.2 Signal quality

The number of bits used in the A/D converter is sufficient to observe signals, including RFI sources with a strength up to 40 dB on top of the whitened integrated sky noise in at least 32 MHz.

The proposed RFI detection and mitigation makes it possible to detect RFIs at the station level by using the cross correlation matrix. With additional software this information can be used to null interferers as well. That is not yet implemented in the station.

The same cross correlation matrix is used to calibrate the signal paths in the station. This can be done each second for one subband or the full bandwidth in about 10 minutes.

The phase relations between subbands can be measured by the station calibration and hence are known.

7.1.3 Performance

The maximal output bandwidth of a station is:

- 42.19 MHz in the 200 MHz clock mode
- 33.75 MHz in the 160 MHz clock mode

This can be regulated to the required 32 MHz by the LCU.

In hardware no restriction in the amount of beams is present, i.e. the number of beams can be equal to the number of beamlets because all operate independent of each other. However, the LCU needs to calculate all settings for all beams each second. The design is such, that with an off the shelf computer this can be done for maximal 8 independent beams.

The restriction of multi beaming is that the bands are located in the same frequency band of the receiver (same mode) and for the HBA in the same main lobe of the antenna array. The number of beams and the bandwidth can be exchanged from 1 beam with 32 MHz bandwidth to 8 beams of 4 MHz. The beam update rate is set to once every second and the beams can be pointed to any direction of the sky with a 0.005º resolution.

A scheduled switching sequence can be done on the one second grid, which is currently used by the LCU to communicate with the hardware. One second should be sufficient to re-synchronize the clock (if a clock setting is switched as well). Current precautions in the control software limit us to test the 1 second switching (no priority is given to this yet). The previous also accounts if there is a scheduled trigger response.

7.1.4 Transient Detection

With the TBB a flexible buffer has been made. It is possible to sample the raw 200 MHz wide inputs for 1 second. This time can be extended by reducing the bandwidth or the number of antennas which are simultaneously stored [33]. The TBB operates in parallel with the "normal" data stream and can be readout on request.

7.1.5 Miscellaneous

The LOFAR stations can provide statistical information to the system health system, each second. This includes autocorrelations of all subbands, cross correlation of one subband and the autocorrelations of all beamlets, which are transported to CEP.

A cold start up time will meet the requirement of 24 hours. The most important limit in these is the GPS and the Rubidium module, which needs time to stabilize. Since, for a warm start up time the GPS is locked and the Rubidium module is already stable the 4 hours will be met easily.

There is not yet a LOFAR EMC standard available.

7.2 Noise

In Figure 16 the noise behavior of the receiver in the low band mode is shown. This plot has been made with the subband statistics of the RSP running at a 200 MHz sample frequency. In cyan the noise of the A/D converter is shown and in brown the noise of the RCU. To measure the antenna and LNA without the sky noise the antenna is placed in an anechoic room. The results are shown in light brown and blue for the 10-90 MHz mode and 30-90 MHz mode respectively. In green and magenta the noise is shown with the antenna in the open field for the 10-90 MHz mode and 30-90 MHz mode respectively. From this measurement it can be seen that the receiver is sky noise limited (11-50% of the measured noise is receiver noise) between 38 and 70 MHz. The receiver noise requirement of <20% (7 dB) of the sky noise is met between 50 and 62 MHz. This non-compliance is caused due to a lower gain in the LBA than budgeted. An improvement can be made by increasing the gain of the receiver.

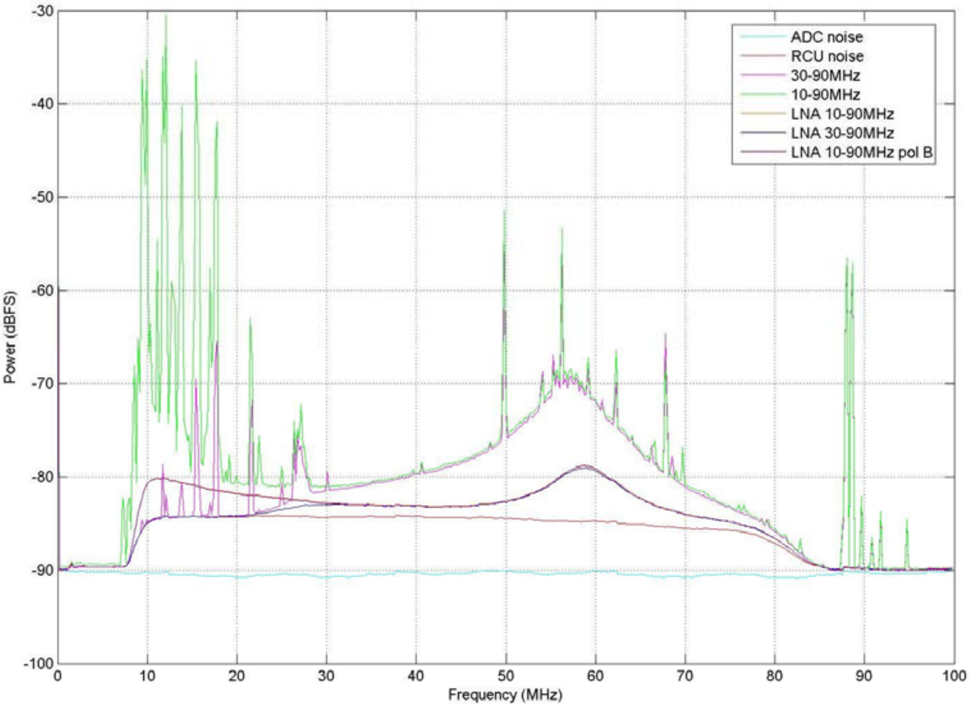

Figure 16 *Receiver noise in LBA mode*

For the high band no measurements have been made yet.

7.3 Linearity

In [42], the linearity requirement is validated based on simulation results with the measured Output Intermodulation Products (OIP) of the LBAs. From there was concluded that the simulation results show that the soft spurious requirement is violated about 4 percent of the time if the 10 MHz high pass filter in the receiver is used. When the definition of in band is defined as 30 - 80 MHz, however, the violation only occurred less than 1 percent of the time.

The linearity of the receiver is validated in [41] and conform the requirement. It should be noted, that intermodulation products of signals outside the band of interest can fold inside the band.

7.4 Selectivity

The filters in the analog circuitry have a suppression of 80dB to out of the band signals while maintaining a passband ripple of 2dB. The suppression of signals in the stopband of the digital filters is 80 dB, while the ripple is +/- 0.5 dB merely at the edges of the subband. The transition region is 0.25 of the subband width, on both sides of the subband [40].

7.5 Clock Accuracy

The jitter of a TDS is <1.5ps [39]. This means that for full power signals above 170 MHz the signal to noise ratio is decreased. The time difference between two remote stations is < 4 ns rms and the maximal drift is <30ps/10s.

7.6 Stability

Although no direct requirements have been given on stability the temperature, time and wind stability was measured and resulted in the numbers as summarized in Table 1. A full band calibration cycle of 10 minutes should be more than sufficient to calibrate for these instabilities.

Stability	Temperature		Time (RMS)		Wind	
	Amplitude (%/°C)	Phase (deg/°C)	Amplitude (%)	Phase (deg)	Amplitude (%)	Phase (deg)
HBA						
LBA	0.1	0.06	0.12	0.03	2	1
Coax	0.2	0.4				
RCU (LBA)	0.1	0.1	0.13	0.14		
RCU (HBA)	0.2	0.2	0.7	0.24		
Clock				0.4		

Table 1 *Stability parameters of station hardware*

7.7 Temperature

Problems may arise with high ambient temperatures. When these temperatures exceed 35ºC the stations have to be shutdown to prevent damage.

7.8 Overview of station parameters

In Table 2 and Table 3 the numbers of some key parameters of a station are given.

Description	Value	Unity
# subbands	512	
Max. number of beams (B = 4 MHz)	8	
Min. number of beams (B = 32 MHz)	1	
A/D converter resolution	12	bit
Sample frequency	200 / 160	MHz
Number of polarizations	2	
Output word width (complex)	16+16	bit
Aggregate output bandwidth	32	MHz
Output data rate	2048	Mbit/s
Transient buffer storage period	1	s

Table 2 *Station key parameters*

Description	Value for fs of		Unity
	160 MHz	200 MHz	
Subband width	156	195	kHz
Number of beamlets	206	165	

Table 3 *Station parameters as function of sample frequency*

8 References

[1] M.P. van Haarlem, H. Kollen (editor), LOFAR System Requirement Specification, LOFAR-ASTRON-SRS-001, March 2007
[2] A. Huijgen, Subsystem Requirement Specification LOFAR Remote Station, LOFAR-ASTRON-SRS-012, June 2004
[3] A.W. Gunst LOFAR Architectural Design Document of the Astronomical Applications LOFAR-ASTRON-ADD-006, March 2007
[4] G.W. Kant, A.W. Gunst, HBA ADD, LOFAR-ASTRON-ADD-016, March 2007
[5] M.J. Arts, Overview of antenna types for the HBA, October 2004
[6] A. Horneffer, S. Lafèbre, The LOFAR VHECR Trigger, LOFAR-ASTRON-SDD-055, 2006
[7] S.J. Wijnholds, Study on LOFAR Core Calibratability Based on Source Statistics, LOFAR-ASTRON-MEM-205, April 2006.
[8] S.J. Wijnholds, Theoretical analysis of the main lobe effects of beamsquint, LOFAR-ASTRON-MEM-151, June 2004
[9] J.E. Noordam, Dealing with the LOFAR BSR effect: A Bandpass Sawtooth Ripple due to the sub-band beamformers, April 2004
[10] S.J. Wijnholds, Pre-correlation Signal Processing Baseine, LOFAR-ASTRON-MEM-105, August 2003
[11] B. Razavi. RF Microelectronics. Prentice Hall, Upper Saddle River, NJ, 1998.
[12] W.A. van Cappellen, Low Band Antenna Architectural Design Document, LOFAR-ASTRON-ADD-009, March 2007
[13] A.W. Gunst, Balancing Bits and Bandwidth for the A/D Converters of, LOFARLOFAR-ASTRON-MEM-121
[14] M.J. Norden, G.W. Kant, RCU II Signal Analysis and Specification LOFAR-ASTRON-SRS-014
[15] Y. Koopman, LOFAR Outdoor Cabinet, LOFAR-ASTRON-RPT-073
[16] K.J. Wierenga Detailed Design Remote Station Real-Time Control LOFAR-ASTRON-SDD-014
[17] S.J. Wijnholds Calibration Algorithms on the Local Control Unit, LOFAR-ASTRON-MEM-171
[18] A.J. Boonstra S.J. Wijnholds Implemention of the LOFAR Interference Mitigation Strategy, Considerations and Trade off , LOFAR-ASTRON-PUB-012, October 2006
[19] A.W. Gunst, Impact Analysis Unequal Antenna Cable Lengths within LOFAR, LOFAR-ASTRON-MEM-159, August 2004
[20] E. Kooistra Test Strategy for the RSP firmware LOFAR-ASTRON-MEM-185, March 2007
[21] A.J. Boonstra LOFAR RFI site studies for Drenthe LOFAR-ASTRON-RPT-097 2.0
[22] D. Kant Receiver Unit & Station Central Oscillator Subsystem Requirement Specification LOFAR-ASTRON-SRS-005
[23] A. van Houwelingen, G.W. Schoonderbeek, Detailed Description of Clock and Sync LOFAR-ASTRON-RPT-057, March 2007
[24] J. Roosjen, Frequentiestandaard LOFARstations, LOFAR-ASTRON-MEM-221 1.0, February 2007
[25] G.W. Kant, LOFAR Intermodulation Analysis and Specifications, LOFAR-ASTRON-MEM-174, November 2003
[26] C.M. de Vos, Some notes on LOFAR IP2/IP3 Specification, LOFAR-ASTRON-MEM-132, December 2003
[27] A.W. Gunst, Digital Filter Requirements, LOFAR-ASTRON-MEM-162, October 2004
[28] A.W. Gunst Core Station Baseline, LOFAR-ASTRON-MEM-224, July 2006
[29] A.W. Gunst Operational Test Strategy for the Remote Station LOFAR-ASTRON-MEM-179
[30] P. Riemers, Power Distribution and Ground Connections in station unit V4, LOFAR-ASTRON-EDR-003 1.0, July 2006
[31] W. Poiesz EPA-MAC Interface description LOFAR-ASTRON-ICD-002 1.0, March 2007
[32] G.W. Schoonderbeek, Remote Station Processing Board II Specification, LOFAR-ASTRON-RPT-039, August 2005

[33] G.W. Schoonderbeek, A.W. Gunst, Transient Buffer Board Specification, LOFAR-ASTRON-RPT-065, September 2005
[34] W. Lubberhuizen, E. Kooistra, RSP Firmware Functional Specification, LOFAR-ASTRON-SDD-001, September 2005
[35] W. Lubberhuizen, E. Kooistra RSP Firmware Design Description, LOFAR-ASTRON-SDD-018, September 2005
[36] A. Doorduin, W. Poiesz TBB Design Description LOFAR-ASTRON-SDD-047 1.0, October 2006
[37] M. Norden, Station Lightning Solution, LOFAR-ASTRON-RPT-122, March 2007
[38] G.W. Schoonderbeek, Station temperature analysis LOFAR-ASTRON-115, March 2007
[39] G.W. Schoonderbeek, A.W. Gunst, Subrack Measurements LOFAR-ASTRON-RPT-075, March 2007
[40] W. Lubberhuizen, Digital Filter Measurements LOFAR-ASTRON-RPT-121, March 2007
[41] G.W. Schoonderbeek, RCU II Measurement Report LOFAR-Astron-RPT-059 1.0, March 2007
[42] A.J. Boonstra, M. Tanigawa, LOFAR Interference Mitigation Approach and Measurement Results, LOFAR-ASTRON-RPT-104-1.0, October 2006
[43] E.Kooistra, HBA Control Design Description, LOFAR-ASTRON-MEM-175, V2.0, March 2007
[44] A.J. Boonstra LOFAR RFI Mitigation Strategy, LOFAR-ASTRON-DOC-004, October 2002
[45] A.W. Gunst, CDR Clock remainders, DMT meeting in Dwingeloo, December 21, 2005