M1 de Physique
École Normale Supérieure de Lyon
Université Claude Bernard

Stage 2005-2006
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M1 Option Physique

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Calibration of the LOIS antennas

Summary:

The LOIS radio telescope will detect the incoming low frequency signals by using an array of simple omnidirectional tripole antennas. These antennas, built in the laboratory, will also be part of the instruments on the Swedish MicroLink-1 probe and many other projects. The aim of this internship was to study these antennas in detail to provide useful information on their behavior.

Key-words:

Radio Astronomy, LOIS, Active Antenna

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April-June 2006

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Introduction

To detect radio signals from the most distant objects in space, astronomers need telescopes with a very high sensitivity, and this sensitivity is not achieved by current radio antennas. That is why the LOw Frequency ARray (LOFAR) is being built. LOFAR will be a new generation digital 'IT-Telescope' operating between 10 MHz and 250 MHz, a part of the spectrum range which has hardly been explored in astronomy, with a resolution and a sensitivity between 10 and 100 times better than the current telescope ones. This will be achieved thanks to an array of thousands of small active antennas, and by a huge network and a powerful computer which will coordinate all the information from these antennas.

The LOIS project will be the Scandinavian extension of LOFAR, with some improvements, especially on the antennas. With these new antennas developed in the IRF laboratory in Uppsala, we are able to find the direction and the polarisation of the incoming waves in addition to their amplitude and frequency. These advantages, and the fact the antennas are small, make it a good instrument for other applications such as radio measurements in satellites.

For the measurements to be as correct and accurate as expected, the antennas have to be calibrated in a careful way. My thesis work was to evaluate some characteristics of both LOIS and LOFAR antennas.

Chapter 1

LOIS and LOFAR

1.1 Presentation

The LOFAR (Low Frequency Array) project started at the end of the 1990's in the Netherlands and was aimed at studying the oldest and most remote objects in space. This radio telescope was designed to operate in the 10 MHz - 250 MHz range of the electromagnetic wave spectrum (HF - VHF) with a very good sensitivity and resolution. A supercomputer combines the signals from 25000 antennas distributed over a 350 km wide zone.

Its Swedish cousin, LOIS (LOFAR Outrigger In Scandinavia), was started in 2001 to extend the possibilities of LOFAR. It will consist of 32 stations of 32 antennas each, and it comes with improved antennas and measurement technologies.

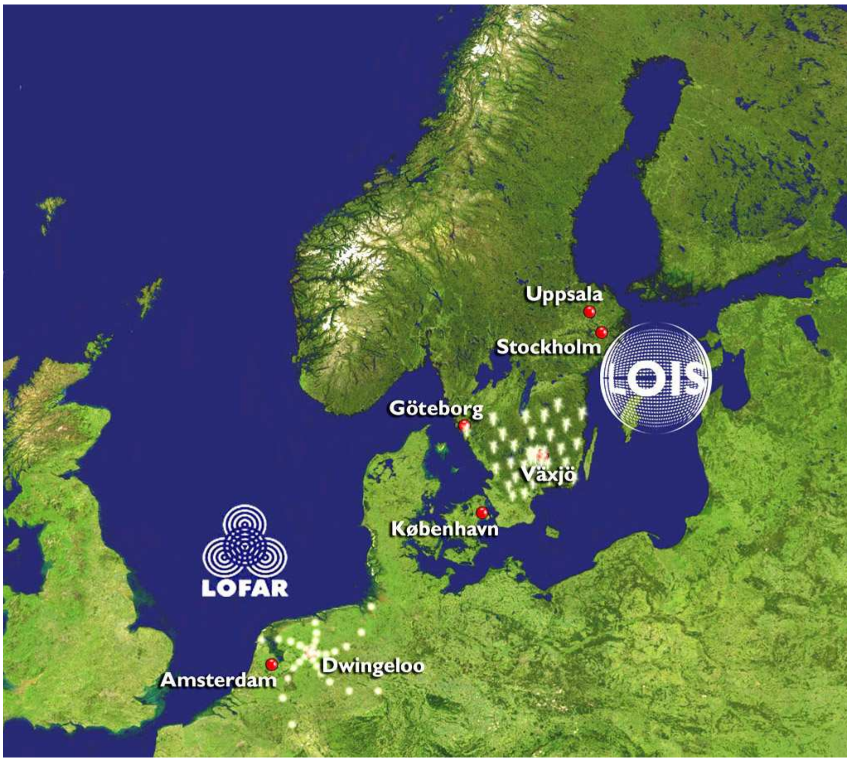


Figure 1.1: Location of the LOIS an LOFAR stations

Both of them will be used to:

- find the red-shifted 21cm radio signals emitted by the original hydrogen atoms shortly after the big Bang.
- study the solar radio emissions.
- study the "electrosmog" from radio, TV and radar transmitters.
- study the ionosphere.
- study the interaction of cosmic particles with the atmosphere (particle shower).
- ...

1.2 An array of antennas

Until now, most of the radio telescopes have been dish antennas, mechanically moved to the wanted direction. To get a sufficient resolution and sensitivity, these aerials have to be as large as possible, especially at low frequencies (large wavelengths) [1].

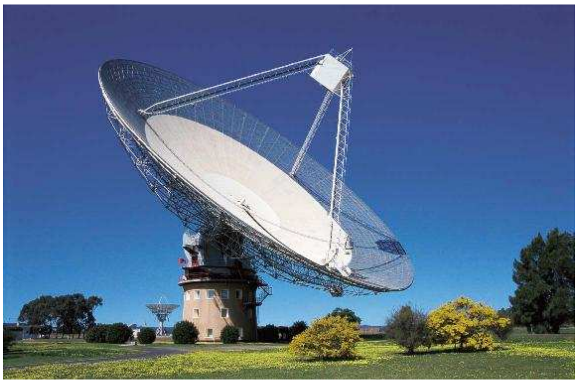


Figure 1.2: Dish antennas must be large to have a good resolution for large λ

Angular resolution The angular resolution θ of an antenna is proportional to $\frac{\lambda}{D}$ where D is the diameter and λ the wavelength. For traditional radio telescopes, $\lambda \approx 1$ m (300 MHz) and $D \approx 100$ m for the largest ones, this makes a resolving angle of $0.6° \approx 35'$arc. The human eye has a resolution of $\sim 1'$arc. Thus, even at relatively high frequencies, the resolution is not good. A 100 m dish antenna receiving a $\lambda = 30$ m (10 MHz) signal (as in the LOFAR/LOIS case) would have a resolution of 6°. Conversely, to achieve a resolution of $35'$arc at 10 MHz, a 3 km wide telescope is needed ...

Sensitivity The new telescopes operating at low frequency need also to be more sensitive than current ones. Indeed, in this frequency range, the external noise is much more important than the one at higher frequency. Thus, the size of the telescope must be augmented again, since the directivity is proportional to the area of the dish.

But building big parabolic antennas is hard and expensive. Therefore, an equivalent dish antenna to LOIS or LOFAR, i.e., 10 - 250 MHz frequency range instead of 30 MHz - 300 GHz for classical telescopes and an increased resolution and sensitivity, cannot be built and astronomers have to find another way to achieve these requirements.

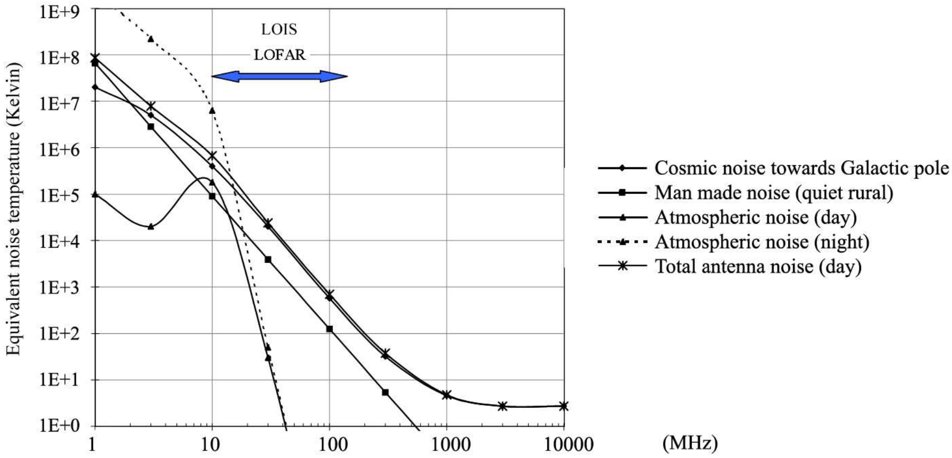
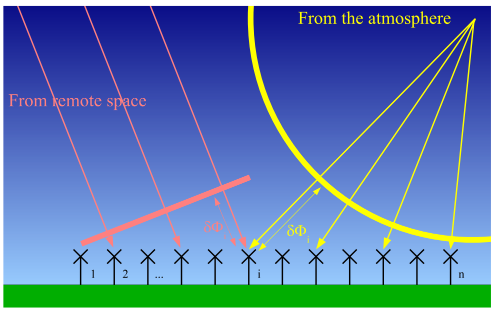


Figure 1.3: Noise level versus frequency

Aperture Synthesis The solution is to use a network of thousands of small inexpensive aerials over a hundred kilometer wide area, the signals from all the antennas being recorded and digitized separately. To obtain the image of a definite point, we just have to delay each signal with the corresponding value, and to combine them. This phase shift will determine the focus and the direction of the telescope. The particularity of LOIS and LOFAR is that this operation is done by a computer. This enables an increased precision in the delay adjustment and flexibility of use.



$$\Rightarrow \begin{cases} S_1 \\ S_2 \\ \dots \\ S_i \\ \dots \\ S_n \end{cases} \Rightarrow \begin{cases} \sum S_i(\delta\phi_i) & : \text{space signal} \\ \sum S_i(\delta\phi_i) & : \text{atmosphere signal} \end{cases}$$

Figure 1.4: Focusing and directing the array

Thus, instead of mechanically moving one big and heavy antenna, we electronically shift the direction of the central interference maximum. The advantage is that there are no mechanical risks of breaking the aerial, the precision is much better, and we can look in different directions at the same time because the signals are all recorded separately and can be manipulated in different ways after the fact. And finally, it is much less expensive than parabolic antennas.

Concerning the resolution, the diameter of the telescope is now $D \approx 200$ km, making a resolution of $\theta \approx 30''$arc at 10 MHz.

1.3 Technical requirements

To be able to carry out this procedure, several technical exploits must be achieved. In particular, the data treatment needs a fast computer to be executed in a decent time: a supercomputer BlueGene/L has been installed at LOFAR and LOIS has its own IBM computer for this purpose. Also, the data flow from the antennas is enormous and requires a fast glass-fiber network (Terabits/sec) to be conveyed to the computer. These elements and many others are now being tested in the test stations.

Test stations for both LOFAR and LOIS have been built with few antennas. With these primitive arrays, we want to have an insight of what the data could look like. Data is already collected from these stations. The calibration and precise localization procedure are also tested here.


Figure 1.5: LOIS and LOFAR test stations

My thesis work concentrated on the antennas. Both LOIS and LOFAR antennas are active antennas. We will see what this means in the next chapter. Furthermore, the LOIS antennas are tripole antennas that allow us to measure the full electromagnetic (EM) vector and to estimate the direction of the EM field. We will see how it works in the following chapter.

Chapter 2

Passive and Active Antennas

2.1 General properties of antennas

A radio wave receiving system consists in two parts: the antenna and the detection system [2].

Receiving antenna As is well-known in electrodynamics, an electromagnetic wave can set charge carriers (electrons for instance) in motion [3]. A radio antenna therefore consists of a good electric conductor of, in principle, an arbitrary shape. This allows electrons to move almost freely in the antenna, following the EM field (at radio frequencies at least). When the electric field of the incoming radio wave interacts with the antenna, the electrons in the conductor will start to oscillate to produce a current density in the antenna: the antenna acts as a current (or voltage) generator. From the Thévenin equivalence, we can draw the equivalent scheme of the antenna.

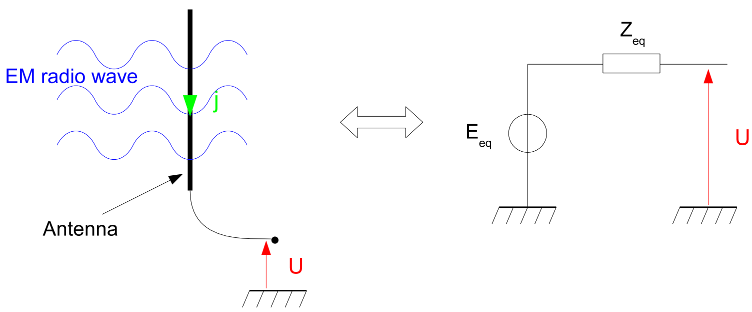


Figure 2.1: Antenna as a generator

Both the open circuit voltage and equivalent impedance depends on the frequency and amplitude of the incoming wave, and on the length and shape of the antenna. The impedance of the antennas will be studied in details in the last chapter.

There exists a lot of shapes for antennas (wire, dipole, loop, Yagi-Uda, parabola, ...[1]), but a very common type is the linear antenna which is a thin and straight wire made of conductive material (copper, aluminium, ...). This type of antenna is common because they are quite easy to model, and their properties are well known. For instance, a $\lambda/2$ long dipole antenna on the ground has an impedance of 50 Ω purely resistive [4]. This antenna has the advantage to have no impedance matching problems with subsequent standard electric devices.

Also, for a short antenna, the open circuit voltage is proportional to hE where h is the length of the wire. This property of linear dipole antennas can be extended to every kind of antenna by defining h_{eq}, the equivalent length.

If the antenna is a linear wire, then the magnetic contribution is negligible. However, if the aerial is a loop antenna, the magnetic field is predominant and the electric field can be neglected. That is why LOIS antennas are of 2 types: one sensitive to the electric field and the other to the magnetic field.

A lot of other parameters (gain, directivity, ...) characterize the antenna but we will not describe them.

Detection system In theory, the receiver can be just a voltage sensitive device, but for many reasons, it has to be more complex [2, 5]. We will see what it consists for the LOIS antennas.

First, the antenna signal passes through a band-pass filter (BPF) to ensure that frequency components which are not interesting cannot reach the subsequent devices. Then the signal reach a pre-amplifier (PREAMP) which amplify modestly the signal, isolates the antenna from signals in the detector and provides impedance transformation. We will detail this part of the detection system in more details in the next section.

After the PREAMP, the signal is ready to be processed. The signal is often split into two identical signals, on two independent lines so that if one fails, the other can still be used. After that, various devices can be connected that allow amplitude, power and phase extraction, or error analysis or many others characterizations. In the case of LOIS and LOFAR, the signal is digitalized and send to a super computer. All the following steps for processing the signal are done by the computer. This includes Fast Fourier Transform [6], Synthesis imaging, transient detection, etc.

Thanks to this system, we can get the information we want from the radio waves with efficiency and accuracy.

2.2 Active antennas

At low frequencies, a $\lambda/2$ long linear antenna would be very long: at 30 MHz, the antenna would be 5 m long. This is not handy and can generate coupling with the other antennas, due to the high amplitude of the current density. A smaller antenna would have a complex impedance and a low Thévenin equivalent voltage. The active antenna has been invented to solve this problem[7].

An active antenna is no more than a passive antenna followed by and combined with a low noise preamplifier. The preamplifier allows impedance matching between the antenna and the receiver, and amplifies moderately the signal received by the antenna so that the dimensions of the antenna can be reduced.

By adding electric devices just after the antenna we decrease the quality of the signal because electric components add noise. Let us study this issue to see if this loss of information is important or not.

2.2.1 Noise considerations

General properties on noise There exists three major sources of noise:

- External sky noise. This noise cannot be decreased. It takes into account the man made noise (radio transmitters, industry, power lines, ...), cosmic noise generated by various processes in the universe, atmospheric noise caused by lightning discharges all around the world. In the LOIS/LOFAR frequency range, it is the prevailing source of noise.
- Noise generated in the active antenna. This is caused by the resistance of the antenna itself and by the pre-amplifier.
- Noise generated in the receiver that is connected to the antenna pre-amplifier.

The usual way to quantify the noise is to calculate the equivalent noise temperature[8, 9] of an element with the formula:

$$P_{\text{n}} = kT_{\text{Sys}}\Delta f \tag{2.1}$$

where P_{n} is the noise power, k is Boltzmann's constant, T_{Sys} is the system noise temperature and Δf is a given frequency interval. This definition allows us to measure the noise from a source, for instance from the sky, or the noise temperature of a resistor.

The noise added in an electric circuit can also be seen as a voltage or current generator. The noise voltage is $\langle v^2 \rangle = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} v^2(t)dt$ and the noise current is $\langle i^2 \rangle$. For instance, the noise voltage in a resistance is $\langle v^2 \rangle = 4kRT\Delta f$. This definition is very convenient to calculate the noise in electric circuits.

For an amplifier, we want to measure how much noise it adds to the signal while it amplifies it. For this purpose, we define the noise figure [5] as follows:

$$F = \frac{P_{\text{n}}^{\text{out}}}{G^2 P_{\text{n}}^{\text{in}}} = \frac{\langle v_{\text{real}}^2 \rangle}{\langle v_{\text{perfect}}^2 \rangle} = \frac{\langle v_{\text{real}}^2 \rangle}{G^2 \langle v_{\text{in}}^2 \rangle} \tag{2.2}$$

where G is the gain of the amplifier (voltage gain), $P_{\text{n}}^{\text{in}}(T_0)$ and $P_{\text{n}}^{\text{out}}$ are the noise power respectively before and after the amplifier, $\langle v_{\text{real}}^2 \rangle$, $\langle v_{\text{perfect}}^2 \rangle$ and $\langle v_{\text{in}}^2 \rangle$ are the noise voltages respectively after the real amplifier, after the amplifier if it were ideal (with the same gain but without noise), and at the input of the amplifier. It can be shown that the noise figure can be written this way:

$$F = \frac{S_{\text{in}}/N_{\text{in}}}{S_{\text{out}}/N_{\text{out}}} \tag{2.3}$$

i.e., the noise figure is the ratio of the signal to noise ratios before and after the amplifier. Thus it really is the measurement of the added noise.

Active antenna noise In order to evaluate the noise in the antenna, we will study the following model[5]:

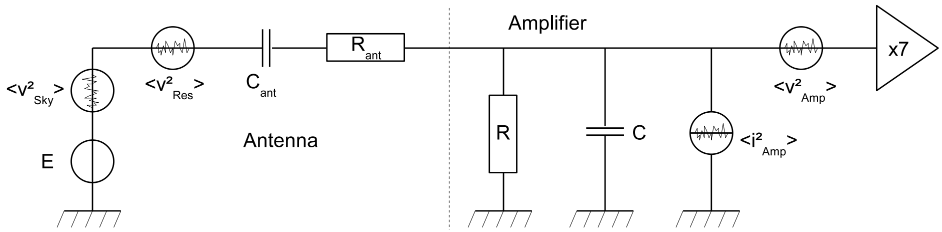


Figure 2.2: Noise model for active antennas

where:

- Passive antenna part:
  - E is the wanted signal.
  - $\langle v_{\text{Sky}}^2 \rangle$ is the sky noise seen as a voltage addition in the passive antenna. At 30 MHz, its value is approximately $\langle v_{\text{Sky}}^2 \rangle^{\frac{1}{2}} = 1.4 \times 10^{-8}$ V.Hz$^{-\frac{1}{2}}$.
  - C_{Ant} and R_{Ant} are the equivalent impedance, respectively for the passive antenna (see next chapters).
  - $\langle v_{\text{Res}}^2 \rangle$ is the noise from the previous resistance. $\langle v_{\text{Res}}^2 \rangle^{\frac{1}{2}} = 9\times 10^{-10}$ V.Hz$^{-\frac{1}{2}}$.

- Amplifier part:

  - R and C make the input impedance of the amplifier.
  - $\langle i^2_{\text{Amp}} \rangle$ and $\langle v^2_{\text{Amp}} \rangle$ stand for the noise from the amplifier. The first is a current generator and the second is a voltage generator. Their values have been measured experimentally. They integrate both noise from the transistor and from the resistor and all that can add noise. $\langle i^2_{\text{Amp}} \rangle^{\frac{1}{2}} = 1.3 \times 10^{-15}$ A.Hz$^{-\frac{1}{2}}$ and $\langle v^2_{\text{Amp}} \rangle^{\frac{1}{2}} = 4 \times 10^{-9}$ V.Hz$^{-\frac{1}{2}}$.

It is important to note that even if they are drawn as (current or voltage) generators on the scheme, the noise generators do not behave as classical ones do. Indeed, noise can only be added in terms of power, so that we have $\langle v^2_{\text{Ant}} \rangle = \langle v^2_{\text{Sky}} \rangle + \langle v^2_{\text{Res}} \rangle$ and not $\langle v^2_{\text{Ant}} \rangle^{\frac{1}{2}} = \langle v^2_{\text{Sky}} \rangle^{\frac{1}{2}} + \langle v^2_{\text{Res}} \rangle^{\frac{1}{2}}$ as it would have been the case if they were classical generators.

This complicated scheme can be simplified if one allows the equivalent noise generator to be frequency dependent:

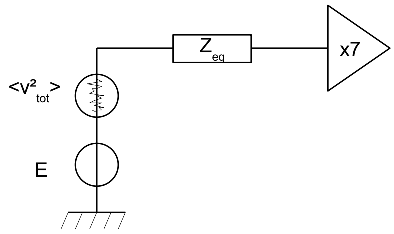


Figure 2.3: Equivalent scheme for noise study

The equivalent impedance and noise voltage are:

$$Z_{\text{eq}} = \frac{\frac{R(R_{\text{Ant}} + \frac{1}{iC_{\text{Ant}}\omega})}{iRC\omega+1}}{R_{\text{Ant}} + \frac{1}{iC_{\text{Ant}}\omega} + \frac{R}{iRC\omega+1}} \tag{2.4}$$

$$\langle v^2_{\text{tot}} \rangle = \left| \frac{Z_{\text{eq}}}{R_{\text{Ant}} + \frac{1}{iC_{\text{Ant}}\omega}} \right|^2 (\langle v^2_{\text{Sky}} \rangle + \langle v^2_{\text{Res}} \rangle) + \langle v^2_{\text{Amp}} \rangle + |Z_{\text{eq}}|^2 \langle i^2_{\text{Amp}} \rangle \tag{2.5}$$

We can now calculate the noise figure of the amplifier, the noise temperature at the output and the signal-to-noise ratio:

$$F = \frac{\langle v^2_{\text{tot}} \rangle}{\left| \frac{Z_{\text{eq}}}{R_{\text{Ant}} + \frac{1}{iC_{\text{Ant}}\omega}} \right|^2 (\langle v^2_{\text{Sky}} \rangle + \langle v^2_{\text{Res}} \rangle)} = 1 + \frac{\langle v^2_{\text{Amp}} \rangle + |Z_{\text{eq}}|^2 \langle i^2_{\text{Amp}} \rangle}{\left| \frac{Z_{\text{eq}}}{R_{\text{Ant}} + \frac{1}{iC_{\text{Ant}}\omega}} \right|^2 (\langle v^2_{\text{Sky}} \rangle + \langle v^2_{\text{Res}} \rangle)} \tag{2.6}$$

$$T_{\text{act}} = \frac{\langle v^2_{\text{tot}} \rangle}{4k|Z_{\text{eq}}|} \tag{2.7}$$

$$\frac{\text{S}}{\text{N}} = \frac{\left| \frac{Z_{\text{eq}}}{R_{\text{Ant}} + \frac{1}{iC_{\text{Ant}}\omega}} \right| E}{\langle v^2_{\text{tot}} \rangle} \tag{2.8}$$

After calculation, the numerical values for each noise component at $f \sim 30$ MHz are:

- $\sqrt{\langle v^2_{\text{tot}} \rangle} = 1.29 \times 10^{-8}$ V.Hz$^{-\frac{1}{2}}$
- $F = 1.1$

- $T_{\text{act}} = 13000$ K

The noise figure is really low, showing that the amplifier does not introduce much noise. This is due to the fact that, at this frequency (30 MHz and lower), the noise from the sky dominates over the noise from the electronic part.

Thus, the addition of the amplifier increases the noise in a controlled fashion, and it also amplifies the signal and therefore it allows the use of smaller antennas. The improvements on the system can be evaluated by the figure of merit[9]: G/T.

G is the gain of the antenna. It consists in two parts: the passive gain, inherent to the antenna, and the active gain, the gain of the preamplifier. The passive gain measures the extent to which the aerial concentrates radiation in one direction. It is the ratio of the flux-density produced by the aerial in one direction to the one produced by an omnidirectional antenna. For small linear dipole antennas, the power gain is approximately 1.5. The gain of our active antennas is $\sqrt{1.5G^2} = 8.6$.

We can calculate what would be the equivalent gain for a passive antenna: $G_{\text{eq}}^2 = \frac{1.5G^2}{T_{\text{act}}} \times T_{\text{Sky}}$. The noise from the resistance of the passive antenna can be neglected compared with the sky noise. The numerical calculation gives $G_{\text{eq}} = 7.5$. The passive gain of our active antennas being 1.5, the effect of the pre-amplifier is to add a $5\times$ gain (+7dB).

2.2.2 Conclusion on active antennas

Active antennas were initially invented as receiving antennas for the frequencies around 30 MHz, where the sky noise dominates over electronic noise. They are based on the fact that shortening the antenna does not affect the signal-to-noise ratio as long as the external noise exceeds the internal noise. The size of a short wave aerial can be reduced from 15 m to 1 m. The advantage of small sensors is that they are much more solid and handy, and that due to the small current amplitude in them, their will be less coupled. Also, their small size allow the antennas to be almost frequency independent. However, shortening it will dramatically change its input impedance, while the nominal impedance of the coaxial cable remains 50 Ω. The preamplifier allows us to pick up the open circuit voltage and also to amplify the signal to acceptable level.

For the two IT telescopes LOIS and LOFAR, these antennas are completely convenient because they can be manufactured in high quantities (both electronic and mechanic components), the power and signal-to-noise ratio is preserved and they are almost frequency independent.

Chapter 3

Tripole antennas

The LOIS sensors are a combination of three classical 1D dipoles, each dipole being orthogonal to the other. From the measurement, with the help of such a sensor, of the 3D antenna current

Figure 3.1: LOIS electric and magnetic tripole antennas

vectors, we can calculate the **E** of the incoming radio beam; we can find both its instantaneous magnitude and direction. The direction of **E** allows us to find or at least to get an approximation of the propagation direction of the incoming wave, the **k** vector of the wave. The Information Dense Antenna is the theory and the calculation method that allows that. We will now present its main ideas.

3.1 Information Dense Antenna

The IDA was invented in 1996 by Jan Bergman *et al.* at the Swedish Institute of Space Physics [10]. They aimed at constructing a small and inexpensive device for direction finding (DF) for radio waves, but it has also other possibilities.

The tripole antennas that are the IDA sensors are not new, but the way information from the sensors are manipulated is. Before revealing what one can and cannot do with IDA, let us look at how it works.

Polarization measurements The first step in direction finding is to find the characteristics of the polarization of the incoming wave.

Thanks to the tripole antennas, we know the instantaneous direction and amplitude for the electric vector **E**. For the following steps, we need to compute the windowed Fourier transform (computationally efficient) of it: $\tilde{\mathbf{E}}(t,\omega) = \int_{-\infty}^{\infty} \mathbf{E}(t-\tau)w(\tau)e^{i\omega\tau}\,\mathrm{d}\,\tau$, where $w(\tau)$ is the windowing function.

Now we can calculate the spectral density tensor:

$$\tilde{\mathbf{E}}\tilde{\mathbf{E}}^\dagger = \begin{pmatrix} \tilde{E}_x\tilde{E}_x^* & \tilde{E}_x\tilde{E}_y^* & \tilde{E}_x\tilde{E}_z^* \\ \tilde{E}_y\tilde{E}_x^* & \tilde{E}_y\tilde{E}_y^* & \tilde{E}_y\tilde{E}_z^* \\ \tilde{E}_z\tilde{E}_x^* & \tilde{E}_z\tilde{E}_y^* & \tilde{E}_z\tilde{E}_z^* \end{pmatrix} \tag{3.1}$$

The **E** field vector for a wave can be described by 6 parameters (real numbers): 3 amplitudes and 2 phases. As we can always multiply by an arbitrary phase factor without changing the underlying physics, the number of true independent parameters is 5. The spectral density tensor can find an equivalent set of parameters which better reflect the physical properties of the field. Let us see what they are, how we can calculate them and their physical meaning.

- The intensity of the field $\mathcal{I}$ is just the trace of the tensor:

$$\mathcal{I} = |\tilde{E}_x|^2 + |\tilde{E}_y|^2 + |\tilde{E}_z|^2 \tag{3.2}$$

- A pseudovector **V** associated to the antisymmetric part of the tensor and which is perpendicular to the plane of polarization, and hence parallel to the wave vector **k**:

$$\mathbf{V} = -2\,\mathrm{Im}(\tilde{E}_y\tilde{E}_z^*\hat{x} + \tilde{E}_z\tilde{E}_x^*\hat{y} + \tilde{E}_x\tilde{E}_y^*\hat{z}) \tag{3.3}$$

- The normalized magnitude $\nu = \frac{|\mathbf{V}|}{\mathcal{I}}$ describes the degree of circular polarization: 0 for linear polarization and 1 for circular. Using spherical coordinates,

$$\frac{\mathbf{V}}{\mathcal{I}} = \nu(\sin\theta\cos\phi\hat{x} + \sin\theta\sin\phi\hat{y} + \cos\theta\hat{z} \tag{3.4}$$

  the direction of arrival in terms of the polar angle, θ, and azimuthal angle, ϕ, can be calculated.

- The fifth and last parameter is the tilt angle, α, describing the spatial orientation of the polarization ellipse.

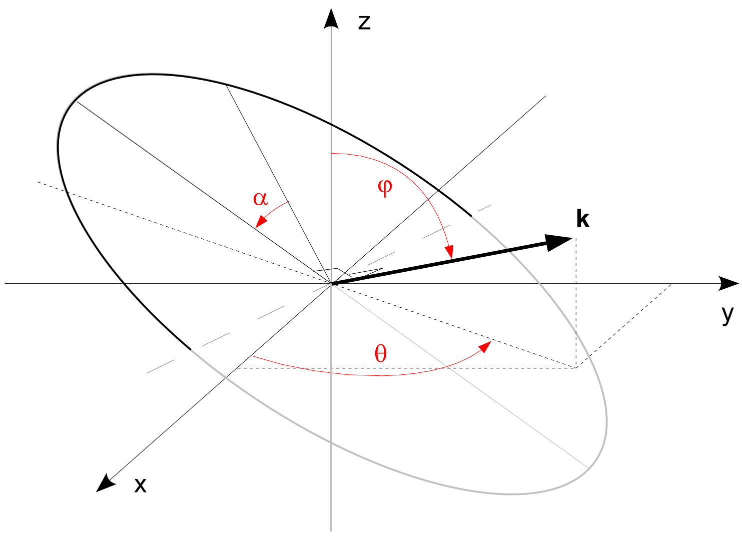


Figure 3.2: Polarization ellipse

Thanks to this **V** we know the direction of the incoming wave, but there remains a 180° uncertainty: we cannot distinguish between a right-hand circularly polarized wave coming from one direction and a left-hand circularly polarized wave coming from the opposite direction. This problem is often solved because most of the antennas are on the ground, thus cannot receive radio waves from the lower half space. If this is not the case, for instance in the case of an antenna on a satellite, the preceding study can be made for both electric and magnetic tripole antennas. The use of the Poynting vector will determine the real direction of arrival. Another method is to use interferometry with several antennas or a combination of these techniques.

The precision of the direction finding depends on the polarization. Indeed, in the case of a linearly polarized wave the vector $\mathbf{k}$ can only be found in a plane. However, the two last methods for raising the uncertainty of direction will also be able to resolve this one.

3.2 Conclusion on tripole antennas

The Information Dense Antenna permits direction finding for radio waves thanks to tripole antennas. The advantage of this theory on other similar concepts is that it can be used with many different kinds of waves: quasi-monochromatic waves of course, but also wide band and non stationary waves. Also, due to the specific shape of the antennas, IDA will never suffer of polarization mismatch because it can intercept all polarizations. Also, using an array of IDA allows us to study non-planar waves, which permit to exploit the more exotic properties of the electromagnetic field.

In addition to that, the IDA has found many new and unexpected applications such as detection of intelligent signal using polarization, multipath communication, etc. All these advantages plus its size and price makes the IDA and its sensor a very interesting device. Currently various scientific projets will or at least study the use of tripole antennas and its direction finding technology. Here are some examples:

- An IDA HF spectrometer for the International Space Station (ISS) as part of the 'Obstanovka' ('Environment') project;
- A miniature IDA receiver for electric fields for the proposed Swedish nano-satellite, 'MicroLink-1', developed at the Angstrom Space Technology Center;
- An ionosphere survey for the American National Oceanic and atmospheric Administration thanks to an array of IDAs;
- A simplified version of the antenna/receiver on board the Compass-2 satellite, launched on may 26, 2006 to measure strong and abnormal EM fields after earthquakes;
- A complete LOIS antenna and radio system on board a satellite around the moon ('LORD' project) to detect radio pulses from the lunar surface as it is bombarded by ultra-high energy cosmic rays and neutrinos;
- A LOFAR/LOIS-type telescope on the far side of the moon: Lunar Infrastructure for Information ('LIFE');
- ...

Chapter 4

Impedance of the antennas

One of the crucial points for an antenna is its impedance, i.e., the voltage divided by the current received, and its matching with the next devices that allow us to get the signal. It has to be carefully controlled in order not to lose any sensitivity. As we will see in this section, the impedance is linked to the size of the antenna. Thus, this study will help to determine which size is the most suitable.

4.1 The problem

An antenna immersed in an electromagnetic (EM) field acts as a current or voltage generator. By connecting it to a *feeder*, one can tap energy and thus information from it. The feeder is the device that allows us to read the information. Here is the simplest way to describe an antenna measurement system:

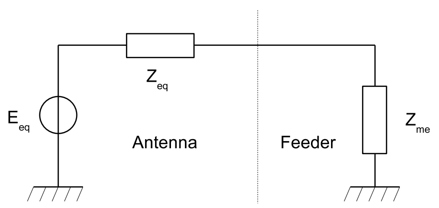


Figure 4.1: Simplest scheme of an antenna linked to its feeder

The E_{eq} generator and Z_{eq} impedance stand for the Thévenin equivalent circuit for the antenna immersed in the EM field, and Z_{me} is the input impedance of the measurement device (the one of an oscilloscope for instance).

For this circuit, the power received in the load is :

$$P = \frac{R_{\text{me}} E_{\text{eq}}^2}{(R_{\text{eq}} + R_{\text{me}})^2 + (X_{\text{eq}} + X_{\text{me}})^2} \tag{4.1}$$

where $Z_{\text{eq}} = R_{\text{eq}} + iX_{\text{eq}}$ and $Z_{\text{me}} = R_{\text{me}} + iX_{\text{me}}$. The power is maximum when $Z_{\text{eq}} = Z_{\text{me}}^* = R_{\text{me}} - iX_{\text{me}}$ according to the well-known impedance matching principle. Then, to get a maximum power and the best sensitivity, we have to make our antenna impedance get to this value. As the feeder is a standard device, its impedance is 50 Ω resistive only, and so must be the impedance of the antenna to ensure maximum power transfer.

4.2 Impedance measurements

The first thing to do is to find out how the impedance of the aerial behaves.

Experiments The HP 4195 network analyzer has an impedance measurement function which measures the impedance of a device for a given frequency range. It uses transmission coefficient to determine it.

Figure 4.2: Hewlett Packard 4195A

I used it to measure the impedance of conductive wires (simple wires for electronic applications) of different lengths. I made the same measurements for different kinds of antennas: monopoles, center-fed linear dipoles, which is the most common case and the one of LOIS, V-shaped dipoles (the LOFAR case) and loop antennas (LOIS magnetic sensors). The frequency range for each measurement was set to 5 - 500 MHz which covers the real LOIS/LOFAR range.

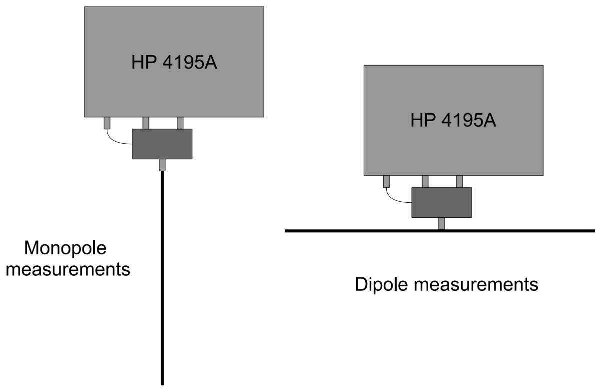


Figure 4.3: experimental setup

Results The first thing to notice is that the different kinds of antennas behave similarly. Thus, I just plot the module and phase for the dipole which is the case that interests us in particular.

In order to see the main behavior, the curves can be averaged.

At low frequencies, the antennas behave as a capacitor: $|Z| \propto \frac{1}{f}$ and $\phi \approx 90°$.

The impedance module is at a local minimum ($|Z| \approx 50\ \Omega$) and the phase is close to zero for a given frequency f_c that depends on the antenna length. Thus, at this frequency, the antenna behaves as a 50 Ω resistor which is what we are looking for. In fact, this standard value for most devices comes from the fact that a $l = \frac{\lambda}{2}$ long antenna has a real and close to 50 Ω impedance. I wanted to check if this (i.e., if $l \approx \frac{c}{2f_c}$) was verified in my experiments. Here are the values for the resonance frequency and the length of the associated antenna:

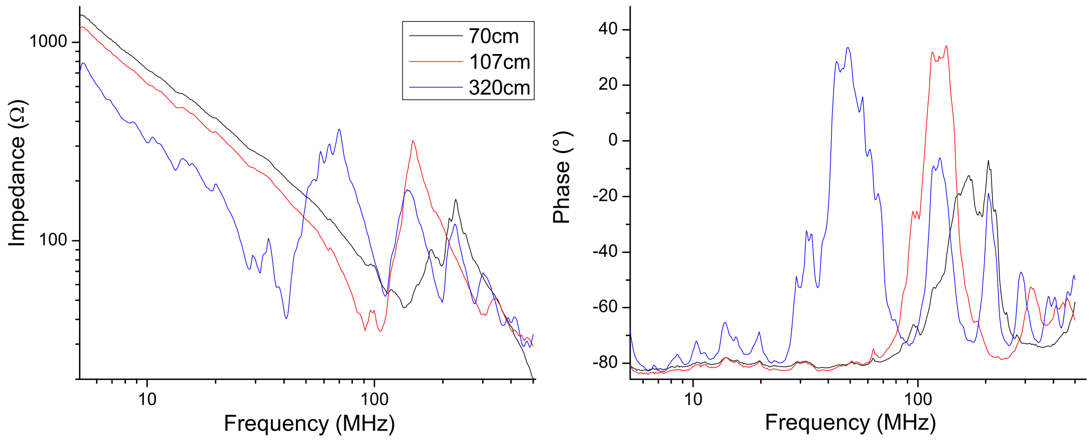


Figure 4.4: Impedance amplitude and phase for dipoles

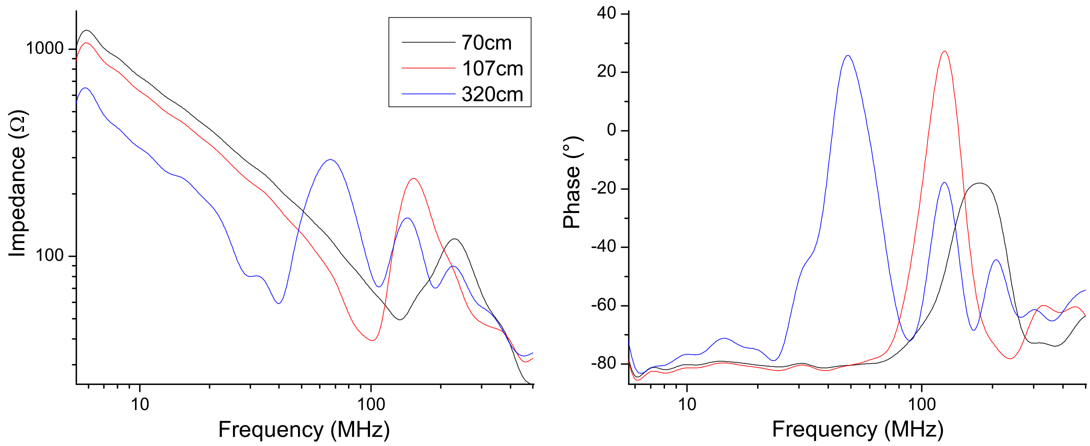


Figure 4.5: Smoothed impedance amplitude and phase for dipoles

l	f_c
0.7m	160 MHz
1.07m	110 MHz
2.16m	60 MHz
3.2m	41 MHz

After calculation, I found $f_c \approx \frac{123\times10^8}{l}$ Hz, which gives a value for $c \approx 2.45 \times 10^8$ ms^{-1}. The order of magnitude is good, but this is not precise. The error can come from the difficulty to accurately measure f_c and from the linking device between the antenna feed-point and the analyzer.

After this frequency, the impedance module and phase oscillate.

Interpretation The expression for the input impedance of a l meter long center-fed linear dipole antenna exposed to a radiation at $k = \frac{2\pi}{\lambda}$ is given by the formula[4]:

$$R_{\text{rad}} = \frac{\eta}{2\pi}\left(\gamma + \ln(kl) - \text{Ci}(kl) + \frac{1}{2}\sin(kl)[\text{Si}(2kl) - 2\,\text{Si}(kl)]\right. \tag{4.2}$$

$$\left. + \frac{1}{2}\cos(kl)[C + \ln(kl/2) + \text{Ci}(2kl) - 2\,\text{Ci}(kl)]\right) \tag{4.3}$$

$$X_{\text{rad}} = \frac{\eta}{4\pi\sin(kl/2)^2}\left(2\,\text{Si}(kl) + \cos(kl)[2\,\text{Si}(kl) - \text{Si}(2kl)]\right. \tag{4.4}$$

$$\left. - \sin(kl)[2\,\text{Ci}(kl) - \text{Ci}(2kl) - \text{Ci}(2ka^2/l)]\right) \tag{4.5}$$

where $k = \frac{2\pi f}{c}$, a is the radius of the wire, $\eta = \sqrt{\frac{\mu}{\epsilon}} \approx 120\pi\Omega$ for a free space medium, Si and Ci are the sine and cosine integrals ($\text{Si}(x) = \int_0^x \frac{\sin(y)}{y}dy$, and $\text{Ci}(x) = -\int_x^\infty \frac{\cos(y)}{y}dy$), and $\gamma \approx 0.5772$ is Euler's constant.

Thanks to this formula, I calculated the theoretical module and phase and compared it to the curves I got from experiments. As you can see, the calculated curves (green line) do not fit the experimental results, but the global behavior is identical. I made them correspond better (blue line) by modifying the 2 parameters we have: the length and radius of the wires. They could be different from the values I measured because the wires were not directly connected to the analyzer: I used a T-shaped plug to make the connection.

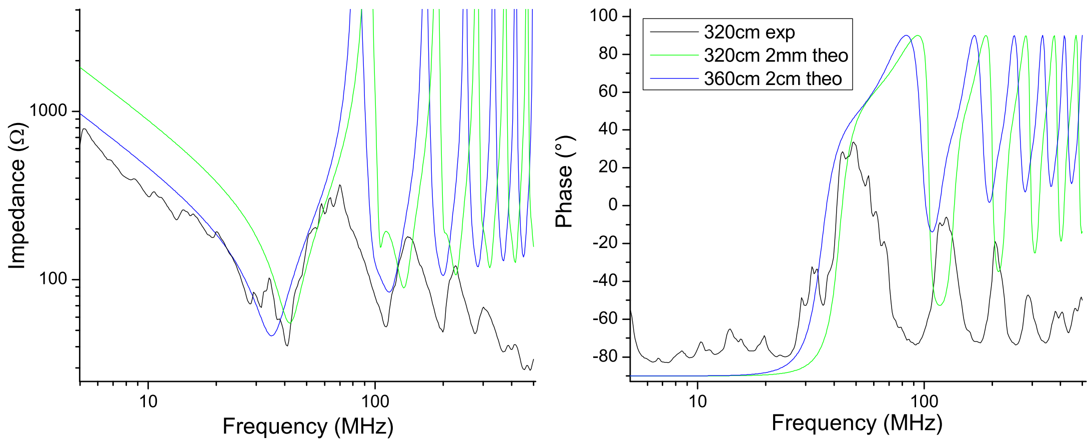


Figure 4.6: Fit for the 320cm long dipole

The dipoles behaves as predicted by the calculation, but the length seems to be multiplied by ~ 1.15. This is due to the radius of the wire which is not zero, and probably also to the T-plug between the antenna and the analyzer.

I did the same fit for the loop antennas, but now the "length" of the dipole must be interpreted differently. Indeed, this mathematical expression for the impedance is only true for (electric) dipoles, not for loops (magnetic dipoles). However, the behavior of the two kinds of antennas is very similar, and I have fitted the curves with the same expression. The results shows that we can use this expression, and we find an effective "length"

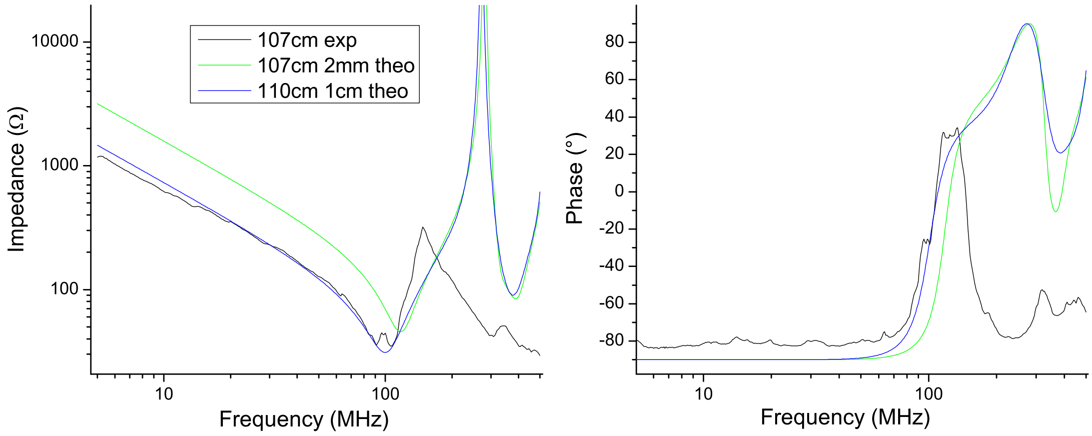


Figure 4.7: Fit for the 107cm long dipole

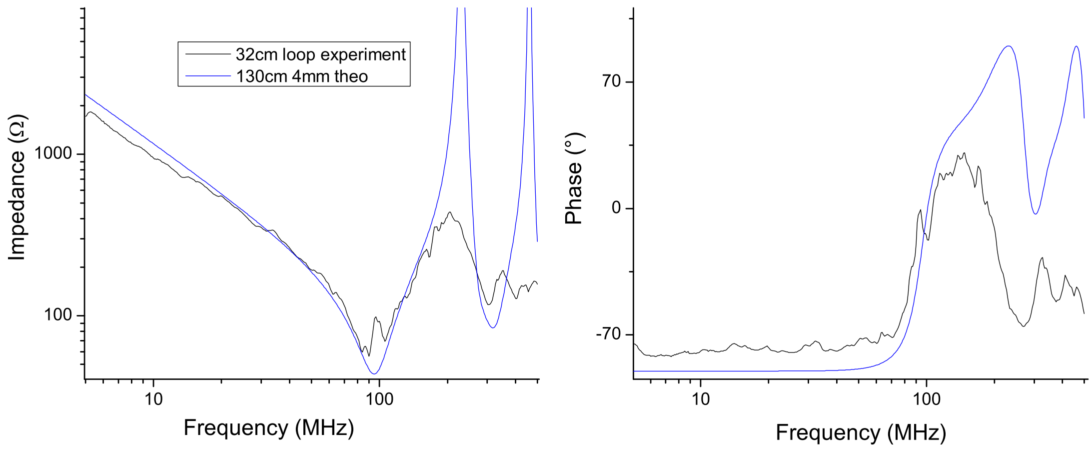


Figure 4.8: Fit for the 32cm wide loop antenna

Conclusion Our experiments show that the antennas behave as expected with some minor modifications. We have especially seen that they behave as capacitors in the low frequencies and that there is a resonance frequency $f_c \approx \frac{c}{2l}$ where the impedance is 50 Ω purely resistive.

Classical antennas are $\frac{\lambda}{2}$ dipoles because the matching condition is simple. But in our case, a $\frac{\lambda}{2}$ antenna would be 15 meter long at 10 MHz. This is not handy and has a lot of other drawbacks, as we have seen previously. This study justify the use of active antenna for solving the problem of impedance matching for small antennas.

4.3 Active antennas

The active antennas we will use will be small dipoles ($\lesssim$ 1 m). Therefore, the impedance will be complex and will behave as a capacitor (see 4.4) in the frequency range we are interested in. Here is the scheme of the system antenna+preamplifier:

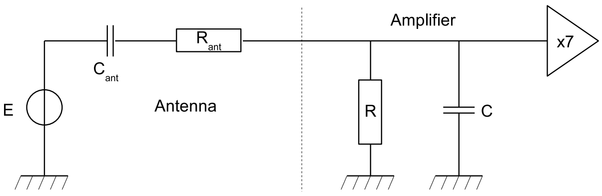


Figure 4.9: Equivalent circuit for the antenna connected to a preamplifier

R_{Ant} and C_{Ant} are the equivalent resistance and capacity of the antenna, and S is the output signal from the antenna.

Now, the impedance matching issue is different: as the amplifier has an (almost) infinite input impedance, we pick up the open circuit voltage at the antenna output. The values for the parameter in this scheme are all known, either from the constructor for the amplifier part, and from the experiment for the antenna part. The resistance for the antenna is approximately 75 Ω from the experiment and the capacity is easily calculated:

l	C_{Ant}
0.7m	20pF
1.07m	23pF
2.16m	30pF
3.2m	40pF

Thus, for the antenna that LOIS will use, the capacitance of the antenna will be around 20pF. With this value, we can calculate the transfer function of the system antenna/preamplifier (the input is the signal from the antenna, the output is taken before the ideal amplifier) :

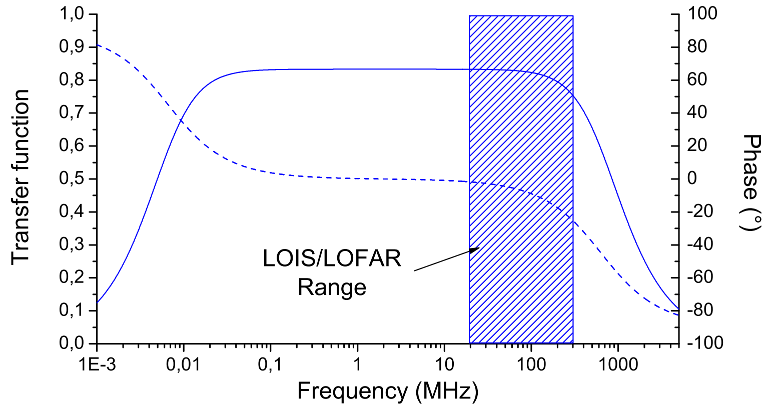


Figure 4.10: Transfer function of the system

The absolute value of the transfer function is approximately constant in the LOIS/LOFAR range and is equal to 0.833 (-1.58dB), and the phase is next to 0. These values are very good, and with such a circuit, the losses due to impedance mismatch are limited. Of course, the amplifier will compensate for these losses and amplify the signal to what standard antennas can give.

The use of longer antennas increases the value of the equivalent capacity, which leads to better impedance matching and losses less than -1dB. But, this improvements are not very significant and the amplification reduces again there relevance.

This study shows that the antennas for LOIS, LOFAR and the other projects using these aerials have a good impedance matching and thus transmit and amplify the signal in an efficient fashion. What is more important is that we can know precisely how efficiently the signal is transmitted and the phase shift it introduces. This can be interesting if the antennas are of different size.

Conclusion

The LOIS and LOFAR projects will come off with the two largest radio telescopes in the world with an equivalent area of 200 km for each one. In their frequency range (10 - 250 MHz), they will achieve a resolution of 30"arc, which is excellent. This resolution and size will be reached by the association of thousands of identical small antennas disposed in an array and piloted by a supercomputer.

The technology of the antennas is far from being insignificant. Both LOIS and LOFAR antennas are small active antennas: to compensate their small size, a preamplifier amplify the signal, allow impedance matching and prevent from receiving spurious results by isolating the antenna itself from the detection system. Thanks to the experiments I carried out, wa have seen that the loss in this part of the system are low and comparable to the classic antennas, as well from an transmitting factor point of view as from a noise point of view. The advantages active antennas have on classical ones reside on their small size: they are solid, cheap, they do not couple with each other and their response is almost frequency independent.

LOIS antennas are tripole antennas and, with the help of the IDA technology, permit to find the direction of the incoming wave and also to study exotic waves. These advantages combined with their small size make it a really interesting instrument for many and various scientific purposes.

LOIS and LOFAR are now already working thanks to their test stations, and soon in their real size. However, many calibration and improvements remains to do. The antennas are already functional and used in some projects. Many others will follow.

Acknowledgment

I want to thank Bo Thidé for this very interesting internship during which I learned a lot of things, and for his help and patience. Thanks especially to Lennart Åhlén for answering all my questions and for his humour. Greetings to my office mate Lars.

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