The Low Frequency Array active antenna system

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ABSTRACT

The Low Frequency Array (LOFAR) will be a radio telescope that opens up a hardly explored part of the spectrum range for astronomy. LOFAR will operate between at least 10 MHz and 150 MHz. Due to its advanced concept using among others active antenna arrays, adaptive interference cancellation and calibration techniques, it will provide unique arc second resolution and milliJansky sensitivity.
Key element for this instrument is a compact active, broadband antenna and this will be the main topic of presentation. Information will be provided on the basic design and performance of both antenna structure and integrated low noise amplifier.
The antenna element is optimised in terms of beam pattern, while the associated amplifier is optimised for very low noise performance and high dynamic range.
Insight is given how the antenna design is systematically tailored to the system requirements. Both simulated and measured performance regarding among others beam pattern and noise performance will be presented.
The active antenna technology developed for LOFAR is the first application of this technology in radio astronomy and will be an important step towards future large radio telescopes.

Keywords: Active antenna, radio astronomy, low noise, broadband, phased array

1. INTRODUCTION TO LOFAR

A first concept to develop and build a low frequency radio telescope was conceived in the Netherlands[1] around 1998. This original plan was based on the wish of Dutch astronomers to explore the universe at long wavelengths for a large variety of astronomical research areas ranging from solar studies to cosmology. Commensurate with the wish for a new observing facility, the Netherlands Foundation for Research in Astronomy was interested in the development and construction of such an instrument in which novel technology could be demonstrated. These technologies in the areas of among others broadband antennas, phased arrays, software radios and calibration methods were being researched by NFRA in the framework of the Square Kilometer Array (SKA) technology roadmap.[2]
Around the same time various groups at the U.S. Naval Research Labs expressed similar astronomical interests. In 1999 this lead to a formal cooperation between the two institutes to establish a joint Dutch/U.S. project for LOFAR.
The use of this versatile instrument for other applications besides astronomy like solar radar, ionospheric research and lightning research is also under investigation.

Since 1996, NFRA is in contact with the German company Rohde & Schwarz. This company develops and manufactures – among other equipment - active and passive antennas for civil and military communication, radio monitoring and radiolocation as well as test and measurement applications since more than 40 years. In 1999, a specialist from NFRA started working in the antenna department of this Munich based company thus jointly with Rohde & Schwarz developing an antenna element prototype for the LOFAR project.

LOFAR is a radio telescope that will operate at least in the frequency band of 10 MHz until 150 MHz. It uses both earth rotation aperture as well as bandwidth synthesis techniques to obtain complete u,v coverage in less then 12 hours of observing. 40 Antenna stations with baselines of at least 150 km between them are used. Each station will consist of 256 dual polarized, broadband antenna elements. An active antenna based on a short dipole above a reflector plane is proposed

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as the key element for this application. The design and performance of this active antenna is the prime topic of this manuscript.
Beam forming using the signals from all 10240 elements will be done in the digital domain. For this purpose at every antenna element a receiver and fast A/D-converter is installed. The digital beam forming approach offers advantages like multibeam capability and adaptive nulling in a more cost effective way compared to analogue beam forming.
A set of minimum technical specifications have been determined which describe the performance of a strawman instrument for LOFAR. In Table 1. a summary of the LOFAR strawman specifications is given.

Table 1. LOFAR Strawman specifications

Instrument type	Earth rotation aperture synthesis array
Frequency range	10 – 150 MHz
Effective collecting area	1 km^2 at 15 MHz
Number of receiving elements	10240 dual polarized short dipoles with integrated LNA's
Number of interferometric stations	40 with 256 elements per station
Number of digital beams in one frequency channel	Maximum 64
Sensitivity (B = 100 Hz, τ = 8 hrs)	< 3 mJy at 15 MHz < 1 mJy at 150 MHz
Maximum bandwidth	32 MHz
Number of spectral channels	4096
Polarization	Linear, full set of Stokes parameters
Baseline range	Between 100 m and 150 km
Spectral resolution	< 100 Hz
Temporal resolution	100 ms
Angular resolution	30" at 15 MHz and 3" at 150 MHz

The specifications of the strawman may change depending on available funds and changing priorities in user requirements.
The final location of the instrument is still under discussion. Besides the primary motivations originating from the astronomical requirements, political issues play a role in this discussion. Locations in Western Europe, the United States as well as Australia are being considered.

2. SYSTEM NOISE CONTRIBUTORS

The system noise temperature of a single antenna element primarily dictates the sensitivity of LOFAR, an aperture synthesis array having phased arrays of equal antenna elements for the antenna stations. The power flux density S_{sys}, in radio astronomy normally expressed in Jansky (10^{-26} $W.m^{-2}.Hz^{-1}$), for a single antenna station equals:

$$S_{sys} = \frac{2 \cdot \eta \cdot k \cdot T_{sys}}{A_{eff}} \qquad (1)$$

Where: k – Boltzmann's constant, T_{sys} – system noise temperature, A_{eff} – station effective collecting area, η – system efficiency factor.

The rms noise level is defined as:

$$\Delta S = \frac{S_{sys}}{\sqrt{B \cdot t}} \qquad (2)$$

B – system processing bandwidth, t – total integration time

The above sensitivity discussion assumes that the array configuration is such that it has sufficient angular resolution to distinguish between the weak source under observation and possible neighbours. To fulfil this assumption the maximum baseline between antenna stations should be sufficiently large.
The system noise temperature is composed of noise generated internally in the receiving system and external noise sources that can be classified in three main categories:

- External sky noise induced in the passive part of the antenna
- Noise generated in the active antenna
- Noise generated in the receiver that is connected to the output of the active antenna

The internal system noise can be influenced and should be minimised by an appropriate design while the external noise sources are fixed. These three contributors to the system temperature are discussed in more detail in the following subsections.

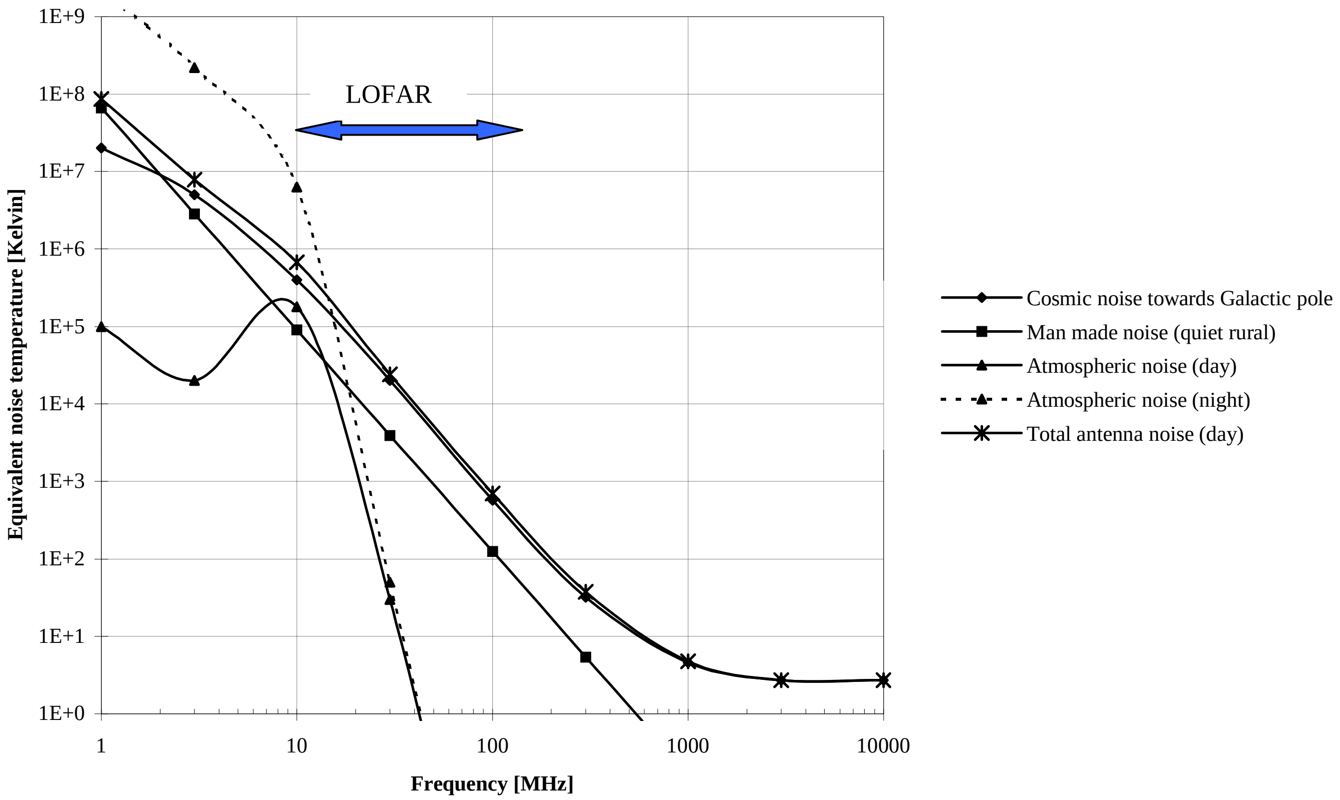
2.1 Sky noise in the LOFAR frequency range

In the frequency range in which LOFAR will operate three major sources of external sky noise can be distinguished:

- Cosmic noise that is generated by various processes in the universe
- Atmospheric noise generated by lightning discharges around the world
- Man-made noise that is caused by various sources due to human activity (industry, power lines, etc.)

In Fig. 1 a graphical summary as a function of frequency is given for these noise sources. The graph is among others based on information found in CCIR reports.[3, 4, 5] The line indicating the total antenna noise temperature during daytime is about the most ideal case that can be encountered. Note that this figure does not include signals caused by deliberate transmission as e.g. from short wave broadcast stations.

Figure 1. Overview of external noise sources between 1 MHz and 10 GHz

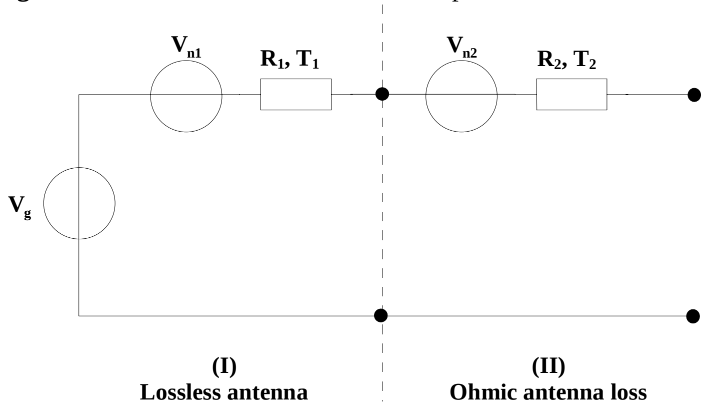


It can be concluded that the external noise contribution in the LOFAR frequency range is relatively high compared to the situation in the frequency range above 1 GHz where the cosmic noise is the only contributor. At the highest frequency of operation for LOFAR, 150 MHz, a minimum antenna noise temperature of approximately 400 Kelvin is encountered. This increases monotonously to a value of almost 10^{+6} Kelvin at the lowest frequency of operation foreseen for LOFAR, 10 MHz. The requirements for the LOFAR receiver system are therefore relatively relaxed compared to systems operating at shorter wavelengths.

2.2 Noise contributions of the active antenna

The noise due to the active antenna is in principle caused by two different parts of it. One part is caused by possible ohmic losses in the radiating structure it self, while the second source of noise is the electronic amplifier of the active antenna.
To quantify the noise contribution due to ohmic losses in the antenna radiator the model in Fig. 2 is introduced. Part (I) represents the antenna without losses. R_1 is the noiseless radiation resistance of the passive antenna, V_{n1} is a source that represents the antenna sky noise and is dependent on T_1, while Vg models the wanted signal to be received. For simplicity sake the impedances are assumed to be purely resistive, however for complex impedances the same results and conclusion are obtained.
Part (II) models the ohmic losses in the passive antenna structure. These losses are represented by R_2. The thermal noise of the resistor is represented by voltage source V_{n2}. As can be seen from the diagram the ohmic losses not only attenuate the wanted signal but introduce thermal noise as well.

Figure 2. Noise model for ohmic losses in passive antenna structure



The signal degradation due to the losses can be expressed in the noise factor of a two-port that is represented by (II). The noise factor is defined as:

$$F = \frac{S_i / N_i}{S_o / N_o} \tag{3}$$

Where S_i/N_i is the signal to noise ratio at the output of network (I) without network (II) connected to it and S_o/N_o respectively the ratio at the output of the cascaded networks (I) and (II).
With:

$$S_i = \frac{\overline{v_g^{\,2}}}{4 \cdot R_1} \quad \text{(4.a)}, \qquad S_o = \frac{\overline{v_g^{\,2}}}{4 \cdot (R_1 + R_2)} \quad \text{(4.b)}$$

And:

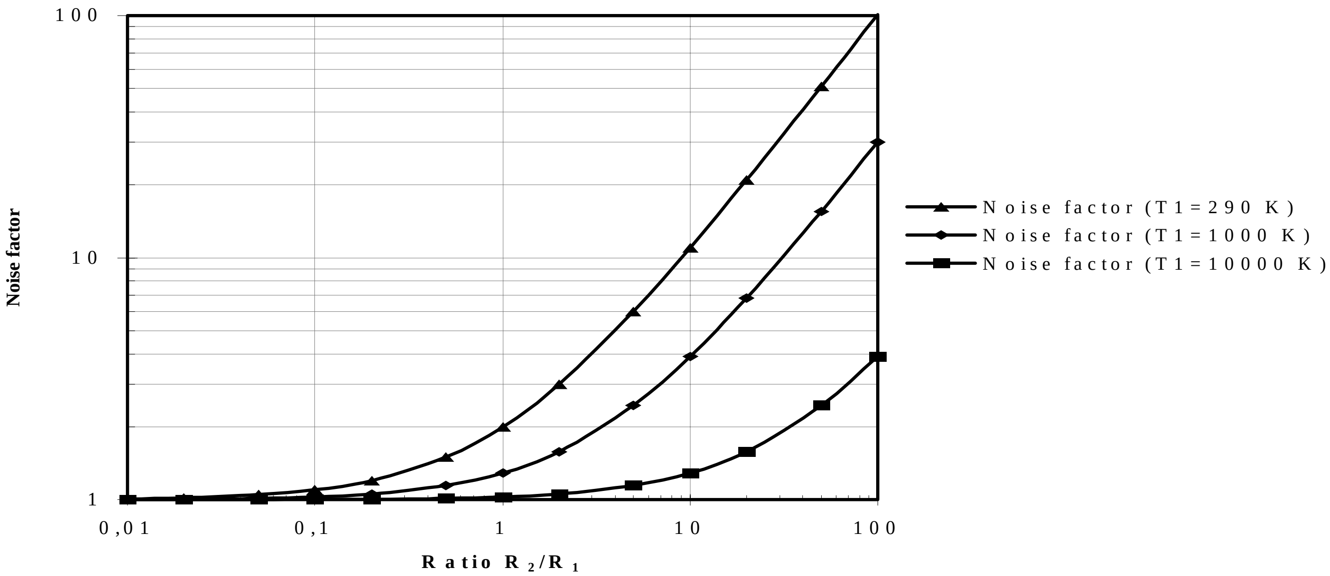
$$N_i = \frac{\overline{v_{n1}^{\,2}}}{4 \cdot R_1} = k \cdot T_1 \cdot B \quad \text{(5.a)}, \qquad N_o = \frac{\overline{v_{n1}^{\,2}} + \overline{v_{n2}^{\,2}}}{4 \cdot (R_1 + R_2)} = k \cdot B \cdot \frac{T_1 \cdot R_1 + T_2 \cdot R_2}{R_1 + R_2} \quad \text{(5.b)}$$

B – noise system bandwidth
Combining definition (3) and expressions (4) and (5), the noise factor of the circuit in Fig. 3 can be written as:

$$F = 1 + \frac{T_2}{T_1} \cdot \frac{R_2}{R_1} \qquad (6)$$

To obtain some more insight a numerical example is given in Fig. 3. Since the antenna structure is approximately at room temperature, for T_2 a value of 290 Kelvin has been assumed. Graphs are shown for three different values for the antenna sky noise temperature T_1. These antenna noise temperatures are typical examples for the values encountered in the LOFAR frequency range as was discussed in section 2.1.
From Fig. 3 it can be concluded that at low frequencies, where the antenna sky noise temperature is very high, the signal degradation due to ohmic losses in the passive antenna structure can still be neglected even for extreme ratios of loss resistance and antenna radiation resistance.

Figure 3. Noise factor due to ohmic losses in antenna for different sky temperatures



The noise in the amplifier is caused by thermal noise in dissipative elements and various sources of non-thermal noise in active components like transistors. Depending on circuit topology and used components the noise contribution of this part can normally not be neglected. Section 3.5 describes in more detail this topic and how to minimise this noise contributions.

2.3 Noise in the receiver

Similar to the noise caused by the amplifier of the active antenna the noise in the rest of the receiver is due to both thermal as well as non-thermal noise in electronic components. In a well-designed receiver system the contribution of the receiver noise to the overall system noise is normally negligible.

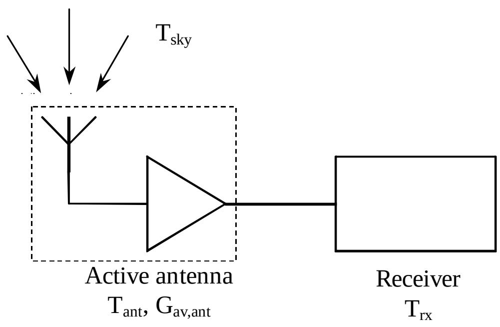
2.4 Optimising system noise

A simplified receiver system to evaluate the noise contributions of different components is given in Fig. 4.
From Friis formula for a cascade of two-ports the system noise temperature can be calculated for the situation given in Fig. 4:

$$T_{sys} = T_{sky} + T_{ant} + \frac{T_{rx}}{G_{av,ant}} \qquad (7)$$

Where: T_{sys} – system temperature, T_{sky} – sky temperature, T_{ant} – noise temperature active antenna, T_{rx} – receiver noise temperature, $G_{av,ant}$ – available gain of active antenna.

Figure 4. Basic receiver system lay out



In general the noise contribution of the receiver is minimised by having a reasonable low value of T_{rx}, but more important by choosing the available gain of the active antenna sufficiently large.
For the LOFAR system where the sky noise is dominant the noise due to the active antenna must be small in comparison with this sky noise.

2.5 Interference from transmitters

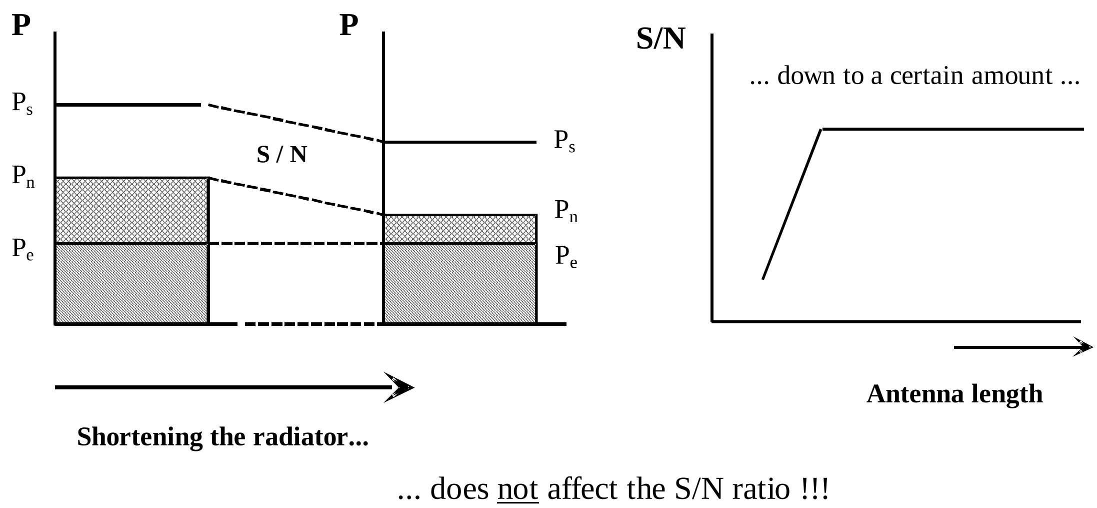
So far, in this section no mention has been made about the unwanted signals caused by transmitters in the LOFAR frequency range. In Fig. 1 these signals are not included, however they can be much stronger then the indicated noise levels in this graph. Most of the transmitted signals have a narrow band spectrum as opposed to the noise signals. Exceptions are those transmitters who use a spread spectrum modulation technique, which results in a noise like signal.
Due to different propagation mechanisms basically two different regimes can be distinguished in the LOFAR frequency range. In the range between 10 MHz and 30 MHz to 50 MHz the ionosphere plays a major role in the propagation of signals around the earth. This results roughly in about the same spectrum occupancy for every spot in the world. Measurements in the Munich area for this frequency range have shown very strong signals, reaching field strength levels in excess of 1 V/m. These signals came from short-wave broadcast systems located a/o in Europe and Asia. Similar strong signals can be expected for other possible LOFAR locations.
The situation above the previously mentioned upper frequency limit of approximately 30 MHz to 50 MHz is different because the propagation is generally according line of sight. As a result the interfering signal levels are very much dependent on the local situation around the LOFAR stations.
Just like other noise sources, the signals from transmitters are unwanted in the LOFAR receiver system and need to be minimised in some way. Except having a radio quiet location for LOFAR additional techniques like spatial, using adaptive nulling, and frequency domain filtering will be a necessity in the receiver system.

3. THE LOFAR ACTIVE ANTENNA

3.1 General concept of active antenna

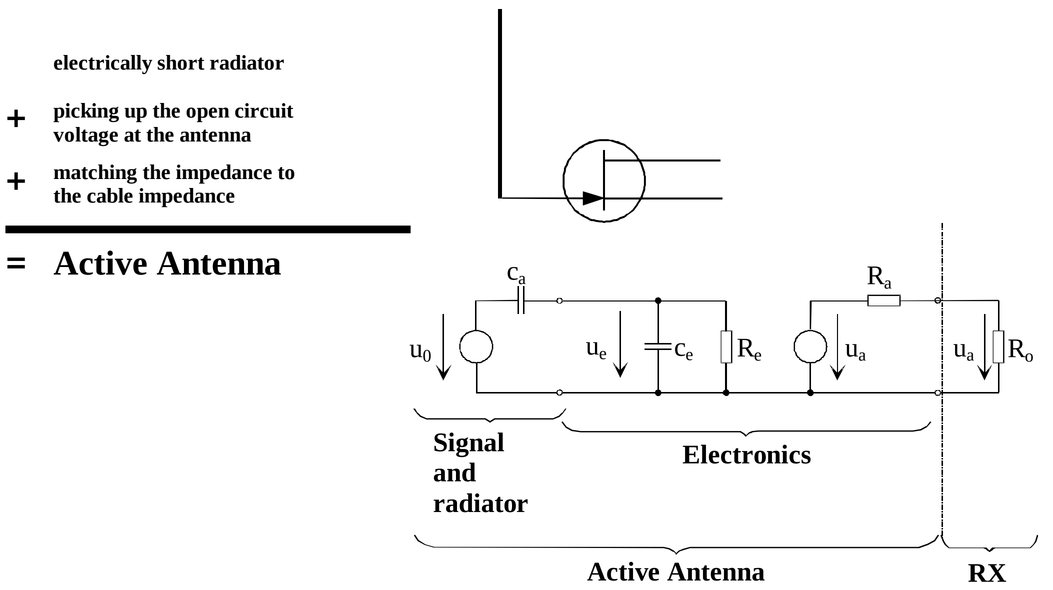
Active antennas have been initially invented as receiving antennas for the frequencies below about 30 MHz where the external noise exceeds the electronic noise considerably. They are based on the matter of fact that shortening the radiator length of a tuned antenna does not affect the signal-to-noise ratio at the antenna output as long as the external noise level is still stronger than the internal one. Thus, the size of a short-wave antenna can be reduced from about 15 m or even more to 1 m or 1.5 m approximately. However, shortening the radiator will dramatically change it’s input impedance, which becomes nearly infinitely large and capacitively, while the nominal impedance of the coaxial cable is usually 50 Ohms. Hence, an active device is attached directly to the radiator to transform the radiator impedance back to the cable impedance.

Figure 5. Basic idea for active antennas



Active antennas exhibit some very interesting advantages if compared with passive ones. Most obviously, they are much smaller than passive antennas designed for the same frequency range and thus for a series of applications (where space is limited) the only remaining choice. Due to the fact that the radiator length is very well below a quarter of the wavelength their radiation pattern and some other important technical data become completely independent of the frequency which allows real broadband operation. Due to the same fact the amplitude of the current distribution on the radiators is very small, and hence the coupling with other antennas or metal structures is usually negligible. This allows easy combination of active antennas in arrays for direction finding or electronically steerable monitoring antennas.

Figure 6. Active antenna principle



These features have meanwhile led to active antennas for higher frequencies as well. Particularly at frequencies well above 100 MHz the active device does not only transform the impedance but also amplify the signal a little bit in order to compensate cable losses. However, active antennas must never be confused with receiving systems consisting of passive antenna and antenna amplifier, and the main task for the active circuit is always the impedance transformation.

Beneath the advantages described above there are some few disadvantages as well: active antennas can never be transmitting antennas, they always need a power supply device and they contain non-linear components which might – if not properly designed – lead to linearity problems in strong electromagnetic fields. Hence, particularly in professional active antennas much effort has been spent to prevent high field strengths from causing distortions.

The effective area A_{eff} of an antenna is a parameter specially defined for receiving antennas. It is a measure of the maximum received power P_r that an antenna can pick up from a plane wave of the power density S:

$$P_{r\,\max} = S \cdot A_{eff} \tag{8}$$

It can be converted to the gain and vice versa by means of the formula:

$$A_{eff} = \frac{\lambda^2}{4 \cdot \pi} \cdot G \tag{9}$$

Where λ is the wavelength and the gain G is defined as the ratio of the maximum received power P_{rmax} (main reception direction, power matching at the output, polarisation matching) to the received power P_{ri} of a loss-free, omni directional reference antenna (isotropic antenna):

$$G = \frac{P_{r\,\max}}{P_{ri}} = \frac{G_{pract}}{(1-|\Gamma_a|^2)} \quad ; \quad \Gamma_a = \frac{Z_a - Z_n}{Z_a + Z_n} = \frac{s_s - 1}{s_a + 1} \tag{10}$$

Γ_a – antenna reflection factor, s_a – standing wave ratio of the antenna referred to the nominal resistance Z_n, Z_a – antenna impedance = output impedance of the active antenna

The practical gain is defined as the ratio of the received power P_r into nominal resistance (main reception direction, polarisation matching) to the received power P_{ri} of a loss-free, omni-directional reference antenna (isotropic antenna):

$$G_{pract} = \frac{P_r}{P_{ri}} = D \cdot G_T \tag{11}$$

Different from the gain G, the practical gain G_{pract} can be measured directly. It can be calculated also if the electronic gain G_T and the directivity D are given.
By means of the equations above, the maximum received power can be calculated from the antenna data.

3.2 Antenna element specifications

Although the final LOFAR system specifications are still under discussion a preliminary list has been compiled for the main antenna element specifications based on the strawman system requirements. These specifications are design targets and might chance due to different system configurations.

Table 2. LOFAR antenna element main specifications

Frequency range	10 – 150 MHz
Beamwidth @ - 3 dB	> 120º
Noise temperature	< 10 % of sky noise
Output impedance	50 Ω nominal
Return loss	< - 10 dB
Polarization	Linear
IP_3	> + 25 dBm

3.3 Benefits of active antenna in LOFAR application

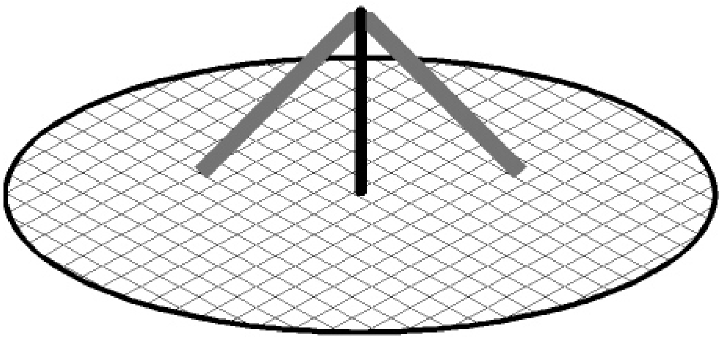
The specifications of the LOFAR project, particularly the large frequency range 10 MHz ... 150 MHz, lead directly to the choice of an active antenna element as a part of a steerable antenna array. Hence, the antenna dimensions are compact with respect to the wavelength without sacrificing effective antenna aperture and thus received power, and mutual coupling with neighbour elements is reduced to a minimum. Moreover, the electronic circuits can be manufactured in high quantities in a modern factory, which makes this solution quite cost effective, while the mechanical design of the antenna element remains simply. Finally, the small dimensions of the active antenna elements reduce the danger of lightning strokes.

Antenna arrays offer particular advantages for both radio monitoring and radio astronomy purposes. By combining the outputs of the antenna elements after their amplitudes and phases have been adjusted the sum radiation pattern of the complete antenna system can be steered. Thus, for instance a narrow pencil beam can be shaped and moved in order to scan the sky. Independent operation of several beams is also possible, and finally by steering the radiation pattern interfering transmissions can be cancelled. Basically, this beam forming can be done analogue and digitally. However, in both cases the radiation patterns of the single elements need to be identical, and certainly their independence of the frequency is very helpful. This once again is an argument for the choice of active antenna elements.

3.4 Radiator

The wide beamwidth needed for the LOFAR application results in a radiator that is electrically small compared to the wavelength for which it is being used. A choice has been made for a short, at least in the lower LOFAR frequency range, dipole. This antenna type has an almost frequency independent radiation pattern that is also very similar for E- and H-plane.
At the upper frequency end where the dipole becomes about half a wavelength the E-plane becomes narrower compared to the H-plane pattern. This effect has been minimised by giving the dipole a V-shape.
To obtain a directional radiation pattern the dipole is combined with a flat metallic reflector. The centre dipole feed point is positioned about ¼ of a wavelength above the reflector at the highest operation frequency. As a result, at lower frequencies this distance, expressed in wavelength, is always less then a ¼. In this way a broad directional beam pattern is obtained which shows no bifurcation over the operational frequency range. Fig. 7 shows a sketch of the LOFAR antenna element.

Figure 7. Impression of single polarisation LOFAR antenna element



The flat reflector is still a topic of research, the idea being that it can be of limited size and extended beyond by using the ground as a reflecting surface. The small reflector would be effective at the upper frequency of operation where noise performance is critical. At lower frequencies this is not an issue and the ground might be a suitable reflector and this would lead to a cost saving.
Fig. 8 and 9 show the simulated radiation pattern of such a V shaped dipole above an infinite reflector plane for frequencies of 10 MHz, 100 MHz, 150 MHz and 200 MHz. The electromagnetic simulator is based on a method-of-moments approach, where the far field radiation pattern is calculated from the current distribution on metallic patches.
Actual radiation pattern measurements have been made on a similar dipole with a reflector having a diameter of 1 m and compared to the simulated results of that same structure. The results from measurements and simulation were in good agreement to each other, so it is expected that the diagrams shown are feasible. So far no simulations have been made that model the ground as a reflector.

Figure 8. E-plane (linear scale)

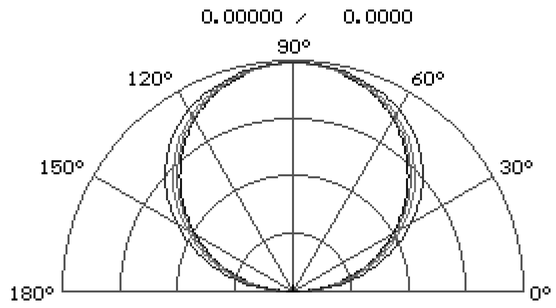
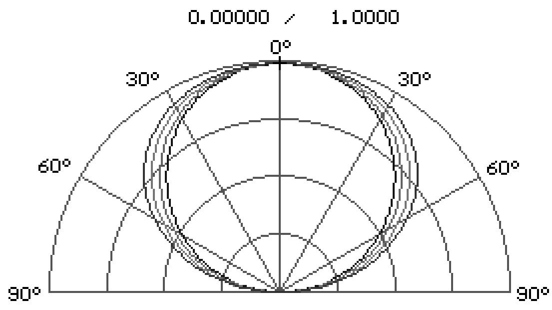


Figure 9. H-plane (linear scale)



3.5 Active circuit

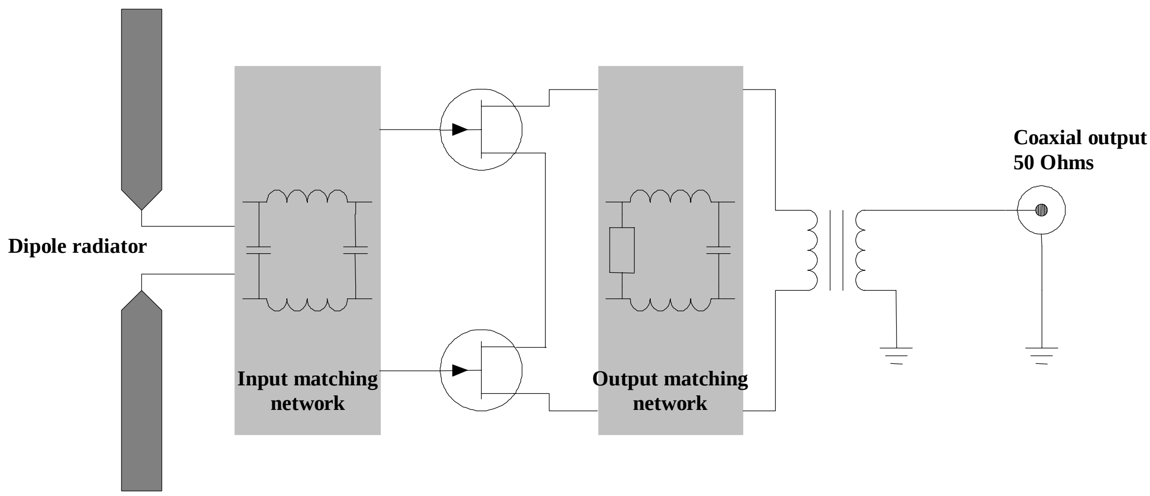
Fig. 10 shows a block diagram for the amplifier used in the active antenna. A balanced circuit topology has been chosen for three reasons:

- To match amplifier input to the balanced output of the radiator, which is important to avoid degradation in the symmetry of the antenna radiation pattern.
- Improved large signal handling capability (increased 1 dB compression point) since two amplifier stages in parallel can deliver power to the output instead of only one.
- Suppression of even order intermodulation (especially 2^{nd} order), which is an inherent property of balanced circuits.

Active devices used for the amplifier stages are GaAs FETs in a common source circuit. The reasons for these choices are the following:

- FETs give better broadband noise performance compared to a BJT for the given source impedance. In this particular application the mostly capacitive source impedance presented by the short dipole.
- GaAs has inherently better noise properties compared to silicon.
- The common source circuit shows best noise performance compared to other circuit topologies like common gate circuit and common drain circuit.

Figure 10. LOFAR active antenna amplifier configuration

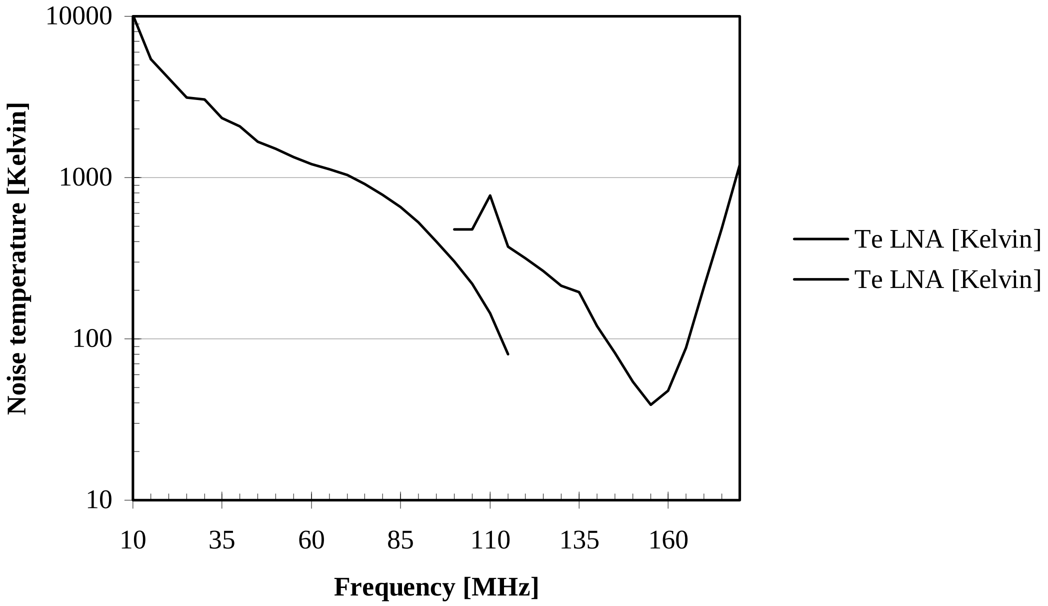


The input-matching network is designed in such a way that the amplifier stages produce a minimum amount of noise. There is no optimisation of power transfer between dipole and amplifier stages necessary since the applied method of noise matching leads to an optimum regarding the signal to noise ratio of the system.
To realise constant output impedance a brute force method, using a shunt resistor in the output matching network, has been applied. However this simple solution is at the expense of the maximum output power capability.

3.6 Measurement techniques of active antennas

The measurement of radiation patterns of active antennas can be done by similar methods as used for purely passive antennas under the condition that the active antenna under test could only be used as the receiving element.
Measuring the noise and gain properties of an active antenna are not straightforward since the input port is the antenna receptor instead of some well defined transmission line interface. Measurement techniques where the active antenna under test is irradiated by another antenna in a well controlled environment like anechoic chamber are not practically suited for this application.[6, 7] This is due to the relative low frequency that results in unpractical dimensions of the anechoic chamber. Attempts to use these techniques on an outdoor antenna range were unsuccessful due to the high interference levels encountered.
Instead an alternative measurement method has been used to determine gain and noise temperature of the active antenna. With this method a 2-port network replaces the radiator of the active antenna. This artificial antenna network presents the same impedance at the input of the amplifier integrated in the antenna as the radiating element when the other port of the network is terminated at the characteristic impedance, normally 50 Ohms, of the measurement system. Since the available gain and noise temperature of the artificial antenna network can be calculated from its S-parameters, the noise temperature of the amplifier can be determined by applying Friis formula, similar to Eq. (7).
Fig. 11 shows the noise measurement results obtained from one LOFAR active antenna. Two different artificial antenna networks have been used for these measurements. One network simulates the radiator impedance over a frequency range from 10 MHz to 110 MHz, while the other network is valid for the range from 130 MHz to 170 MHz.

Figure 11. Measured noise temperature LOFAR active antenna



4. CONLUSIONS

An active antenna based on a short dipole has been presented as a receiving element for LOFAR. This choice provides a physically compact solution usable over the frequency range of interest. Radiation pattern is nearly constant with frequency for both E- and H-plane, while the noise performance matches closely with the set objective.

The –3 dB beamwidth has a value of approximately 90 degrees and is less then the design goal of 120 degrees. If this is unacceptable from a system point of view needs further investigation. Possibly for earth rotation synthesis measurements this problem is overcome by the fact that the decreased signal levels away from zenith are compensated by the higher, absolute antenna gain compared to an antenna element with broader radiation pattern.

Concerning the antenna element itself, further work is proposed in the following areas:

- Investigate the effect of real ground as a reflector on the radiation pattern
- Optimise the design in terms of cost and reliability for the large quantities needed in the LOFAR instrument
- Improved measurement method of the active antenna noise temperature. This can possibly be achieved by applying these antennas in a simple interferometer using galactic sources with known flux density.

Finally the antenna should be properly interfaced with a receiver. For the all-digital telescope approach where all antenna signals are digitised in might be interesting to integrate the receiver with the active antenna in one single package.

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