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Assessment of RFI measurements for LOFAR

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In the North-Western part of Europe, ASTRON is building the world-largest largest low-frequency radio telescope. The telescope is based on phased array principles and is known as the LOw Frequency ARray (LOFAR). LOFAR is optimized for detecting astronomical signals in the 30-80 MHz and 120-240 MHz frequency windows. Since this part of the spectrum is in extensive use by others, special care must be taken in the selection of possible out-station sites for LOFAR. RFI measurements were made to be sure that the radio spectrum at the potential out-station locations is suitable for LOFAR operations. An assessment procedure is presented here and specific issues are discussed, such as the impact of Digital Video Broadcast, and wind turbines. The results of the RFI observations has generated a list of specifications for (international) LOFAR out-stations.

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1. Introduction

The Low Frequency Array (LOFAR) is a large radio telescope based on phased array principles, distributed over several European countries with its central core in the Northern part of the Netherlands. LOFAR is optimized for detecting astronomical signals in the 30-80 MHz and 120-240 MHz frequency windows [1, 2, 3]. Since this part of the spectrum is in extensive use by others, special care must be taken for the selection of possible LOFAR sites. In this paper we present the method of assessing possible LOFAR locations by looking at RFI measurements. In section 2 an impression of the current RFI situation is given, after which we discuss the impact of RFI on LOFAR measurements in section 3. The measurement equipment, the mobile RFI monitoring station, the measurements and the assessment methodology will be discussed hereafter. This leads to a set of LOFAR site requirements, which are presented in section 7. We end this paper with some conclusions.

2. RFI situation

For astronomical applications each LOFAR station will contain 96 Low Band Antennas (LBAs) and 48 to 96 High Band Antenna (HBA) tiles to cover the whole frequency range with sufficient sensitivity. The LBAs cover the spectrum from 30 to 80 MHz and the HBA tiles from 120 to 240 MHz. The spectrum from roughly 30 to 240 MHz is in use by many other applications. In Figure 1, a typical spectrum is shown of the LOFAR band.

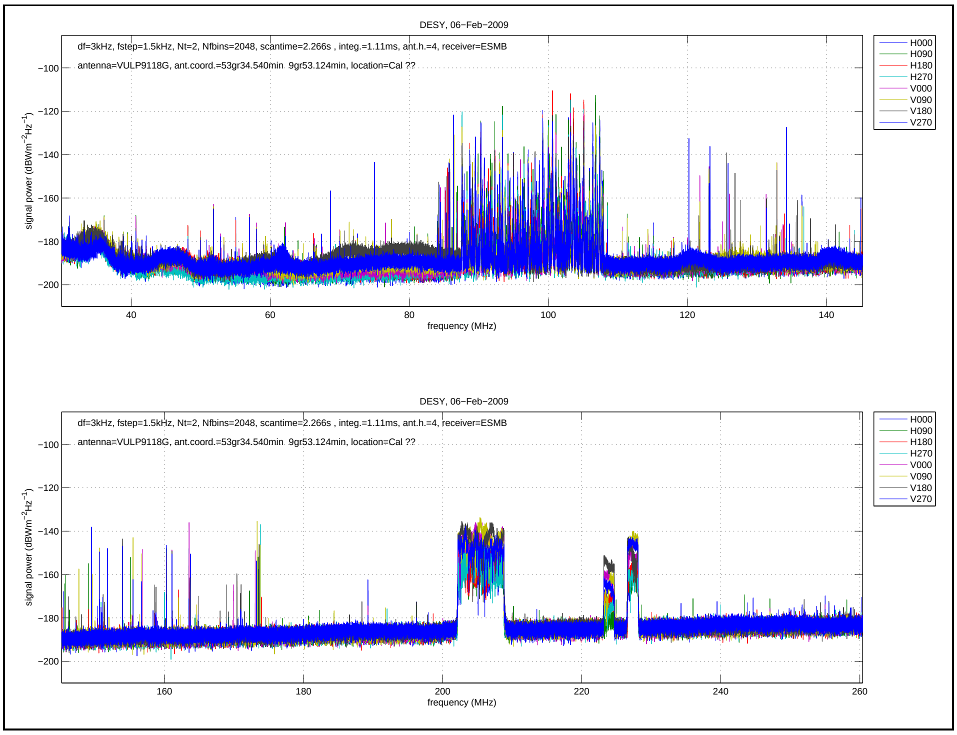

Figure 1: Spectra of the LOFAR monitoring campaign in February 2009.

The spectra were obtained by a special LOFAR monitoring van, which is described in section 4. The FM radio band is clearly visible in the figure. Also DVB-T and DAB-T signals in TV band III, from 202-230 MHz are prominent in the spectrum. As can be seen, the spectrum contains many interferers. The spectrum is recorded in Desy, close to Hamburg in Germany. The site is close to the Hamburg airport, which generates many signals in the aeronautic band that are seen in the spectrum.

3. Impact of RFI on LOFAR

Knowing the RFI situation, we can determine their impact on LOFAR observations. The use of the radio spectrum in terms of signal power and time-frequency occupancy is roughly known from allocation tables, from monitoring observations, and for future spectrum developments from spectrum management agencies. In order to estimate the maximum allowable RFI levels, the observed spectrum power needs to be related to the LOFAR sensitivity and system linearity:

- *Sensitivity* . One of the key parameters of the LOFAR aperture synthesis mode is that LOFAR will be sky-noise dominated. The specifications set for LOFAR are a sensitivity of 2 mJy at 10 MHz down to 0.03 mJy at 240 MHz for a 1 hour integration over a 4 MHz bandwidth. For a 1 kHz bandwidth (the typical channel bandwidth of the correlator) this corresponds to 127 mJy at 10 MHz down to 2.1 mJy at 240 MHz. In [4][5] this is related to the ITU-R RA769 levels in bands allocated to radio astronomy.

- *Linearity* . For bands which are not allocated to radio astronomy, there can be strong observed transmitter power present. These signals must not cause linearity problems for the receiver systems. The strongest observed transmitter signal in the north-east part of the Netherlands, apart from the FM band which is filtered-out by the LOFAR receivers, is a pager at 170 MHz. The LOFAR systems were designed such that a limited number of transmitters having the same observed field strength as the pager, would not affect the linearity of LOFAR. Also, the design was such that the induced spurious signals would be acceptable. Monitoring observations give a maximum observed signal strength for this pager of 65 dBμVm^{-1} in a 3 kHz band. This corresponds to a maximum allowable flux of

$$S|_{dBWm^2Hz^{-1}} = S|_{dB\mu V/m} - 10\log_{10}(\Delta f) - 10\log_{10}((10^6)^2) - 10\log_{10}(120\pi) = -115 \text{ dBWm}^{-2}\text{Hz}^{-1} \tag{3.1}$$

The considerations and criteria mentioned above are used for the assessment of suitability of the proposed sites for placing LOFAR stations in The Netherlands and elsewhere in Europe. The focus of the assessment is on the effects of the strongest observed RFI signals, and much less so on the spectrum occupancy of weak signals, as the sensitivity of a monitoring system is obviously rather limited when compared to the RA769 levels.

4. RFI monitoring station

The instrumentation needed for vetting potential LOFAR sites was specified once the maximum allowable levels of RFI had been established. The equipment we used for the mobile measurements is fairly simple. A Rhode & Schwarz ESMB receiver is the data acquisition instrument, which connects to a notebook computer control and readout system. The input is connected to either the Rhode & Schwarz HE010 active antenna, the Schwarzbeck Vulp9118G passive antenna directly or the output of a LNA which connects to the Vulp9118G antenna. A Miteq 10-1000 MHz amplifier can be used, which has a noise figure ranging from 2.1 dB at 100 MHz to 1.14 dB at 610 MHz to 1.2 dB at 1 GHz. The reason for having an option to bypass this LNA is to be able to quickly verify whether strong transmitter signals or RFI signals are forcing the LNA or the ESMB into nonlinear operation. Nonlinear operation leads to intermodulation products and decreased sensitivity, and should be avoided. For this reason the amplifier gain is a rather moderate 18 dB. In the case of the current measurements, the LNA was always switched off. This choice was made because the focus of the measurement campaign is on the occurrence of strong interfering signals.

These measurements are intended to survey the low and high band LOFAR ranges for signals that are present in the radio environment. Included are relatively fine frequency resolutions. Also a survey of a larger frequency range at lower resolution is done to make an inventory of signals that potentially could drive the LOFAR electronics into non-linear regimes, even if those signals fall outside the nominal LOFAR bands.

5. Measurements

Several strong interferers were detected in the measurements shown in Figure 1. Digital audio and video broadcasting from DAB-T and DVB-T are some of the major challenges. We see these broadband signals popping up in all the measurements we took. The maximum in-band DAB/DVB signal is $-120 dBW m^{-2} Hz^{-1}$, which gives $60 dB\mu V m^{-1}$ for a 3 kHz bandwidth. The maximum allowable signal strength is $65 dB\mu V m^{-1}$, so no linearity problems are expected. DAB-T and DVB-T will be one of the RFI sources with large impact. Although the transmitters will have one or two orders of magnitude lower ERP than the old analogue transmitters, the dense network of transmitters will compensate for that. The integrated received power of a digital transmission will be of the same order of magnitude as the integrated received power of an analogue system, or less. The signals are spread spectrum signals with bandwidths up to 8 MHz. That makes it very difficult to observe astronomical sources at the same frequency. In most cases the occupied band will be flagged in the data (or the specific subband will not be chosen). But, there is another issue. Although the subband with the DVB-T signal is not taken into account, we need a good subband filter to eliminate this band. In LOFAR, the digital subband filter provides approximately 80 dB of attenuation. So, if the level of a DVB-T signal for example is 100 dB above the noise floor, a 10% increase of overall system temperature will appear in all subbands. And this is generated from only one subband.

That might give problems in the future, since the rollout of DVB-T and DAB-T will happen soon. That is one of the reasons why the LOFAR core is treated in the Netherlands as an RFI coordination zone, which makes it possible to discuss optimal locations for new transmitters with the operators of DVB-T networks.

Wind turbines will have impact on the EM spectrum as well. One of the prominent effects is the reflection of RFI due to the rotation of the blades of the windmill. This introduces time variable multipath effects of the RFI at the LOFAR antenna. Close to the wind turbine we observed variations of more than 4 dB in a FM radio signal. Since the position of a wind turbines is fixed, RFI

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mitigation techniques at the station must be able to counteract this source of RFI. Wind turbines are the subject of active RFI research at this moment.

6. Assessment methodology

In the assessment of the measurements we have to give answers to the following questions: Is it possible from an RFI point of view to place a LOFAR station at the measured sites? What is the ranking of available and measured sites and what are the arguments for such a ranking? What are the current limitations of the site(s) from an RFI point of view and what are future limitations?

In the assessment several aspects are taken into account:

- *Linearity, in-band and outside LOFAR bands.* Are there signals present which exceed the limits calculated for the LOFAR system.
- *RFI summary.* In this part we will elaborate a little more on the RFI situation at the measured sites. In our assessments of potential LOFAR sites, we identify three frequency regions (30-80 MHz, 108-180 MHz and 180-270 MHz) and identify an objective number between 1 and 5 for the usefulness of the band for LOFAR measurements: (1) unsuitable, (2) partial suitable, (3) suitable, (4) good, (5) excellent. We note that the assessments are based on statistics with a limited sensitivity. We only measured for four hours in total. Although this is not an extensive RFI observation, it will give good information and will identify the potential problems in using the site for a LOFAR station.
- *Specific RFI issues.* Are there specific issues at the locations or in the measurements to take into account.
- *Limitations of the measurements and additional comments.*

We studied various site locations for LOFAR. As an example of the process, we will look at one of the situations in Germany. There is funding for a LOFAR site, either in Juelich or near Hamburg in Germany. The first step in the process is to look at the sites. Is there enough space, clear views, etc? The next step is to measure the sites using the special mobile monitoring station. In the assessment the first step is to look at the linearity. Are the in-band interference levels below our threshold? Interference levels in Juelich are considerable lower than those at the Hamburg location. The number of interference signals is greater in Hamburg where the strongest interference is in the aerospace bands. Also the DVB/DAB signals are very strong. The strongest interference is measured at $-120 dBWm^{-2}Hz^{-1}$ in a 3 kHz bandwidth this gives $60 dB\mu Vm^{-1}$. Table 1 provides an overview of the signal strengths in the data.

The conclusion is that no linearity problem with the in-band interferers is expected at either the Juelich or the Hamburg sites. This includes the digital communication signals, DAB and DVB-T, and the measured aerospace signals.

As can be seen in the table, the RFI levels from the FM radio transmitters, the digital communications at UHF and the GSM signals are all very strong. In the design, filters are placed to reduce the levels of out-of-band interferers. The FM radio signals may cause some (low-level) intermodulation product which can result in narrow-band interference in the LOFAR bands. In the

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	Frequency	Site 1 - NorderSted			Site 2 - Desy		
		Min	Max	Avr	Min	Max	Avr
FM radio band	88-104	-140	-105	-124	-142	-110	-127
Low frequency band	30-90	-195	-146	-173	-180	-140	-160
Aerospace band	110-160	-165	-120	-140	-190	-127	-156
Pager band	160-200	-180	-148	-164	-175	-132	-154
Digital TV/Audio	200-400	-146	-138	-142	-150	-135	-143
Mobilophone band	270-500	-158	-120	-137	-150	-130	-139
UHF band	500-800	-145	-128	-138	-150	-135	-144
GSM-band	900-1000	-145	-123	-134	-118	-100	-111
	Frequency	Site 3 - Kirchwerder			Site 4 - Juelich		
		Min	Max	Avr	Min	Max	Avr
FM radio band	88-104	-135	-90	-116	-138	-100	-120
Low frequency band	30-90	-180	-160	-170	-180	-145	-165
Aerospace band	110-160	-170	-130	-135	-170	-135	-153
Pager band	160-200	-180	-130	-152	-170	-135	-153
Digital TV/Audio	200-400	-145	-120	-134	-165	-142	-154
Mobilophone band	270-500	-150	-110	-132	-155	-118	-141
UHF band	500-800	-137	-117	-127	-155	-138	-148
GSM-band	900-1000	-132	-115	-121	-136	-112	-126

Table 1: RFI levels in the measurements in $\mathrm{dBWm^{-2}Hz^{-1}}$ for each of the frequency bands (in MHz). In the columns the data is given for respectively the minimum of the observed maximum levels of site, the maximum of the observed maximum levels of the site, and the average signal strength of the site.

comparison between the four sites we see that the RFI levels of the Juelich site are on average lower than the three Hamburg sites.

Looking at the RFI situation at the measured sites, we identify three frequency regions (30-80 MHz, 108-180 MHz and 180-270 MHz) and identify an objective number between 1 and 5 for the usefulness of the band for LOFAR measurements. We note that the assessments are based on statistics with a limited sensitivity. We only measured for four hours in total. Although this is not an extensive RFI observation, it will give good information and will identify the potential problems in using the site for a LOFAR station. The best results were obtained at the Juelich site.

The conclusions of this assessment are limited to the current situation. The observations were measured during daytime in a four hour slot; daytime measurements probably see the worst situation at the site, though not necessarily. The results should therefore be considered as a rough guide as to whether a LOFAR station at the site would actually contribute to the overall LOFAR configuration (and be functional as a stand-alone station).

7. LOFAR site requirements

For practical reasons we made a list of requirements for potential LOFAR stations which is based on experience and measurements.

- Fairly isolated
- No power lines within 2 km
- No highway within 500 meters
- No urban development within 500 meters
- No railroad, tramway within 2 km
- No windmills within 2 km
- No forest or high trees within 100 meters, to the south no trees within 500 meter
- No other radio interference sources in the neighborhood
- A location in or at the fringe of a nature reserve is favorable but requires good communication with environmentalists and nature organizations.

This list of requirements is used for looking for possible LOFAR site locations. Once a site is identified (or a few sites), measurements are done with the mobile monitoring station and an assessment is performed as presented in the previous section. Note that RFI will still be present, even if these requirements are fulfilled!

8. Conclusions

RFI measurements should be done at potential LOFAR sites to assess their RFI burden. In this paper we describe the mobile LOFAR RFI monitoring station, which is available to measure the RFI situation at possible LOFAR locations. We also presented the assessment methodology we used to assess these possible LOFAR locations. LOFAR has been designed to cope with RFI signals of up to $65dB\mu Vm^{-1}$ successfully. Experience has suggested a list of practical LOFAR site requirements.

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