Author: W.A. van Cappellen, M. Ruiter, G.W. Kant	Date of issue: 2007-03-21 Kind of issue: public	Scope: Low Band Antenna Doc.id: LOFAR-ASTRON-ADD-009
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Low Band Antenna

Architectural Design Document

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Accepted:		
Work Package Manager	System Engineering Manager	Program Manager
W.A. van Cappellen	A.W. Gunst	J. Reitsma

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Abstract

This is the Architectural Design Document of the LOFAR Low Band Antenna (LBA) subsystem. It gives an overview of the final design. The design tradeoffs and all implementation details are documented in separate engineering reports.

Table of contents

1 Introduction

1.1 Purpose of this document

This document gives a high level overview of the LOFAR Low Band Antenna and indicates where detailed information can be found.

1.2 Applicable documents

The LOFAR system baseline documents:

[1] LOFAR-ASTRON-SRS-001 LOFAR System Requirements Specification 3.0 03-05-2004
[2] LOFAR-ASTRON-SRS-004 Low Frequency Antenna Subsystem Requirement Specification 1.0
[3] LOFAR-ASTRON-ADD-006 System Level Architectural Design Document 4.0 11-12-2006

The following documents outline the detailed design and performance of the final LBA:

[4] LOFAR-ASTRON-RPT-040 Concept of Low Band LNA 2.0 24-09-2004
[5] LOFAR-ASTRON-EDD-008 Design and Measurement Report Low Band Antenna LNA
[6] LOFAR-ASTRON-RPT-107 EM-simulations of the final design of the LOFAR low band antenna
[7] LOFAR-ASTRON-MDD-008 LOFAR LBA Mechanical design at CDR
[8] LOFAR-ASTRON-RPT-077 Environmental tests on Low Band Antenna 1.0 24-04-2006

They are supported by the following detailed LBA documents which are available on the document server:

Electrical:

[9] LOFAR-ASTRON-EDD-002 Design report low-band LNA 1.0 24-09-2004
[10] LOFAR-ASTRON-RPT-005 Evaluation of the Rohde & Schwarz Active Antenna Unit 1.0 23-05-2002
[11] LOFAR-ASTRON-RPT-026 EM simulations of a LOFAR LBH antenna 1.0 29-08-2005
[12] LOFAR-ASTRON-RPT-030 Pattern measurement results and comparison with simulations of an LBH element 1.0 01-06-2005
[13] LOFAR-ASTRON-RPT-042 LOFAR LBA antenna pattern measurements with and without a metal ground plane 1.0 29-08-2005
[14] LOFAR-ASTRON-RPT-043 Influence of conductor material on the antenna noise temperature of the LOFAR low band antenna 2.0 29-08-2005
[15] LOFAR-ASTRON-RPT-044 Equivalent circuit of the LOFAR low band antenna 2.0 29-08-2005
[16] LOFAR-ASTRON-RPT-049 Low Band Antenna SE-LNA lab measurement results 2.0 23-11-2004
[17] LOFAR-ASTRON-RPT-050 The time-averaged power and the momentary voltages of a typical LOFAR RFI signal 1.0 01-12-2004
[18] LOFAR-ASTRON-RPT-053 Low Band Antenna PP-LNA measurement results 1.0 18-03-2005
[19] LOFAR-ASTRON-RPT-055 Common mode analysis of the LOFAR low band antenna 1.0 29-08-2005
[20] LOFAR-ASTRON-RPT-063 LOFAR LBA LNA3 measurement report 1.0 08-09-2005
[21] LOFAR-ASTRON-RPT-064 Low Band Antenna FTS-2 beam pattern simulations 1.0 10-01-2006
[22] LOFAR-ASTRON-RPT-068 LBA impedances in an array environment 1.0 24-10-2005
[23] LOFAR-ASTRON-RPT-071 Target scenario sensitivity simulations 1.0 09-11-2005
[24] LOFAR-ASTRON-RPT-099 LBA Station Beam Simulations, 1 of 5 1.0 25-10-2006
[25] LOFAR-ASTRON-RPT-100 LBA Station Beam Simulations, 2 of 5 1.0 25-10-2006
[26] LOFAR-ASTRON-RPT-101 LBA Station Beam Simulations, 3 of 5 1.0 25-10-2006
[27] LOFAR-ASTRON-RPT-102 LBA Station Beam Simulations, 4 of 5 1.0 25-10-2006
[28] LOFAR-ASTRON-RPT-103 LBA Station Beam Simulations, 5 of 5 1.0 25-10-2006
[29] LOFAR-ASTRON-MEM-033 Noise performance of ferrite loop antennas 1.0 13-05-2002
[30] LOFAR-ASTRON-MEM-106 First results of power matched active balun measurements at ASTRON 1.0 08-10-2003

Mechanical
[31] LOFAR-ASTRON-RPT-048 Test report potted LOFAR antenna LNA 1.0 12-10-2004
[32] LOFAR-ASTRON-RPT-060 Tension test on EPDM material for Low Band Antenna 1.0 06-09-2005
[33] LOFAR-ASTRON-MDD-001 Results of the LBL/LBH antenna brainstorm sessions 1.0 19-10-2004
[34] LOFAR-ASTRON-MDD-002 LOFAR LBA concept comparison 2.0 16-11-2004
[35] LOFAR-ASTRON-MDD-003 LOFAR LBA dipole wire specification 1.0 23-08-2005
[36] LOFAR-ASTRON-MDD-004 LOFAR LBA Ground Anchor specification 1.0 24-08-2005
[37] LOFAR-ASTRON-MDD-005 LOFAR LBA Ground plane specification 1.0 24-08-2005
[38] LOFAR-ASTRON-MDD-006 LOFAR LBA LNA housing specification 1.0 24-08-2005
[39] LOFAR-ASTRON-MDD-007 LOFAR LBA Vegetation blocking foil specification 1.0 24-08-2005

RTV
[40] LOFAR-ASTRON-RPT-031 Design FMEA description Low-band antenna and LNA 1.0 11-09-2003
[41] LOFAR-ASTRON-RPT-047 LOFAR FMECA LBA Antenna 1.0 24-11-2004
[42] LOFAR-ASTRON-RPT-078 Solar radiation test on the wire construction 1.0 24-04-2006
[43] LOFAR-ASTRON-RPT-062 Solar radiation on the LOFAR LBA antenna 1.0 07-09-2005
[44] LOFAR-ASTRON-RPT-112 Temperature dependency and stability of the LOFAR LBA 1.0 26-01-2007

Other
[45] LOFAR-ASTRON-MEM-174 LOFAR Intermodulation Analysis and Specifications 1.0 21-04-2005
[46] LOFAR-ASTRON-SRS-014 LOFAR RCU II signal analysis and specification 1.0 23-03-2007
[47] McGraw-Hill Education J.D. Kraus, Radio Astronomy, October 1966

1.3 LOFAR System overview

This section explains where in the overall LOFAR instrument, the Low Band Antenna (LBA) subsystem is located. The system level architecture of LOFAR is described in [1]. LOFAR sensor hardware is organized into stations. Stations consist of antennas and the signals from these antennas are beam formed into digital station beams. The antennas are at the start of the LOFAR signal chain and they are the key elements which convert the radiation out of space into electrical signals. Next these signals are being processed in the rest of the LOFAR system. The sensitivity of the LOFAR system is determined by the number of antennas used to receive radiation in a given frequency band and by the performance of the used antenna elements. Since LOFAR is able to receive radiation in a broad frequency range, there are three types of antenna elements foreseen to cover the whole range. One of these elements, the one for the lowest frequency range, has not been implemented yet.

Figure 1 shows the functional block diagram of a LOFAR station. The three types of antenna elements are respectively denoted as LBL, LBH and HBA in this diagram. At the bottom there is the control layer. Control, monitoring and synchronisation signals are distributed to the relevant subsystems in a station. The LBA subsystem, consisting of the Low Band Low (LBL) and the Low Band High (LBH) antenna elements, is one of the few subsystems which doesn't require control or synchronisation signals. After the received radiation is converted into electrical signals, the analogue signals are transported over coaxial cables towards the receiver. The receiver converts the signals into the digital domain and once digital, the filter block takes care of representing the broad band signal at the input of the filter by a set of narrow band signals at the output of the filter. The narrow band signals (subbands) are converted into station beams by the beam former. The resulting beam signals can be selected for transport from a station over the LOFAR optical fibre Wide Area Network (WAN) towards the CEntral Processor (CEP) in Groningen.

The LBA subsystem covers the frequency range from 10 to 80 MHz, whereas the High Band Antenna (HBA) subsystem covers frequencies from 120 to 240 MHz. The HBA antenna is a square 4x4 element phased array which will be covered in the HBA ADD document. The HBA subsystem is implemented with one type antenna element whereas the LBA subsystem requires two elements for covering the whole LBA frequency range at full performance. Currently, only one antenna (LBH) is available in the LBA subsystem and this element is optimized for the higher part of the LBA frequency range. Because the sensitivity of this LBH antenna at frequencies below 30 MHz is limited, an extra Low Band Low antenna is foreseen to increase the sensitivity below 30 MHz. Despite an LBL antenna is not implemented yet, the receiver (RCU) subsystem already has an input reserved for this purpose.

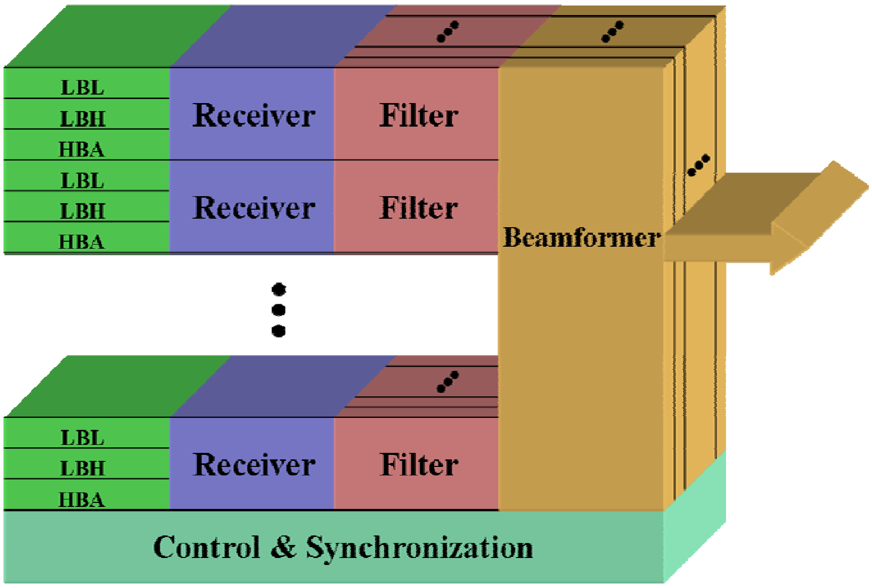

Figure 1 Functional overview of a LOFAR station

In the remainder of this document the terms LBA or LBA antenna are used to refer to the LBH antenna element exclusively. The LBA subsystem is located at the beginning of the LOFAR signal chain, end ends at the F-connector of the LBA antenna. The coaxial cables connecting the LBA to the RCU are not considered as being part of the LBA subsystem, however they are included in the noise analysis described in this document. The primary function of the LBA is to receive radio waves and to condition and amplify the resulting signals after which the signals are sent to the receiver unit (RCU) over coaxial cables. One LBA unit is sensitive to two orthogonal linear polarizations. Each polarization has its own output on the antenna and hence two coaxial cables per element are used. Power is supplied over the same coaxial cables.

1.4 A guide through this document

In the first part of the introduction an extensive list with references is provided to documents with detail design information about the LBA and other relevant LOFAR topics. In the previous subsection an overview is given about the location of the LBA and its surroundings in the LOFAR system. In section 2, a more detailed description of the LBA subsystem is presented. The requirements for the LBA subsystem and the current compliance are given in section 3. In section 4, the design of the LBA is described and in section 5, the implementation is presented. Yield and reliability of the low band are explained in section 6.

2 The LBA

A side view of the Low Band Antenna is given in Figure 2. One LBA antenna element is sensitive to two orthogonal linear polarizations. One polarization is constructed using two copper wires, which are held in place by one EPDM spring on one side and polyester rope on the other side. A constant tension force due to the spring and location of the ground anchor holds the antenna up straight and minimizes the antenna wire resonances due to wind loading. The height is determined using a PVC rod, which is clamped to the moulding head. The ground plane is made of a concrete reinforcement metal mesh. A foil is used to minimize vegetation growth underneath the antenna. Each polarization has its own output on the antenna and hence two coaxial cables per LBA element are required. Amplifiers for the two polarizations are situated on the top and bottom of a four layer FR4 PCB board. Metal tin cans provide screening against unwanted coupling effects. Power is supplied over the same coaxial cables using a phantom configuration.

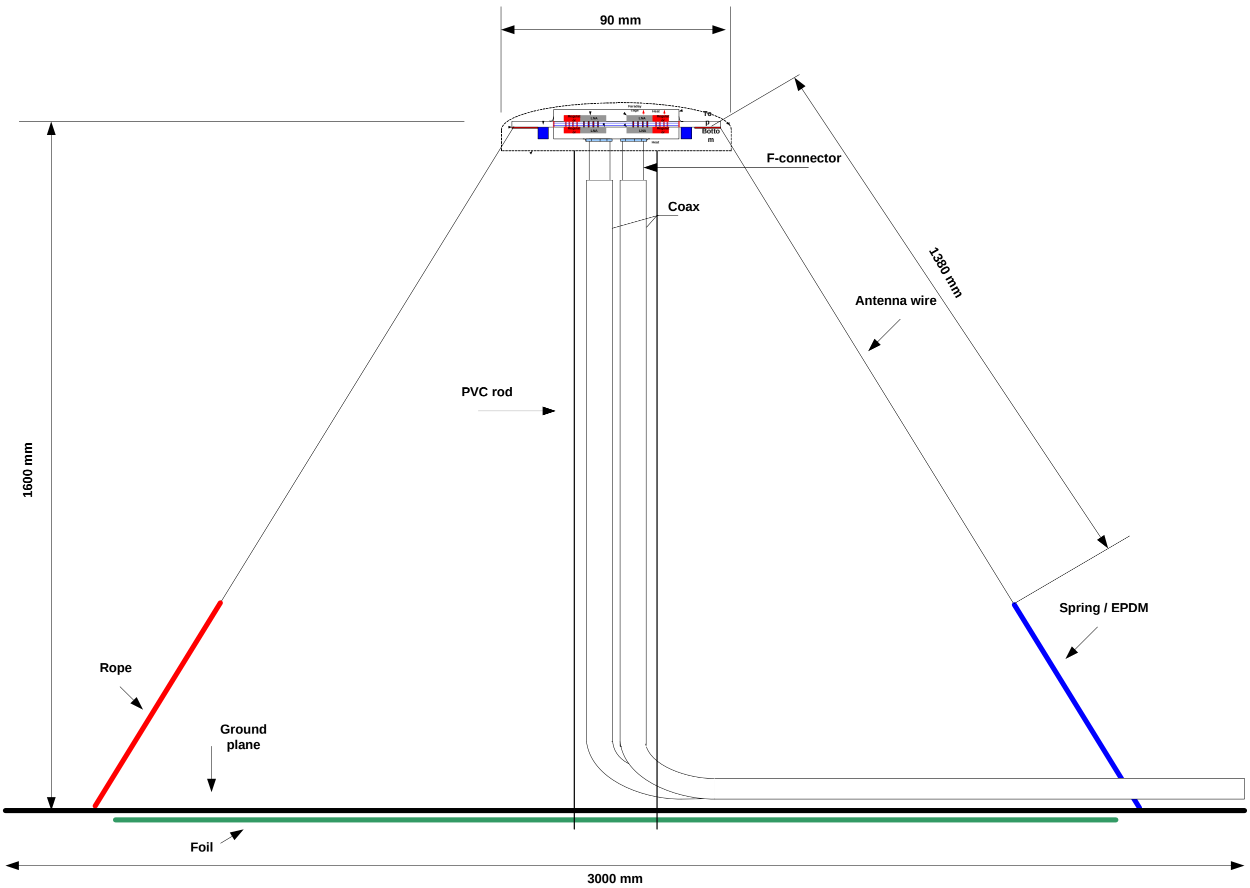

Figure 2 Side view of the LBA

3 Requirements and performance characteristics

The complete set of requirements for the LBA is specified in the LBA System Requirement [2]. The table below summarizes the most important requirements. Compliance of the LBA can be found in [5]. Chapter 3.2 will give additional details of the differences.

3.1 Requirements and compliance

Table 1 Requirements and compliance

DC specification

Item nr.	Parameters	Conditions	Min	Typ	Max	Unit	Simulated & Measured	Comply	ref
DC.1	Supply voltage		6.6	8	8.5	V	5,3 V < Vcc < 12 V	YES	[4]
DC.2	Power consumption				2	W	<1,5 W @ Vcc=5.3 V	YES	[4]

RF specification

Item nr.	Parameters	Conditions	Min	Typ	Max	Unit	Measured		ref
RF.1	Passband frequency range		10		80	MHz	10 MHz < f < 80 MHz	-	[4]
RF.2	CMRR		tbd			dB	15 dB without antenna	-	[4]
RF.3	Output P1dB	In band interferers	1			dBm	>4 dBm	YES	[4]
RF.4	Output IP2	In band interferers	41.8			dBm	>61 dBm	YES	[4]
RF.5	Output IP3	In band interferers	11.5			dBm	>17 dBm	YES	[4]
RF.6	Tsky / Trec	30-80 MHz	10			dB	4 dB < Tsky/Trec < 14,6 dB	NO	[4]
RF.7	Tsky / Trec	10-30 MHz	tbd			dB	-9 dB < Tsky/Trec < 4 dB	NO	[4]
RF.8	Available gain	10-90 MHz		7		dB	-18 dB < Gav < 26 dB	NO	[46]
RF.9	Output power	Sky noise integrated over the band	-69.2	-68.2	-67.2	dBm	-		[4]
RF.10	Output reflection coefficient	Within passband			-20	dB	-15 dB < |R| < -22 dB	NO	[4]
RF.11	Isolation between polarisations		20				>30 dB	YES	
RF.12	3dB beamwidth		120			deg	>80 deg in E-plane	NO	[5]
							>120 deg in H-plane	-	[5]

Environment and operational specification

Item nr.	Parameters	Conditions	Min	Typ	Max	Unit	Measured		ref
Env.1	Operational air temperature range	All parameters within specifications	-25		45	°C	-	-	
Env.2	Maximum wind load during operation				80	km/h	No data available	-	[6]
Env.3	Lifetime		15			min	>15 years	YES	[7]
Env.4	Assembly time				5		No data available	-	[6]
Env.5	ESD			tbd			>2 KV	-	[4]

Mechanical specification

Item nr.	Parameters	Conditions	Min	Typ	Max	Unit	Measured		ref
Mech.1	Antenna height					m	1.7 m	-	[6]
Mech.2	Dipole length					m	1.4 m	-	[6]
Mech.3	Ground plane size					m	3 m	-	[6]

3.2 Remarks

Amplifier

The LBA has been designed to actively suppress signals above 80 MHz (the FM-band). The configuration resembles a band pass filter where the low frequency corner is far below 10 MHz. Below 30 MHz a best effort has been made. There the performance is mostly limited by the radiation characteristics of the dipole.

The sensitivity requirement RF.7 is nearly met. The configuration is based on a voltage amplifier which senses the open terminal output voltage of the antenna. A benefit of this approach is a reduced coupling between the antennas [4]. However at the band edges the output impedance of the antenna becomes high in comparison to the input impedance of the amplifier, resulting in the reduced performance as shown in Figure 3. Carefully tuning of the antenna wires in combination with matching has been applied to optimize the configuration further for noise performance.

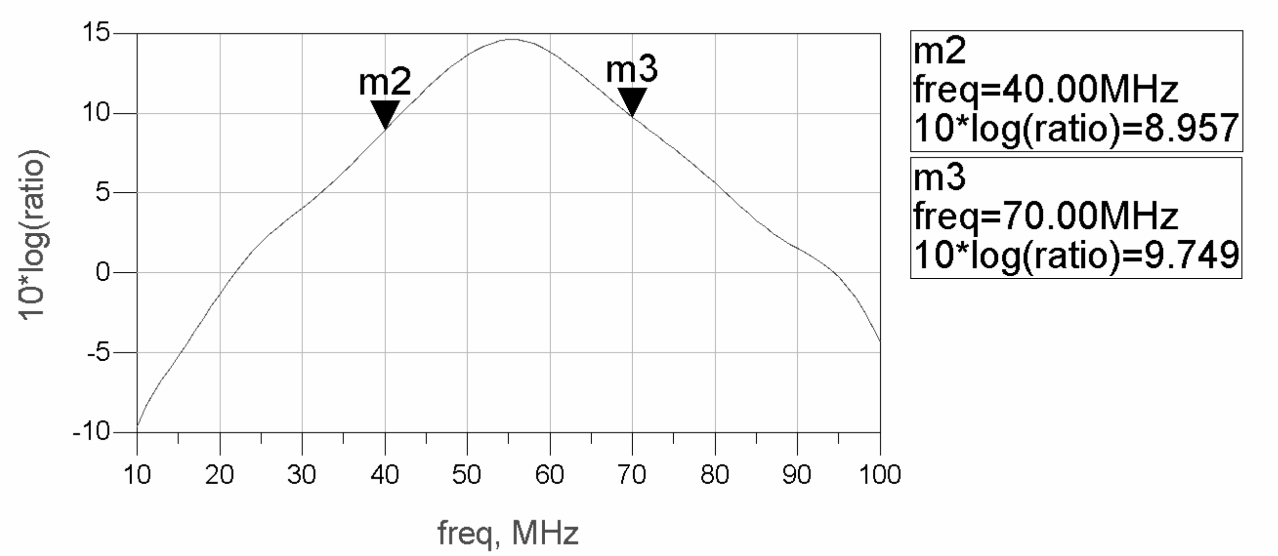

Figure 3 Tsky / Trec (dB)

Available gain RF.8 is not within specification at the low frequency corner (10MHz). Antenna efficiency η is very low, which is the primary cause of the low available gain value. Additional gain increase of the amplifier will create unfeasible intermodulation requirements on the amplifier, causing additional complexity and power dissipation. The LBL will be a more logical choice for performance improvement for this frequency band (10 MHz - 30 MHz).

Output reflection (RF.10) is almost within specification. At 80 MHz the return loss is 15 dB at the output connector of the LBA. In principal this requirement could be relaxed a bit. When we look from the RCU to the LBA, the loss of the coaxial cable (110 m) will increase the return loss to an acceptable level for system performance. At 80 MHz the coaxial cable has a loss of 5.5 dB resulting in a return loss of 26 dB at the RCU.

Antenna

A worst case 3 dB beam width of 80 deg. is achieved in an E-plane. The results are obtained using an EM - LBA model above a ground plane [6]. The 3 dB difference between the E-plane and H-plane can be explained by approximating the setup with a general dipole without ground plane. In an E-plane orientation the LBA dipole will have a zero, which makes the beam shape less broad than the beam shape in H-plane. These results are for the case of an isolated element. However in LOFAR, the elements are used in an array configuration. Therefore, the embedded element pattern, which results due to coupling effects to the surrounding elements, is more important than the isolated element pattern. It is expected that the embedded element patterns provide an improved beam pattern. However, this still needs to be confirmed by measurements.

Mechanical

The mechanical dimensions of the LBA are mainly determined by the antenna performance requirements. The angle between the antenna wire and PVC rod is a compromise between mechanical stability and antenna performance. Also the ropes, ground anchors, and EPDM rubbers are designed to find the best compromise in a typical Dutch outside environment. Dimensions of the moulded head are determined by the implementation of the electronics.

4 Design concept

This section deals with the design and key performance issues of a single LBA antenna, without coupling effects to other antenna's. The LBA antenna is considered to be an isolated dual polarised passive element with a differential low noise amplifier for each polarisation.

4.1 System

The Low Band Antenna is required to be a sky noise limited system. This means that the noise at the output of the system (and consequently at the output of the antenna) has to be dominated by the sky noise contribution. Since sky noise increases at longer wave lengths, it allows for a small and cost-effective design. Being sky noise limited implies that the dominant noise source is located outside the system. The noise resulting from the losses in the antenna itself can be neglected as will be shown later. After all, not only the 'signal' but also the noise is equally affected by these losses. As long as the system is dominated by sky noise, we can build a very inefficient antenna without compromising the system sensitivity! The important thing one has to do is to ensure that the receiver temperature remains well below the sky noise [46].

Typically, wideband antennas covering frequencies down to 10 MHz are very large. For example, the spiral antennas at the Nançay Decametric array (operating from 10 – 100 MHz) are 9 meter high and have a diameter of 5 meter. Due to their large volume, their impedance will be fairly constant over the band and one can match the LNA to the antenna. The LBA uses a completely different approach. Electrically, the LOFAR LBA consists of two crossed dipole antennas above a metal ground plane. The dipoles are made of thin wire and are resonant around 55 MHz (in the middle of the band). Each dipole is connected to an active balun. This is an LNA with a differential input and an unbalanced, coaxial, output (the LNA's of both dipoles are integrated on a single pcb). The antenna impedance away from the resonance frequency is either strongly capacitive (below resonance) or inductive (above resonance). The LNA aims to be a voltage amplifier. Its input impedance is very high. In Figure 4, an equivalent circuit of the antenna and LNA combination is shown.

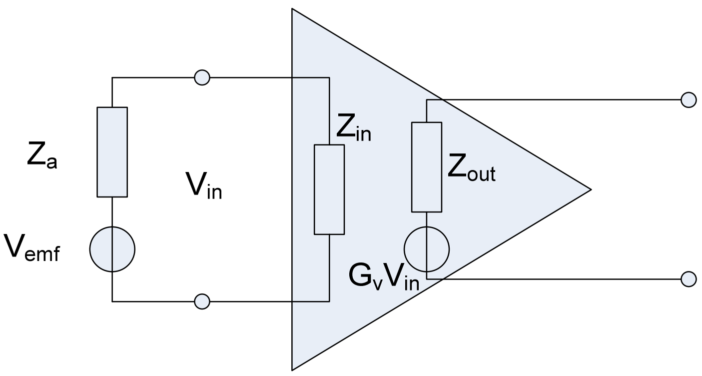

Figure 4. Equivalent circuit of the LBA.

In this equivalent circuit V_{emf} represents the electromagnetic force, V_i is the voltage at the input terminals of the LNA, Z_a is the antenna impedance and G_v is the voltage gain. As long as the amplifier input impedance Z_{in} is large with respect to the antenna impedance, the current through the antenna impedance can be ignored and consequently there will be no voltage drop across it. The voltage V_{emf} induced in the antenna is copied to the input of the LNA and the output voltage of the LNA does not (in the first order) depend on the antenna impedance.

The fact that the LNA is not noise matched to the antenna means that we do not reach the lowest noise temperature that could have been obtained in the matched case. But as indicated above, as long as the realised noise is well below the sky noise this does not impact the system sensitivity. Additionally, this 'intentional mismatch' allow us to make a very wideband system using a cheap and simple otherwise narrowband (dipole) radiator.

As a marginal note, it is remarked that because we use a voltage sensing input, the input reflection coefficient of the LNA is very large. Even stronger, if the LNA would be an ideal voltage amplifier (which we assume for this example), no power is transferred from the antenna to the LNA at all. One should realize that this doesn't matter since the information is contained in the voltage and not in the power.

Summarizing, the design of the LBA is based on two observations:

1. Because the sky noise is very high at low frequencies, the antenna efficiency can be low. This allows for electrically small antennas.
2. Bandwidth of the LBA can be chosen large despite the increase of the receiver temperature at the low frequencies as long as the sky noise remains dominant.

These two effects are the key to the final design of the LOFAR Low Band Antenna as will be shown in the remainder of this document. The main performance drivers of the LOFAR LBA subsystem are discussed in the next subsections. For a prediction of the used antenna impedance, an LBA antenna model in the EM package Zeland is used [11]..

4.1.1 Gain

The gain of the LBA is characterised using the available (power) gain. The available gain depicted in Figure 5, describes the performance of the amplifier in the real situation including varying source impedance as function of frequency and a fixed output impedance. In addition, the available gain provides a straightforward way to analyse noise behaviour under mismatched conditions.

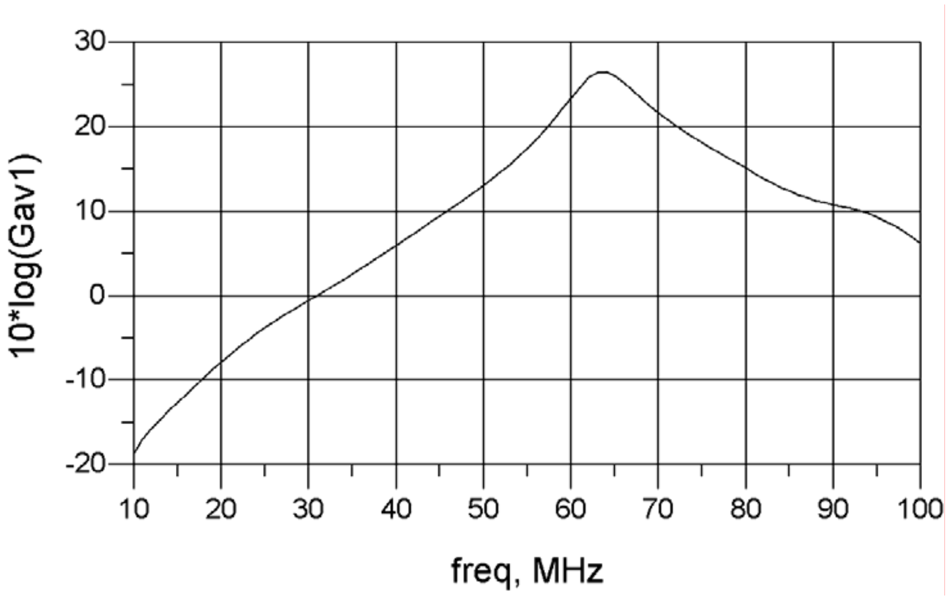

Figure 5 Simulated available gain of LBA with antenna

4.1.2 Noise

Noise is one of the most important design parameters of the LBA. First the used sky noise model is given. Next this model is used to analyse the noise performance of the LBA.

4.1.2.1 Sky noise

The sky noise temperature in the LOFAR LBA frequency band is shown in Figure 6. We use an empirical model and it resembles the measurement results given in [47]. The sky noise temperature can be modelled as a superposition of cosmic, background and absorption noise temperature respectively

$$\text{Tsknoise} := \text{Tcosmic} + \text{Tbackground} + \text{Tabsorption} \tag{1}$$

For the LBA frequency range, the sky noise is dominated by the cosmic noise which is proportional with the wave length raised to the power 2.55.

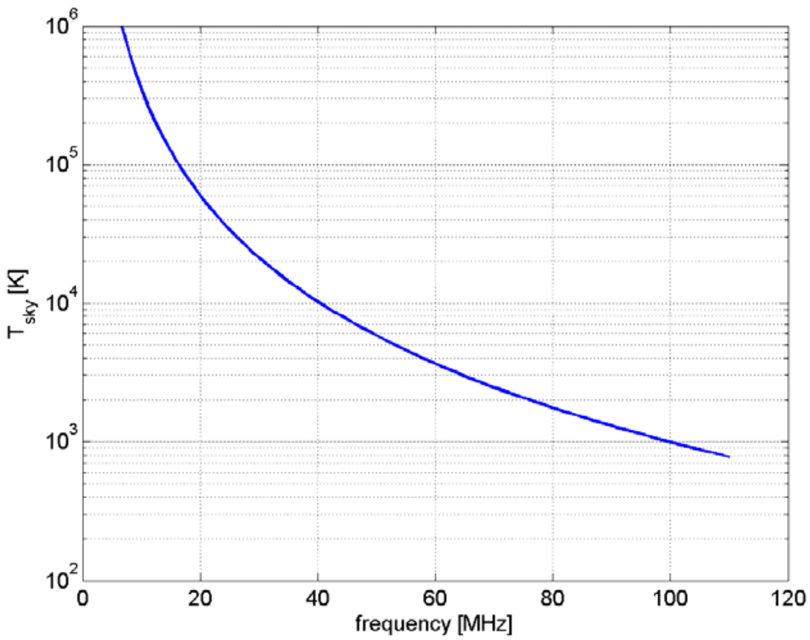

Figure 6 The sky noise model used to analyse the LBA

4.1.2.2 Antenna efficiency

When the losses in the LBA antenna volume are modelled as a loss resistance R_{loss} in series with the radiation resistance R_{rad}, the antenna efficiency can be written as

$$\eta := \frac{\text{Rrad}}{\text{Rrad} + \text{Rloss}} \tag{9}$$

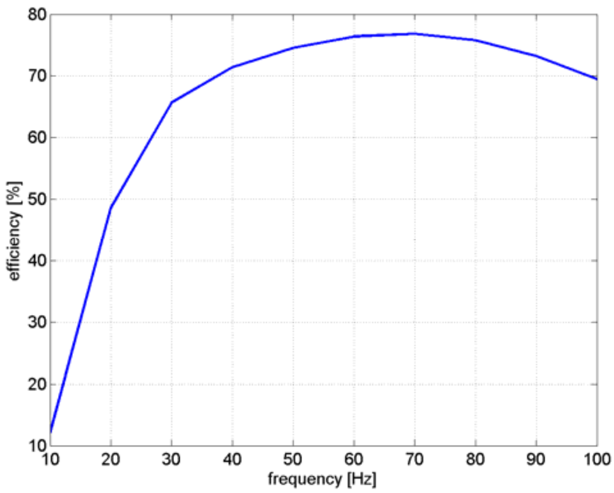

Figure 7 Antenna efficiency

For one LBA dipole element the efficiency is predicted with Zeland and shown in Figure 7. Using Thevenin, the antenna can be modelled as a lossless element followed by an attenuator with a loss factor equal to the inverse efficiency. It is assumed that both the temperature of the ground plane below the antenna and the antenna wires are equal to T_0. This way the antenna noise is modelled by R_{loss} at temperature T_0. In Figure 8 the attenuated sky noise temperature, $\eta \times T_{sky}$ is plotted together with the noise temperature of the antenna at the output of the attenuator $(\eta - 1) \times T_0$. From this figure we can conclude that the noise contribution related to the antenna efficiency can safely be ignored.

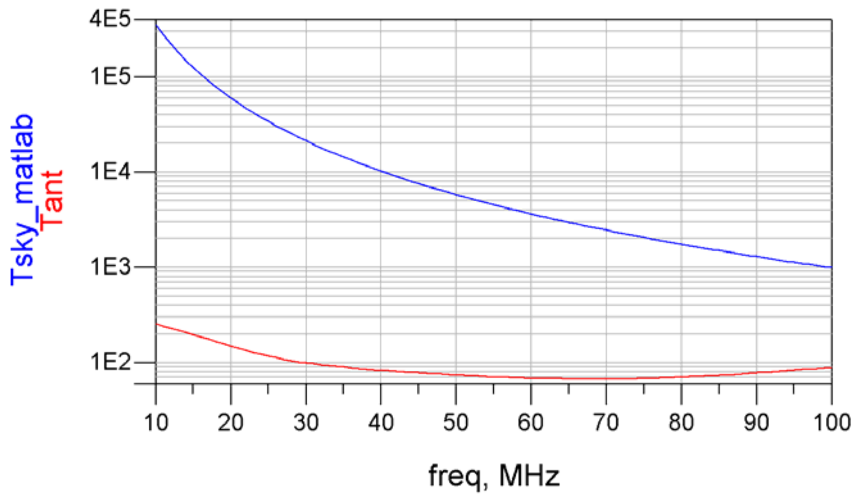

Figure 8 Sky noise temperature and antenna noise temperature. The antenna noise temperature is a consequence of the losses in the antenna and it is small compared to the sky noise.

Noise performance

Using antenna efficiency η , the LBA-noise temperature can be expressed as

$$T_{lba} = \frac{T_0(1-\eta)}{\eta} + \frac{T_{\ln a}}{\eta}, \qquad (15)$$

where T_0 is the physical (effective) temperature of the antenna and $T_{\ln a}$ is the effective noise temperature of the LNA. When antenna efficiency η is close to 1 than T_{lba} is mainly determined by $T_{\ln a}$. If the antenna efficiency η reaches 0, then the LBA subsystem temperature T_{lba} behaves like $\frac{1}{\eta}(T_o + T_{\ln a})$, this becomes the dominating term at the low end of the spectrum.

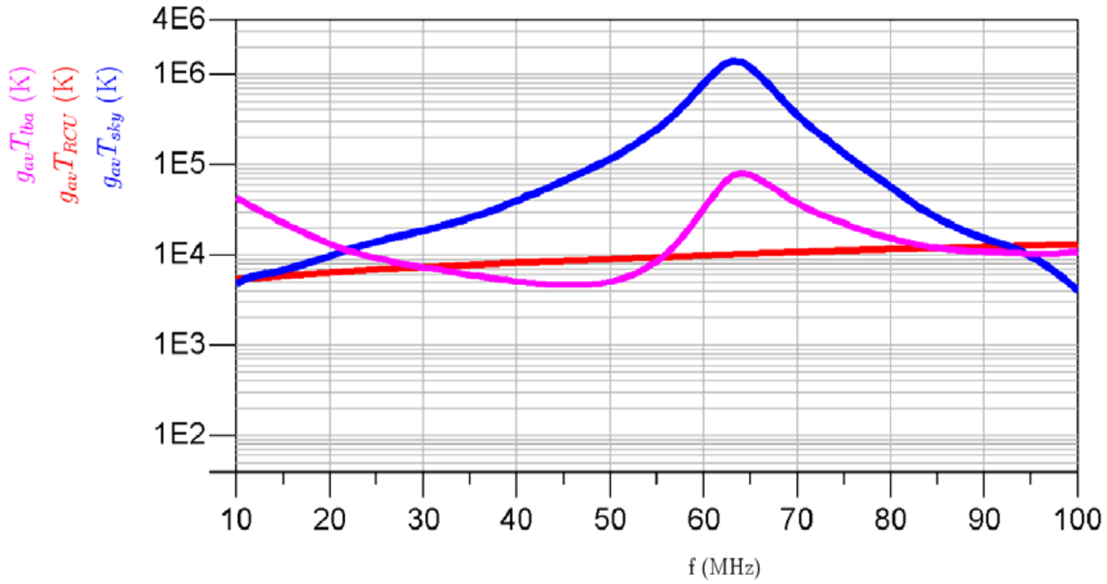

Figure 9 Noise temperature overview of the LBA LOFAR system presented at the output of the LBA

In Figure 9 an overview is given of the noise performance of the LBA LOFAR system. The noise temperature levels are calculated at the output of the LBA subsystem. In the figure, g_{av} is the available gain of the LBA subsystem. The blue curve represents the sky noise, the magenta curve represents the noise of the LBA subsystem and the red curve represents the remaining noise of the LOFAR system behind the LBA system including the cable connecting the LBA subsystem to the RCU. The LBA noise temperature doesn't meet the requirement that it should be minimal 10% below the sky noise. It also follows that in the frequency range from 30 MHz to 55 MHz, the sensitivity is limited by the RCU. However, this should not be difficult to solve. From the figure, the receiver noise temperature $T_{rec} = T_{lba} + T_{RCU}$ at the output of the LBA subsystem follows from superposition of the magenta and the red curve. The system noise requirement is not met at all frequencies. However, in the frequency range from 30 MHz to 80 MHz, at least the sky noise power is stronger than the receiver noise power.

4.1.3 Intermodulation

The linearity requirements OIP2, OIP3 and P1dB are derived from the soft-spurious requirement in [4] and it has been validated with measurements that these requirements are met. Up to now, common mode is not considered as an issue. The amplifier provides a 15 dB CMRR and it should be confirmed that this is sufficient in harsh RFI situations. It has been verified that especially for RFI waves near the horizon, the antenna structure is susceptible and converts these waves into unwanted common mode signals.

Figure 10 gives an impression of a 24 hour survey at Dwingeloo using the LOFAR backend in the measurement lab [17]. When considering a measurement time window of 90% of the available time, the interference levels of the system are reasonable. A clean spectrum is measured with a resolution bandwidth of 195 kHz. When the measurement time is increased the spectrum becomes full of interferers. Especially pulsed interferers in the time domain, destroy the measurement data. Electric fences can cause a great deal of problem. Their pulse frequency lies between 1 second and larger. The night time provides the quietest period, due to the absence to ionisation inversion layer. A maximum interference level at the lower frequencies is found in the afternoon. An inventory of the interference levels together with their time stamps can provide a good insight to find clean measurement windows.

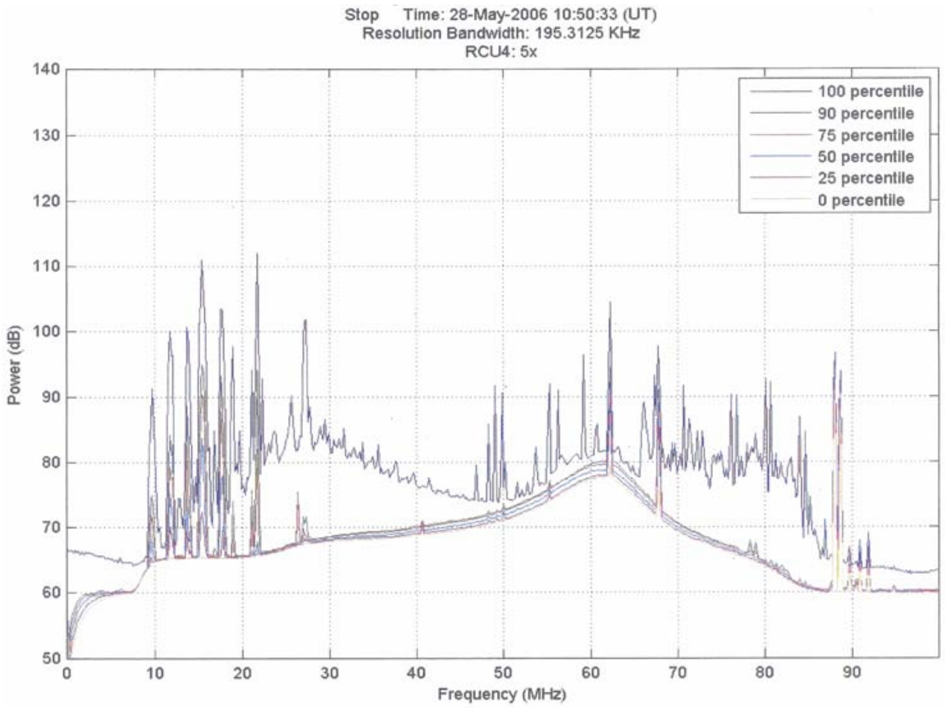

Figure 10 Measured LBA RFI spectra at Dwingeloo using LOFAR backend

4.1.4 Temperature stability

The temperature stability of the LNA (supply current and complex gain) has been extensively tested in a climate chamber. The results are documented in [44]. For example, the gain variations of the LNA as function of temperature and the stability of the gain over time (at a constant temperature) have been measured for several LNA samples. For example Figure 11 shows the gain variation over temperature at 50 MHz. The maximum measured change rate of the gain is 0.1% per degree (amplitude) and 0.06 degree phase shift per degree, which is very small. The standard deviation of the stability measurements over time is 0.005 dB or 0.12% for amplitude and 0.03 degree for phase.

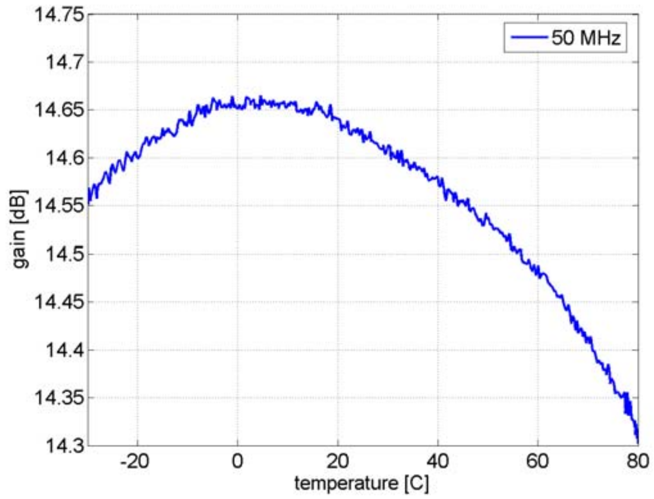

Figure 11. measured LBA gain variation over temperature.

4.2 Antenna

4.2.1 Radiation patterns

The radiation pattern of a single dipole and of a complete station has been determined using numerical simulations [6]. Two attempts have been made to verify the single element results with measurements. One measurement campaign was performed at NLR (the National Aerospace Laboratory) and one at the WSRT. Although the accuracy of both campaigns was limited due to the influence of the measurement setup, they confirmed the general trends of the simulations [12], [13]. The station beam patterns are currently being verified with the first operational stations.

In Figure 12 and Figure 13 two cuts through the radiation pattern of a single element are shown at 30 and 80 MHz respectively. A complete overview of the patterns, including patterns represented in Stokes I, Q, U and V are given in [6] A trade-off study for the station configuration, including simulated station patterns, is presented in [12], [13]..

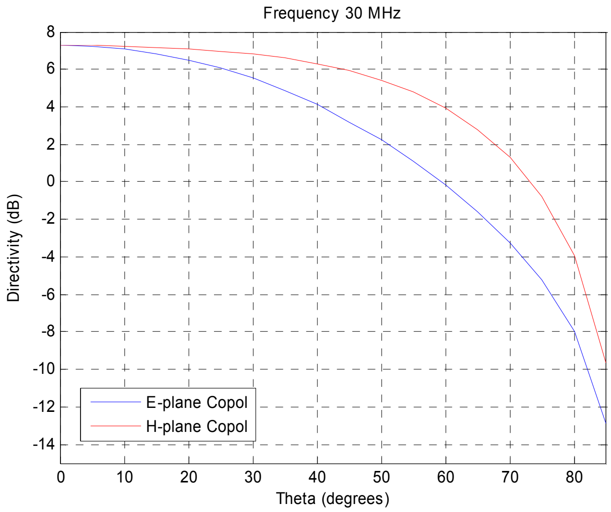

Figure 12. E- and H-plane patterns at 30 MHz

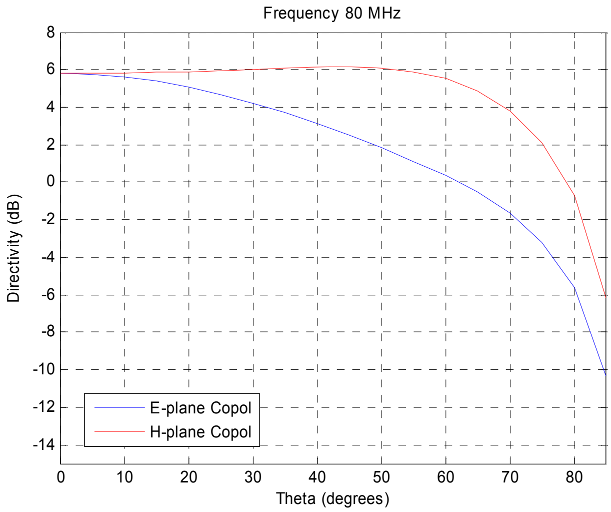

Figure 13. E- and H-plane patterns at 80 MHz

4.3 Cabling

Main driver for the coax cable is cost. For a single station an approximate cable length of 22 km is required. This coax cable should have a respectable shielding effectiveness, low loss in the band of operation, low DC resistance and low phase instability. The coax cable typed “coax 9” is a good compromise and has been selected for the design. It is generally used for base band satellite applications operating between 900 MHz and 2200 MHz.

4.4 Mechanics

Mechanically the antenna concept has been changed from a PVC rod concept to a wire concept. The main reason was reliability. The electronics are completely moulded, which increases the lifetime of the electronics. The present concept is easy to produce and install. Most parts are generally available. A detailed concept study can be found in [34], [7]

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5 Implementation

The Low Band Antenna (LBA) consists of two perpendicular inverted-V shaped dipole antennas and two active baluns, integrated on a single pcb, to provide amplification and impedance transformation. Isolation on the pcb between the two polarizations is larger than the isolation between the antenna polarizations. The received signals are transported to the station cabinets via two coaxial cables. The active baluns are powered via the same coaxial cables. Mechanically, the antenna consists of a centre pole that is kept upright by four guy wires as shown in Figure 14. The top part of each wire is made of copper and these wires form the four dipole arms. The lower parts of two (perpendicular) wires consist of rubber springs. The lower parts of the other two wires are made of stiff polyester rope. The active baluns are encapsulated into an epoxy or polyurethane block by PCB potting. This block is located at the top of the centre pole. The height of the antenna is 1.70 m. A mesh of 3x3 m (mesh pitch 15 cm, wire thickness > 5 mm) is located under the antenna to screen the antenna from the ground directly below. A plastic foil (also 3x3 m) is placed below the metal ground plane to prevent the growth of vegetation below the antenna and its direct surrounding. The guy wires are under an angle of approximately 45 degrees and are connected to four tent pins. Two F-connectors are provided for the connection of the coax cables. The coax cables will run through the centre pole.

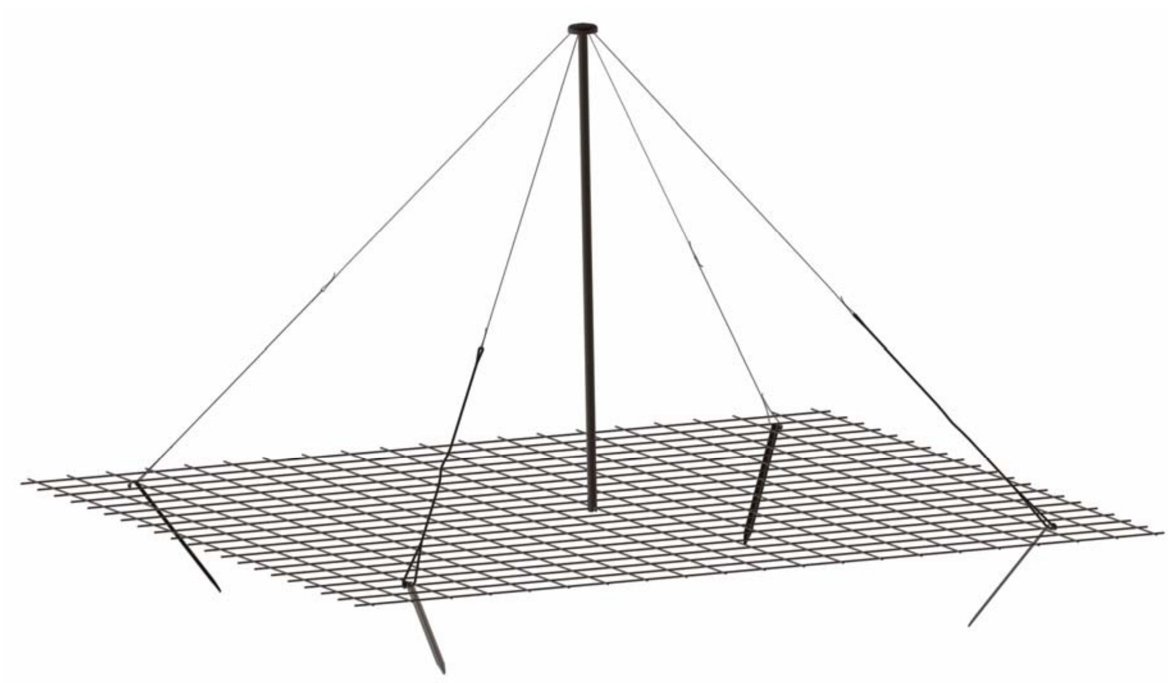

Figure 14 Overview of an LBA antenna unit

5.1 Antenna

5.1.1 Dipole antenna

The dipoles have an inverted-V or pyramid shape. The dipole arms have been placed under this angle of 45 degrees to broaden their beam width in the E-plane.

5.1.2 Antenna height

The radiation resistance of a dipole antenna above a metal ground is proportional to h^{-2}. This effect will reduce the antenna efficiencies dramatically for small heights. But on the other hand, a horizontal dipole located half a wavelength above a metal ground plane will have a minimum towards the zenith direction due to destructive interference between the original dipole and its image. So the height of the antenna feed point is governed by the radiation pattern at the highest frequency and the sensitivity at the lowest frequency. A higher antenna will increase the sensitivity at lower frequencies, but will degrade the pattern (the sensitivity towards zenith) for the highest frequencies. The optimum height as suggested by many text books is around 3/8 of the shortest wavelength. The LBA complies with this rule and its height has been fixed to 1.70 meter.

5.1.3 Antenna orientation and polarization

When the LBA is placed in an array configuration, polarisation and orientation of the single LBA are very important. Figure 15 shows the top view of a LBA antenna, together with the north direction. The PVC pole is placed right-angle on the ground plane, which is in parallel with the local ground surface. Each station has a local z-axis reference, which is used to install all 96 LBA antennas on the same z-plane. With this configuration the x polarisation is located at the north.

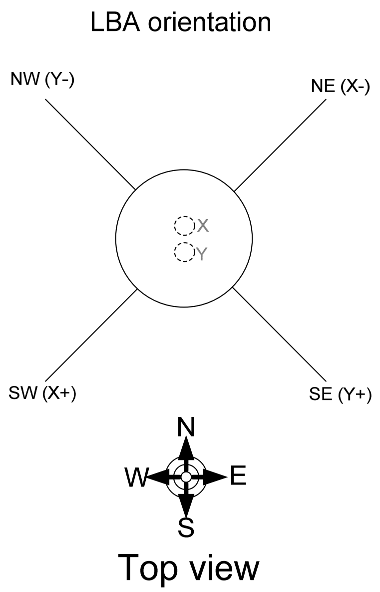

Figure 15 LBA Orientation

5.1.4 Dipole length

The dipole arms have a length of 1.38 meter, resulting in a resonance frequency of 52 MHz. This dipole size balances the sensitivity at the outer ends of the frequency band.

5.2 Amplifier

The concept of the LNA is described in [4] and the detailed design including the schematic in [9]. The LNA is a high input impedance (voltage input) negative feedback amplifier. A voltage sensing input is selected because such an amplifier is largely independent of the antenna impedance. Proven low frequency techniques, combined with discrete microwave low noise pHEMT devices achieve the required ultimate low noise performance. Due to the high f_t of the applied pHEMT device, design and analysis had to take care of microwave properties of the circuit components and PCB layout. The main challenge was to realize the required behaviour in the operating band, as well as stability for microwave frequencies up to 15.8 GHz.

Due to the voltage input, no filtering could be applied for the signals below 10 MHz. This had serious consequences for the required linearity because the RFI signals below 10 MHz are very strong.

The LNA is shielded by metal cans. These shields are essential for the correct operation of the LNA. Furthermore, they avoid direct contact between the electronics and the moulding material (PU or epoxy). Direct contact would result in de-tuning of filters and transmission line impedances.

The performance of the LNA has been extensively tested. The results are incorporated in [5].

Figure 16. LBA active baluns pcb, RF shield has been removed.

5.3 Lightning & ESD protection

No requirements have been specified for ESD and lightning protection. Nevertheless, some protective measures are implemented to provide a basic level of protection Figure 17. They will lower the LNA input impedance, making the LNA more dependent on the antenna impedance, but their expected impact on the overall performance is small. The protection, consisting of diodes and gas discharge tubes, are located at the inputs and the outputs of the LNA. The design routes the discharge currents around the LNA through the metal shielding cans to avoid damage to the amplifier itself.

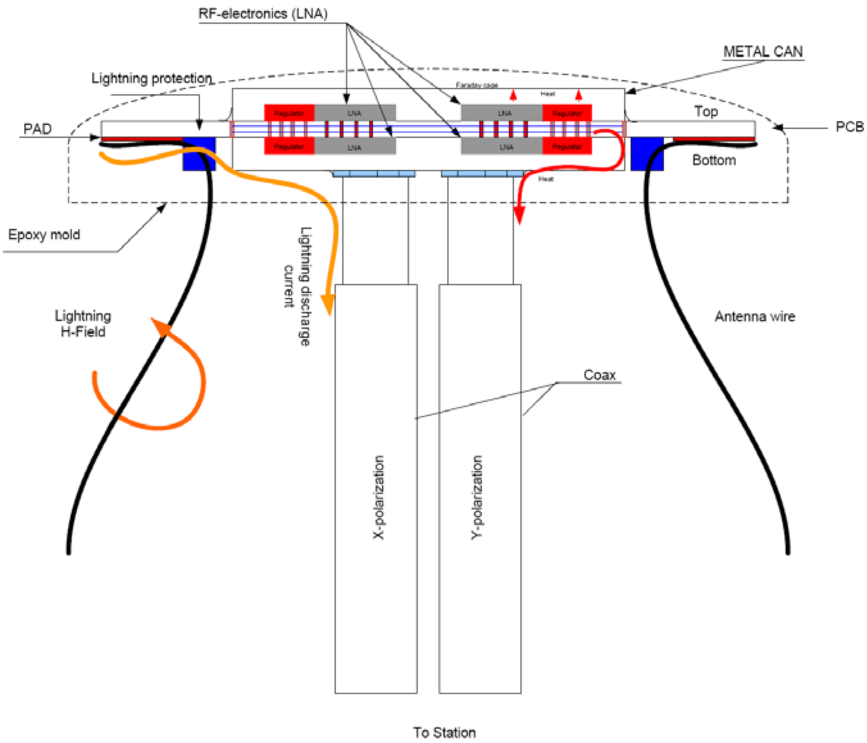

Figure 17 Lightning protection at the input of the LBA

5.4 Cabling

A 110 m “coax 9” coaxial cable is used to connect the LBA to the station. The cables are buried in the ground. The precise length of the cables is determined on the basis of measured electrical time delay. In this way the calibration is less difficult. Additional length of the cable is folded in the trenches nearby the station. Insulation of the cable is made of gas injected foam (PE). Copper shielding is made out of a copper braid and a foil for high frequencies. A shielding effectiveness of 85 dB is specified. F-connectors are used to connect the coax cables to the LBA and station.

Figure 18 TKF coax 9 cable

5.5 Mechanics

5.5.1 Guy wires

The antenna is kept upright by four guy wires. The top part of these wires consists of the copper dipole arms. The lower part of two (perpendicular) wires consists of EPDM rubber springs. The lower parts of the other two wires are made of stiff polyester rope. The dipole arms, rubber springs and rope are connected with clamps, see Figure 19. The guy wires are anchored to large tent pegs. The stability of these pegs has been confirmed with a long lasting tension test at the ITS.

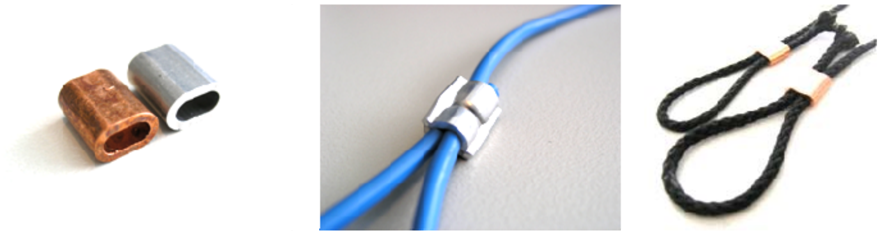

Figure 19. Clamps are used to connect the dipole arms to the rubber springs and the polyester rope.

5.5.2 Ground plane

The ground plane is a 3 m x 3 m square mesh. The mesh size is at most 15 cm ($\lambda/20$ at the highest frequency of operation) and the wire thickness > 5 mm. An EPDM foil is put below the ground plane to prevent plants from growing through the plane. The size of the ground plane is a compromise between cost, performance and transportability. Its effect has been determined by simulation and measurements [36], [37].

5.5.3 EPDM springs

At first, the feasibility of the EPDM springs raised many concerns. Extensive effort has been spent, including contacts with suppliers, long lasting test setups and accelerated environmental tests, to prove their reliability and durability [14]. These tests have confirmed their lifetime, only very minor degradations have been observed after the environmental tests that were equivalent to 15 years outdoor conditions. The final EPDM springs are specially designed for the LOFAR LBA and a dedicated mould has been made.

Figure 20 EPDM spring

6 Reliability

6.1 Environmental tests

The requirements specify a lifetime of at least 13 years plus a period of maximum two years for rollout. This results in a formal required lifetime of at least 15 years. However, it is anticipated that LOFAR operation will be longer and because the antennas are widely distributed it would be very costly to replace (parts of) the antennas. Therefore, a longer lifetime would be preferable.

Numerous environmental tests are conducted on the low band antenna to confirm a lifetime of 15 years in an outdoor environment in the Northern part of the Netherlands (see [8]) Table 1 The test levels are defined in accordance with IEC 60721 and the tests are executed in accordance with IEC 60068. The initial locations are covered by the tests. Additional analysis and tests should be executed when LOFAR stations will be placed in areas of the world with other environmental conditions.

It was concluded that the LBA can withstand the outdoor climate during a life time of 15 years. Analyses after the tests showed discolouring of the materials and only minor mechanical deviations. There is no difference between epoxy material for potting and poly-urethane material. The antenna can be classified as ingress and dust protected: IP66.

Table 2. Overview of environmental tests

Test description	Appl. standard	Parameters	Pass/Fail	Remarks
Rain	IEC 60529	IP X7	P	
Dust (incl sand)	IEC 60529	IP 6X	P	
IP classification	IEC 60529	IP 67	P	IP 66
Humidity	IEC 60068-2-66	95% / 60C / 10 days	P	
Humidity cycling	IEC 60068-2-30	95% / 20C <->60C / 20x	P	
High temperature	IEC 60068-2-2	+55C / 48 h	P	
		+70 C / 10 days	P	
Low temperature	IEC 60068-2-1	-20C / 48 h	P	
		-40 C / 10 days	P	
Solar radiation	IEC 60068-2-5	1120 W/m / 1000h	P	Temp. measurement in product
Vibration			P	Field test showed no deviations
Shock	IEC 60068-2-27		P	On product
Free fall test	IEC 60068-2-32			Cracks on concrete no problems on normal ground
Corrosion	IEC 60068-2	Salt mist	P	Tested on connectors and plastics
Corrosion connectors	IEC 60068-2-49	H_2S/SO_2	P	Salt mist test is Pass
Push and pull		Connectors 10kg	P	Push and pull
ESD	IEC 61000-4-2	-15/+15 kV air discharge	P	Test executed on proto's, single pol only
	IEC 61000-4-2	-8/+8 kV contact discharge.	P	Test executed on proto's, single pol only
		Changing connections	P	Probl. f. power supply nof for LBA
		Short circuit connectors	P	Probl. f. power supply nof for LBA
Maintenance tests				
		Push/pull connectors 10kg	P	
		20x connect/remove cable	P	
		Changes of +/-	P	Probl. f. power supply not for LNA
		Connect wrong cable to connector	P	Probl. f. power supply not for LBA
		Short circuit connectors	P	Probl. f. power supply not for LBA

6.2 Yield

The production yield of the LBA is determined by multiple factors, because the LBA undergoes a number of processes like the production, assembly, packaging, transport, unpackaging, installation and testing. In this section two high risk categories of these processes are discussed.

6.2.1 Production Yield

6.2.1.1 Electronics

The LBA electronics are being built using a PCB, SMD components and mechanical parts. When the electronics are assembled to a working LBA, the electronics will be tested using an electrical RF test setup. Testing is performed to guarantee 100% fully functional LBA units. The yield of the tests is determined by production errors only. Design spread determines the tolerance window at certain frequency points of the test setup. Measurement data of the RF test setup is used to control the production yield.

6.2.1.2 Mechanics

Moulding and attachment of the wires are done at a different company. The LBA will be visual inspected when they arrive at LOFAR HQ.

6.2.2 Installation Yield

There is no data available yet.

6.3 Failure mode analysis

A FMECA has been performed to investigate the possible risks in the design and usage of the LBA. From the executive summary is quoted [41].

‘All three-antenna types have uncertainties regarding influences of ESD and lightning. ESD and lightning protection shall be detailed analysed and tested. All three antennas have one or more pipes that are placed on the ground. The design should withstand ice around and in the pipes. The following construction ranking is made from a reliability point of view:

(1) Wire construction
(2) Pipe construction
(3) Rod construction

The rod construction is poorly protected against environmental influences. Specifically should be mentioned the connection between copper rod / electronics and the F-connector. Corrosion, rain, dust and vibration will have influence on these connections.

The pipe construction is a usable concept but the electronics are minimal protected against influences of condensation water and corrosion.

The wire construction gives a good protection of the electronics. A weak point is the spring that should withstand large forces and vibration due to wind but which is also subjected to the environmental. A high amount of small remarks and special attention points are important for the development of a reliable wire construction antenna but most of these can be easily solved. An advantage of the wire construction is the relative small amount of raw material that is used, the transport size and the small amount of work to install the antenna on a LOFAR field. Another important advantage is the automatically protection of the incoming cables by the central pole. A disadvantage of the wire construction is the separation of materials during the disposal phase at the end of the lifetime. This is compensated by the small amount of raw material that is used.

7 LBA performance in an array configuration

The former part of this documents deals mainly about an LBA subsystem considered as an isolated unit. However when the LBA's are configured in an array their behaviour in an array environment becomes important. References [[24] – [28]] give detailed results on the LBA performance in different array configurations. From [ref] we can conclude that the antenna impedance will not change significantly when it is installed in an array configuration. Measurements in the final array configuration are required to validate this statement.

Figure 21 An impression of the LBA units in station configuration