Agentschap Telecom
Ministerie van Economische Zaken

Disturbance of the electromagnetic environment at the site of the LOFAR core by wind farm Drentse Monden and Oostermoer

Effects on the Astronomy receiving system LOFAR

Colophon

To	Dir. Energy and Environment **Drs JMC Smallenbroek** Dir. Telecom Market **Drs. JC De Groot**
From	Dep. Dir. Radiocommunications Agency **Drs. MGH Verhagen**
Number	2016-0919-001

https://www.rijksoverheid.nl/ministeries/ministerie-van-economische-zaken/documenten/rapporten/2016/09/19/verstoring-van-het-elektromagnetische-milieu-ter-plaatse-van-de-lofar-kern

Date 19 September 2016

ADDENDUM Research "Disturbance of the electromagnetic environment at the site of the LOFAR core by wind farm Drentse Monden and Oostermoer".

Radiocommunications Agency Netherlands, Groningen, September 19, 2016

In the summer of 2016, commissioned by the Ninistry of Economic Affairs, AT investigated the possible disturbance of Lofar by the planned wind farm Drentse Monden and Oostermoer. After their report on this, the Ministry of Economic Affairs asked AT to do additional research on the issue of mitigating measures, in particular the mitigation which can be reached by improving the wind turbine design. The estimation of AT on the basis of information then available was that a reduction of 15 dB could be achieved on reduction in electromagnetic interference radiation in the direction of the LOFAR core. During the investigation period there was no direct contact with manufacturers of wind turbines.

The application of EZ has led to bilateral talks with five different manufacturers of wind turbines. The results can, due to the company's confidential nature, not be reported in detail. These discussions learned that manufacturers see opportunities with additional adjustments to turbines for a further reduction of electromagnetic interference radiation from the turbine direction LOFAR than the 15dB which AT had assumed for safety reasons. In the discussions and written information is specified by the manufacturers how further reduction could be achieved, and how they think this can be achieved. The reduction opportunities can be significantly higher than estimated in the AT report. The discussions have made it clear that manufacturers want to make an effort to actually get a higher reduction than the estimation mentioned in the AT report. In the discussions, however, they also found that a further reduction is associated with considerable uncertainties concerning defined measurements and of experience. The method to make reliable measurements on the impact of wind turbines on LOFAR has yet to be determined. Reflections by wind turbines electromagnetic interference radiation is not yet as clearly defined than for direct electromagnetic radiation produced by wind turbines. Turbine manufacturers do have AT offered their help with this, including measurements at test mills and locations. AT has already made a start with determining a reliable measuring method and measurements result to contribute. These efforts will be continued in the coming months with the aim to establish a reliable measurements method. Given the complexity and innovative nature of measurements of electromagnetic radiation to target low levels, it is expected that 6 to 9 months' time are required. Participation by ASTRON, promoters and wind turbine manufacturers is promised.

Content

Resume

Cause for this report
The area Drentse Monden and Oostermoer is designated as a destination for a wind farm. [1] The wind turbines at this location can potentially disrupt the reception capabilities of the LOFAR [2] radio astronomy antennas that are placed in close proximity. Earlier research on these effects in the context of the Environmental Impact Assessment (EIA) in 2015 did not reach consensus on the expected impact of the wind farm on LOFAR. This prompted the Minister of Economic Affairs to commission Radio Communications Agency (AT) to research this. This report is the out com of this research.

Problem
The presence of wind turbines in the vicinity of the array, causes changes in the electromagnetic environment on the spot. The LOFAR system has a certain degree of resilience for these changes, but if the changes are too big theu which will manifest itself as a fault in the LOFAR receiving system with a degradation of the reception potential as a result.

Research assignment
Radio communications Agency has commissioned DGETM study of the effects of the proposed location of the wind farm Drentse Monden and Oostermoer for the receiving station LOFAR ASTRON. The research project was:

1. What disturbances can occur through the wind farm Drentse Monden and Oostermoer by LOFAR and what is the probability thatthey will occur?
2. What are possible solution and mitigation opportunities?

To answer this research assignment, AT has examined the following questions:

1. What is the expected disturbance of the electromagnetic environment at the location of the LOFAR core on the basis of the proposed wind turbine park Drentse Monden and Oostermoer?
2. What is the effect of these disturbances on the LOFAR receiving system?
3. What are the possible mitigation[1] measures?

Disruption electromagnetic environment
Regarding the first question a quantitative analysis is carried out by the expected change in the electromagnetic environment in the LOFAR core as a result of the wind turbines in the wind farm Drentse Monden and Oostermoer. To this end, different (interference) mechanisms identified. The interference mechanisms with the highest level of disturbance in the electromagnetic environment is the EMC emission from the wind turbines and the reflections from the turbines.

"EMC radiation" in this context refers to electromagnetic interference radiation caused by the electrical / electronic components in wind turbines and associated electrical installations blasted toward the LOFAR core. For this radiation, there are legal maximum levels to which wind turbines must meet. [2]

[1] Fault Oppressive measures

"Reflection from the wind turbines" in this context means the electromagnetic interference radiation that is generated outside the wind farm (as in the nearby metropolitan Stadskanaal by electrical equipment and installations but also by broadcasters) and are reflected by the wind turbines in the direction of the LOFAR core. Measurements carried out by the AT confirm that both wind turbines interfering mechanisms in practice actually occur.

In order to quantify the distortion of the electromagnetic environment, it was necessary to get notion of the (EMC) emitted- and reflection characteristics of individual wind turbines. For EMC the limits according to the European harmonized standard EN 55011 [3] for industrial equipment / installations, including wind turbines, apply. To clarify the reflection characteristics of wind turbines, in addition to measurements, theoretical and model-based calculations are made and searched for in literature. However, for the frequencies used by LOFAR not much information is available in the literature about reflection properties of wind turbines.
The interference levels calculated by the agency are displayed graphically by frequency. Also, in these graphs, for comparison, the recorded noise levels in rural areas to be expected according to the ITU (ITU-R P 372-12 [4]).

The conclusion is that the overall effect of the wind farm on the EM environment at the site of the LOFAR system is dominated by the mechanism "EMC appearance of wind turbines", and (after a correction of 20 dB as explained below) is calculated at **-62 dBμV / (m.Hz)**.

It should be noted that the calculated final values in this report don't have to be- one hundred percent exact. These calculated values are a result of different parts that all have a certain margin. For these parts assessments are made regarding margins and uncertainties. This has ultimately resulted in the end values as presented in this report. With the correction of 20 dB a practical translation is made that more accurately reflects the current situation. The correction is as follows:

- Regarding the methodology, we propose that the application of a more realistic propagation model (Modified Hata) means that the disruptive effects on the EM environment can be 10 dB lower than the originally calculated values with the so-called 'free space' model.
- It is likely that the EMC emission level of a wind turbine does not *exactly* meet the requirements for the statutory maximum EMC at all frequencies, directions and time intervals. These can and may be lower. This is taken into account by reducing the disruptive effects on the EM environment by 10 dB.

The contribution of the mechanism "reflection of spurious radiation from the environment through the wind turbines" is berekend3 at a level of -124 **dBμV / (m.Hz)**. This is 62 dB lower than the mechanism "EMC emission from the wind turbine."

---

[2] European EMC Directive 2014/30 / EU
[3] Here is the 10 dB adjustment to more realistic propagation model included for 2paden (source of interference for turbine and turbine to LOFAR). 10 dB correction for EMC emission levels is also included.

The spurious radiation as a result of the two mechanisms contains both continuous and time-varying components in the period of time (by the wick rotation) and is partly dependent on the design of the wind turbine. For measurements on pulsar, the time-varying interference radiations are of particular interest. For other measurements, the continuous interference signals are disturbing. Due to a good EMC design of the wind turbine, it is possible to reduce the time-varying behavior of the spurious radiation due to the interference mechanism 'EMC of wind turbines'. Time varying interference radiation on the other hand is more difficult to avoid in the mechanism "reflection of spurious radiation from the environment through the wind turbines." The reflections from the rotating vanes plays an important role here.

Disruption of the LOFAR system?
In order to estimate the 'robustness' of the LOFAR system for the EM radiation, the agency must dig into the LOFAR receiving system [5-7]. The exact knowledge of the system is at ASTRON. Based on literature study, data from ASTRON and own calculations by the agency the sensitivity of LOFAR measurement system for desired signals and spurious signals from all the information for the various types of observations with LOFAR is calculated. The resulting levels are authenticated by ASTRON and converted by the agency to the same unit as the (previously expected delivery) anticipated disruption of the EM environment. In this way, the sensitivity of the array, can be used for comparing interference signals (robustness) with the EM interference levels arising after placement of the wind turbines. This survey showed that there are different methods for filtering desired signals from the noise and get the desired sensitivity for such signals from space. Those methods may relate to the direct reception of the individual LOFAR antennas and preamplifiers, but also at the digital operations that occur later in life (post-processing). Depending on the field of research in this way the desired signal can be obtained by suppressing the unwanted noise to suppress as much as possible.

If the EM environment changes in such a way that, the minimum levels of robustness that are associated with different types of space-based research at this time are exceeded, this will as a result be harmful for carrying out research in this observation modes. Also, additional disturbance (increased EM environment) limit the possibilities to be able to "listen" even deeper into the noise floor for future types of space research.

In the most sensitive LOFAR observations (such as pulsars and "Epoch of Reionization") that are currently carried out by ASTRON, the LOFAR system reaches sensitivity of -164 dBµV / (m.Hz). In a generated EM level above or comparable to this level observations will be affected by this and lose their scientific value.

Analysis of the distortion
Because the noise emissions from wind turbines penetrate the LOFAR antennas at a low angle (the wind turbines from LOFAR seen on the horizon) only a limited part of these interfering radiation will enter the LOFAR system.
The LOFAR antenna stations decrease signals entering at a low angle on average by 35 dB. In addition, (by a longer dwell time) still a suppression of 10 dB of an interfering signals may be reached as a result of the way in which LOFAR processes the measurements.

By doing longer observations a certain noise reduction can be obtained. However, there are limits to this reduction. A rough averaging, because it is dependent on the used frequency band and base line length, yields with a continuous observation time of 10 hours, yields in a correction of the noise by 10 dB. Given that this suppression is a consequence of the smearing of the point spread function during a long observation this correction plays no role in pulsar measurements.[4]

Therefore 45 dB is deducted with regard to the ultimate interference effect of the calculated value of the disturbance of the EM environment as a result of the wind turbines.

This means that the actual meaning of the changing effect of the electromagnetic environment due to the wind farm for the LOFAR system is determined as follows:

EM Disturbance environment	- 62 dB dBµV / (m.Hz)
Damping by low angle	- 35 dB
noise reduction by longer observations:	- 10dB
Total:	- 107 dBµV / (m.Hz)

The actual generated EM effect for LOFAR as a result of the wind turbines is thus set at
-107 dBµV / (m.Hz). Earlier we had seen that the sensitivity of LOFAR system is the most sensitive detection modes -164 dBµV / (m.Hz)). The EM noise level of -107 dBµV / (m.Hz) which thus generated will exceed the spot level most sensitive observation modes with 57 dB.5

If the contribution of the mechanism "reflection of spurious radiation from the environment through the wind turbines" is similarly corrected the effect of this mechanisme6 is calculated: -124, 62 -35-10 dB = -169 dBµV / (m.Hz) lower than the mechanism "EMC appearance of the wind turbines."

Mitigation
There are a number of possible mitigation actions that might decrease the disturbance of the EM environment as a result of the wind turbines. The most profit can be achieved by reducing the EMC emission from the wind turbines themselves. A reduction of 15 dB is possible. Another 5 dB additional reduction can be achieved as a total of the other possible mitigation measures. Since the undesirable effects on the environment EM exceeds the minimum robustness of LOFAR by 57 dB, it will also additional 20 dB of reduction is not sufficient to overcome the effects of the wind turbines.

In the thesis "Algorithms for Radio Interference Detection and Removal" by AR Offringa [6] June 22, 2012 is suggested that under certain conditions RFI signals can be averaged over the measurement bandwidth. To what extent do EMC signals from wind turbines comply to the conditions as stated in the thesis is not immediately clear. Possibly more mitigation can be gained here.

[4] For pulsar measurements will be the crossing of the most sensitive lower limits by the disruption of the EM environment derived in this report so 10 dB higher.
[5] For pulsar measurements is therefore 67 dB.
[6], the effect in which interfering radiation is generated by the wind turbine itself, and is reflected by other wind turbines in the direction of the array, is not included in this calculation. If this effect is included increasing the noise level but remains well below the noise level of -107 dBµV / (m.Hz) associated with the dominant mechanism of the EMC emission from the wind turbine.

Configuration windfarm
The configuration of the wind park has an impact on the level of the interfering radiation which is generated on the LOFAR location. In general, that, as the distance is increased and the number of wind turbines is reduced, the interference is smaller. As the angle of incidence of the interfering radiation (relative to the earth) is smaller, the more LOFAR antennas will dampen the interfering radiation. This lower angle of attack can be achieved, in particular, by lowering the wind turbines in height, or by increasing the distance. Also considerable profit by placing in wind turbine design by placing potential sources of interference lower in the base of the tower (if possible). This could also have a positive effect on the direct EMC impact of the wind turbine itself on LOFAR. It should be noted that there has been no contact during the investigation initiators of the planned wind farm or wind turbine manufacturers. This can lead to additional insights.

There has been no investigation by AT to the minimum distance that must be maintained between wind turbines and LOFAR to avoid unacceptable disturbance of the LOFAR system. Assuming that existing wind farms currently do not cause interference on LOFAR, it can be assumed that these parks are on a "safe" distance. Currently there are in Rütenmoor and Heede, (D) about 20 wind farms and 30 km from LOFAR. The minimum distance at which LOFAR encounters no distortion from wind turbines would have to be somewhere in the distance range of approximately 15 km to 30 km. (Key input is the dimension windmills)
A jointly with ASTRON, executed measurement campaign could provide more information about keeping a "safe" distance.

Conclusion coexistence LOFAR and wind farm Drentse Monden
According to ASTRON, the expected changes in the 'EM environment' for a number of LOFAR interesting types of research, exceed the levels that can be tolerated for LOFAR. From this, the following conclusion can be drawn:

> *Different interference mechanisms have been investigated by the agency. The types of disturbance "EMC radiation from the wind turbine" and "wind turbines via reflections" result in significant distortive effects. The level of the former effect is such that even with mitigation measures, it will lead to degradation of certain types of observations as to pulsars and "epoch of reionization". For the other investigated mechanisms, it is likely that its effect is limited and / or can be solved by LOFAR.*

1 Introduction

1.1 Background and context

The possible interference with the planned wind farm in Drentse Monden and Oostermoer [1] LOFAR was already part of the Environmental Impact Assessment (EIA) [8] in 2015. The English research bureau Pager Power has then examined these potential disruption [9]. The conclusion in the EIA was that the impact on LOFAR were considered 'acceptable'. With the final determination of the geographical planning of the wind farm the conclusions were taken into utmost account. However, ASTRON, the manager of the LOFAR telescope, had major concerns and fundamental criticism of the methodology and conclusions of the research by Pager Power. This has ultimately resulted in the Minister of Economic Affairs requesting Radiocommunications Agency to do an additional investigation to the possible disruption of the planned wind farm on LOFAR[7]. This led to this report.

There are different interference mechanisms are conceivable whereby disturbance of the array, may be caused by the planned wind farm. This report examined the extent to which these mechanisms may affect the observations made with LOFAR. In addition, various options for mitigation are inventoried.

1.2 Research Question coexistence LOFAR and wind turbines

The central research questions of this report are:

1. What disturbances by the wind farm Drentse Monden and Oostermoer may occur with LOFAR?
2. What are solution and mitigation options?

To answer these research Telecom Agency has examined the following:

1. What is the expected disturbance of the electromagnetic environment at the location of the LOFAR core?
2. What is the effect of these disturbances on the LOFAR receiving system?
3. What are the possible mitigation measures?

To determine how LOFAR could be disturbed, it was necessary to gain insight into the extent to which the planned wind farm Drentse Monden and Oostermoer affects the electromagnetic environment of LOFAR. On the other hand, it was necessary to understand what measurements and observations are being executed by LOFAR and under which circumstances (degree of interference), these measurements were not possible anymore. On this basis can be assessed to which extent coexistence of LOFAR and the planned wind farm is still possible. Then an inventory is made of possible mitigation capabilities.

[7] See also Supplementary motion of the member Agnes Mulder et al (t.v.v 30196, no. 414) take on account of the investigation of LOFAR in placing windmills [j]. https://www.tweedekamer.nl/kamerstukken/detail?id=2016Z04543&did=2016D09370

During the study AT used their own independent measurements, and scientific sources and information supplied by ASTRON, the manager and owner of the LOFAR radio telescope. To ensure traceability and transparency of basic information indicated the source as much as possible.

Chapter 2 is a general introduction about LOFAR. It also discusses the various types of scientific space research covered by LOFAR 'listening' is to electromagnetic waves from space. Chapter 3 describes the planned wind farm Drentse Monden and Oostermoer. Chapter 4 analyzes the expected impact of the planned wind farm on the electromagnetic environment at the site of the LOFAR core. Chapter 5 examines the extent to which this change in the electromagnetic environment affects or limits the reception capability or reception quality from LOFAR.

In Chapter 6 mitigation possibilities ('solutions') are reviewed.

The report concludes in Chapter 7 and 8 respectively with a conclusion and recommendations.

The bibliography which are referred to in the text can be found in Annex F.

2 Radio astronomy receiving system LOFAR

2.1 Overview

The LOFAR [2] system is a receiving system for radio astronomy consisting of 7,000 antennas spread across much of Western Europe. The system is designed to receive signals from space and to be processed. These signals are generally very weak. With LOFAR system measurements can be performed for various scientific studies in the field of radio astronomy. A unique property (also seen international) of the array, is the ability to examine space phenomena with a high resolving power in the relatively low frequency range from 10 MHz to 240 MHz. The high sensitivity of LOFAR is mainly achieved in the central core, which is located near Exloo. This environment is characterized by low EM (electromagnetic) environment noise due to the low population density and lack of nearby industrial activities. This was for ASTRON (the manager of LOFAR) an important reason for choosing this location for the LOFAR core. ASTRON is the owner and operator of LOFAR and has largely developed it itself.

LOFAR is built modularly in stations, each with a large number of antennas for the high and low band accompanied by the necessary receivers and processing equipment. The central core (the core LOFAR) consists of 24 closely spaced stations (or groups of low drawn antennas). The stations that belong to the core each have 96 low band antennas in a seemingly random circle pattern and two arrays of every 24 high band 'tiles'. Six of these nuclear stations are grouped within a circle of 250 meters, the so-called super-mound. See Figure 1. For the (remote) calculations in the report, the location of this super mound is used as a reference. So there are also stations of LOFAR core closer than a kilometer and a kilometer farther away from the planned wind farm.

Furthermore, there are 14 stations, roughly distributed in spiral arms in northern Netherlands and 12 more stations in Europe, with some still under construction or in concept. All of these stations form a single telescope. Due to the large sizes (from Sweden to France) observations can be done with very high resolution (less than 0.001 degree) [2].

Because of the large number of antennas in the core, the desired high sensitivity is achieved. The key lies in Drenthe, near the village of Exloo, a location selected because of the low population density and low level of interference in the immediate area. A comprehensive description of system LOFAR can be found in the scientific article LOFAR: "The Low-Frequency Array" [2]. The LOFAR website [11] provides a popular scientific explanation.

2.2 Scientific goals of LOFAR

With the LOFAR system, with several measurements can be carried out in support of various scientific studies in the field of

Radio astronomy. To get an impression of the research by LOFAR below are selected number of key areas[8]:

1. Epoch of reionization (period of re-ionization of hydrogen);
2. Survey of the low-frequency sky (research of the universe on low frequencies);
3. Transient Radio Sky (transient events in space);
4. Pulsar studies and surveys (investigating pulsars);
5. Astro particle physics (research on high energy particles);
6. Magnetic fields in the universe (magnetic fields in space);
7. Solar physics and space weather (physics of the Sun and space weather).

Figure 1: Upper left: LOFAR Super mound; top right: the LOFAR core (core), the circle indicates the super mound again surrounded by a number of stations. Lower left: antenna for the "low band (30-80 MHz) and below right: the 'High' band (120-250 MHz). Source: LOFAR website [11].

[8] This report only lists the various investigations. A detailed description is beyond the scope of this report. See also Table 2 on page 28.

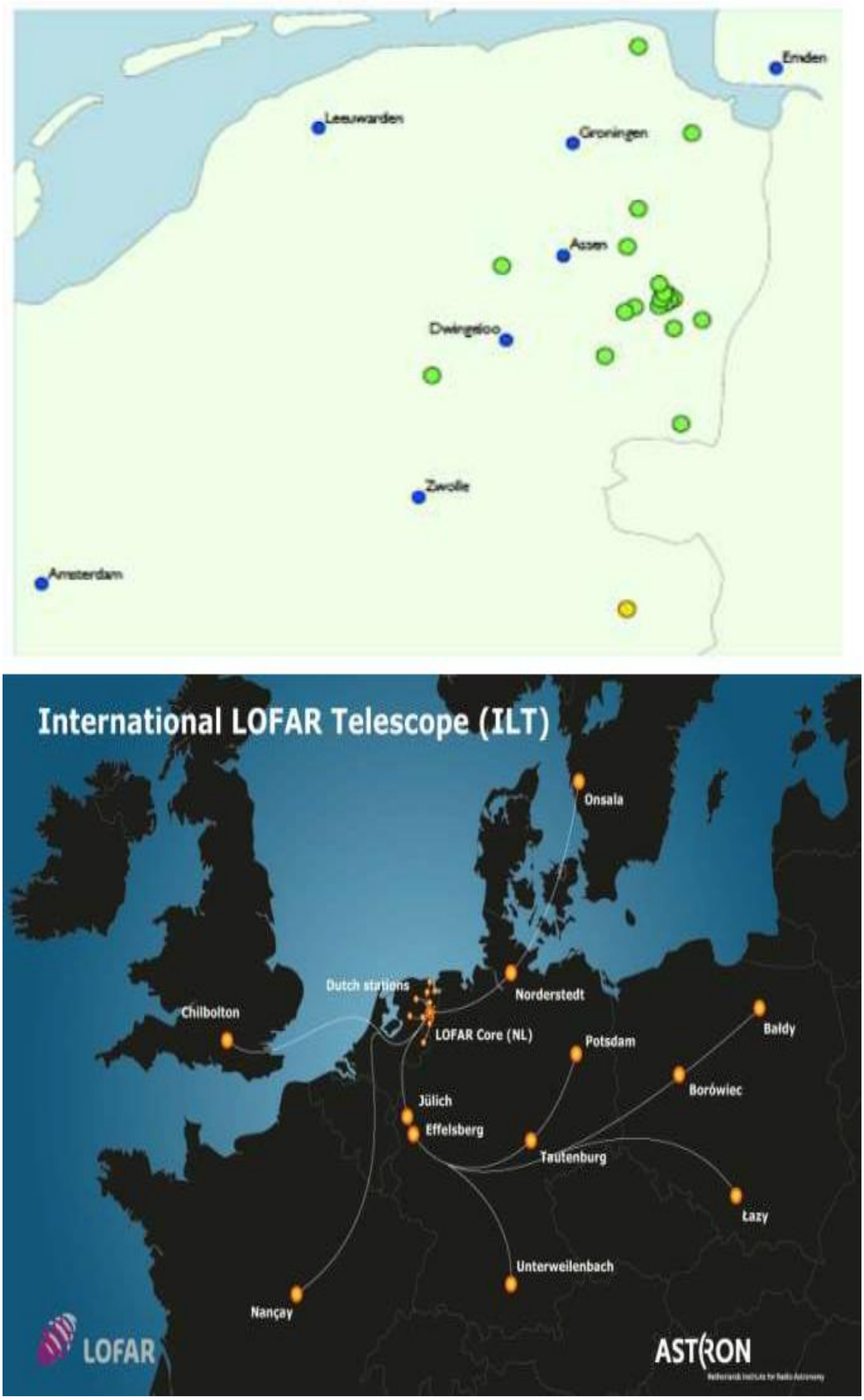


Figure 2: LOFAR stations in the Netherlands and Western Europe. Source: LOFAR website [11]

3 The planned wind farm Drentse Monden and Oostermoer

3.1 Description of planned wind farm

The wind farm Drentse Monden and Oostermoer is planned near Stadskanaal [1]. The planning is based on 50 turbines each approximately 3 MW. The nearest turbines are scheduled for approximately 5 kilometers from the LOFAR Super mound. The type of turbine has not yet been selected during the writing of this report. Turbines can be expected with heights of the tower of up to 135 meters and blade lengths of about 60 m. Diameters of varying the masts of wind turbines and are in the order of magnitude of a few meters.

Figure 3: Estimated turbine arrangement [12].

NB. Exactly halfway between Borger and 2nd Exloërmond the LOFAR core (red dot) can be seen. For a detailed description of the geographical planning and considerations herein refer to the environmental impact, "Windpark Drentse Monden and Oostermoer" [8]

4 Disturbance of the electromagnetic environment by wind turbines.

In this chapter, the major distortions of the electromagnetic environment by the planned wind farm are quantified. Chapter 5 assesses to what extent it is likely that the performance of the LOFAR receiving system will be affected.

The LOFAR receiving system is designed to receive extremely weak (electromagnetic) signals from space. LOFAR is therefore deliberately placed in an environment with an electromagnetic environmental noise level which is relatively low because of the low population density and the absence of nearby industrial activities. Such an environment with low ambient noise level is defined by the International Telecommunication Union (ITU) as "Quiet Rural" [4].

The placement of wind turbines in the vicinity of the array, will cause changes in the electromagnetic environment on the spot. The LOFAR system has a certain degree of robustness for these changes, but if the changes are too large they will manifest itself as a fault in the LOFAR receiving system with a degradation in the performance as a result.

Below are listed the relevant distortions identified by the agency of wind turbines that can affect the electromagnetic environment at the site of the LOFAR core.

1. Interference Radiation (unintentionally) is caused by the electrical / electroniccomponents in wind turbines and associated electrical installations. Further on in the report, this phenomenon is called EMC (electromagnetic compatibility) generated by wind turbines.

2. Spurious Radiation generated unintentionally outside the wind farm (by electrical equipment and installations) and that is reflected by the wind turbines in the direction of the LOFAR core.

3. Reflections of unwanted emissions from the wind farm itself.

4. Reflection of broadcast signals (DAB +).

5. Blocking and diverting to observe astronomy radio signals from space that are just over the horizon where a wind turbine is in the propagation path.

6. Reflect, scatter and deflect radio astronomy observing signals from space (desired signals).

7. Discharges of rotor blades charged by friction phenomena.

8. Interfering signals that spread across the grid. The connection to the mains allows the wind turbine as a source of interference, as it were much larger, so that distortions are much more noticeable.

In this chapter, a paragraph is included for each of these disturbances in which the interference mechanism will be described, and in which the interfering radiation is quantified at the location of the LOFAR core. The chapter concludes with an overview of the contribution of each of these disturbances.

4.1 EMC emission from wind turbines

This section is an analysis of the expected level of interference radiation on the location of LOFAR, caused by electrical / electronic components in wind turbines and associated electrical installations.

Europe is governed by statutory provisions in respect of the level of interference radiation that may be caused by electrical appliances and installations. The regulatory framework for this is the EMC Directive [13] which aims to prevent interference to radio services. [9]

The harmonized EMC standard EN 55011 [3] dictates in the frequency range of 30 MHz to 230 MHz for measurements at a location an in situ limit of 10 to 30 dBμV / m in a bandwidth of 120 kHz and 30 m distance[11]. A source with a radiated power of 2.5 * 10^{-13} W / Hz e.i.r.p. exactly meets this limit. For measurements performed in a laboratory situation a limit of 50 dBμV / m applies in a bandwidth of 120 kHz at 10 m distance. This corresponds with a radiated power of 2.8 * 10^{-12} W / Hz e.i.r.p.[12]. In the report, it is assumed that wind turbines effectively radiate this latter power at all frequencies and in all directions.

Assuming the maximum radiated power, it can be calculated how large the field strength of spurious radiation is on the edge of the LOFAR mound. The calculation is based on two different propagation models: the 'free space' model and the 'Modified Hata model [14]. Both of these models have been described in Annex A.

In the figure below the electric field strength that is one such source (read wind turbine) may cause at a height of 100 m at the position of the LOFAR core, with a distance between the core and LOFAR wind turbine of 5 Km [13]. To make an impression indicate how this value compares with an environment without the interference source, the field strength is compared to the expected noise level in the countryside, as expected according to the ITU [4]. To this end, the level of the calculated interference field strength of a wind turbine is shown in a single figure. For reference purposes, the expected ambient noise levels in accordance with the ITU [4] peculiar added at two different reference environments: "Rural" and "Quiet Rural". In "Quiet Rural" environment is the ambient noise level below the galactic noise; This curve is also added.

It is difficult to predict whether this interference signal constant in nature or will be modulated by the influence of the rotating rotor blades (in varying strength).

---

9 EMC directive: EMC Directive 2014/30 / EU

10 On the basis of an in-situ measurement, Class A (intended for industrial environments) and group 1 (devices that do not use the radio spectrum)

11, in which with a Quasi-peak detector to be measured. The filter that is required is Gaussian pulse with a bandwidth of 120kHz, the noise bandwidth will be slightly larger, this is not included in the calculation

12 On the basis of a laboratory measurement, Class A (intended for industrial environments) and group 1 (devices that do not use the radio spectrum)

13 As seen in Figure 1 (above, right) are also still antenna stations around the LOFAR Super mound to more than 1 km away.

This depends entirely on the design and realization of the technical installation of the wind turbine.

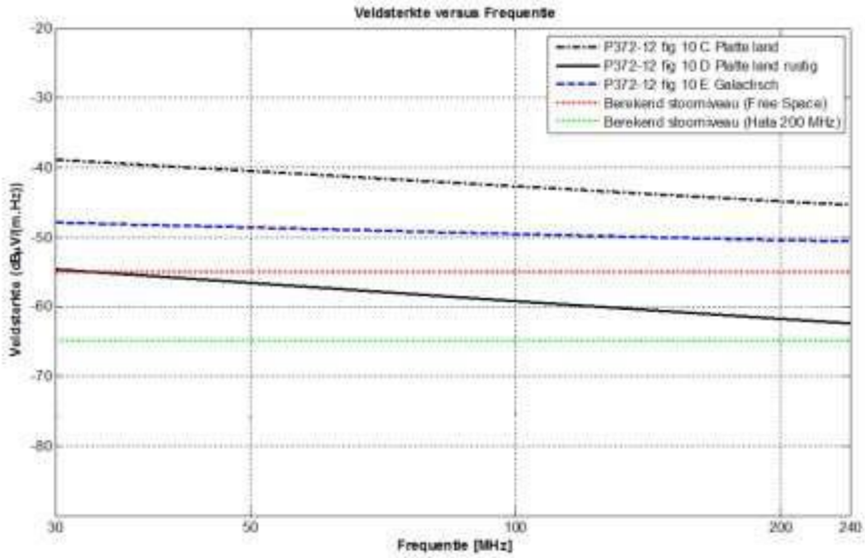


Figure 4: *Electric field strength in dBμV / (m.Hz) as a result of one wind turbine at a distance of 5 km which complies with Class A EN55011 limits, [3], corresponding to a source strength of 2.8 * 10^{-12} W / Hz. Calculations are performed with the 'free space' model and the 'Modified Hata model [14].*

Then calculated by the cumulative interference field strength of the overall wind turbine park is calculated at the location of the LOFAR core. The method used is described in Annex A. The results of this calculation are shown graphically in **Figure 5**. In the calculations, in **Figure 4** and **Figure 5** the wind turbine is considered as an electromagnetic source that at all frequencies and directions exactly transmits up to the allowed limit interfering radiation. In practice, this level of radiation is often highly frequency dependent and will not be equally high in the whole band in which LOFAR measures. Single emission measurements by the Radio Communications Agency of wind turbines, which are located at Eemshaven, show that there were measurable interference signals in the frequency bands used by LOFAR. They were measured by standing a few meters away from the turbine base with the measuring equipment of the agency.

There is also conducted a standard EMC measurement in accordance with EN55011. Due to the corresponding, relatively large measurement bandwidth of 120 kHz, and the attendant noise level of the measuring system, transmitted emissions from the nacelle (100 m altitude) are not does not or barely detectable. Therefore, the standard EMC measurement methods and equipment are not suitable for the determination of the effect of wind turbines on the EM environment at a greater distance. The presence of emissions however, is demonstrated.
Due to the large dimensions of a wind turbine can with a measurement at a short distance (3 m or 10 m) to the wind turbine on the ground, it cannot be predicted what occurs to disturbance fields at greater distances. The narrowness of the EMC measurement procedure for large installations (eg wind turbines) is internationally recognized and is currently the standards group IEC TC 88 PT 61400-40 is busy defining EMC requirements and methods of measurement for wind turbines.

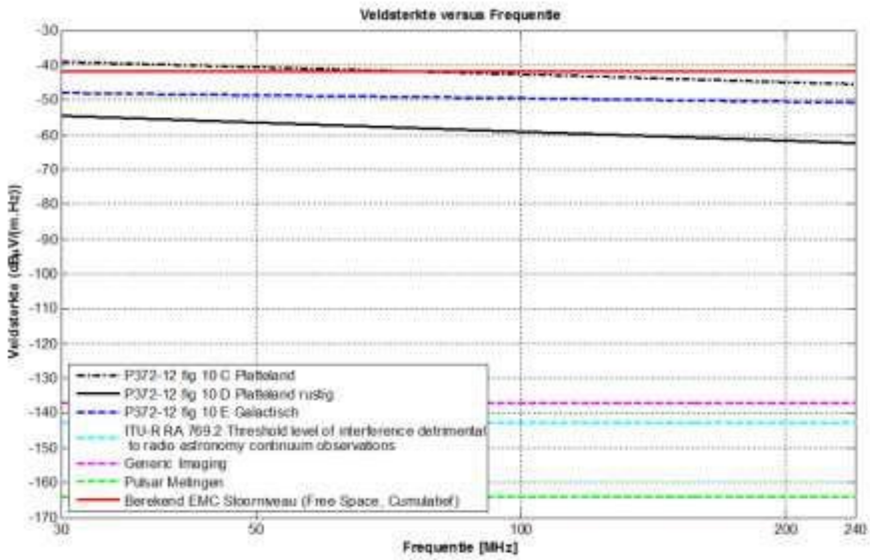


Figure 5: Electric field strength in dBµV / (m.Hz) as a result of all wind turbines together, each of which meet Class A EN55011 limits, [3], corresponding to a source strength of 2.8 * 10^{-12} W / Hz. Calculations here are performed only with the 'free space' model.

4.2 Reflection of interference signals from outside the wind farm

This section discusses interfering radiation generated unintentionally outside the wind farm (by electrical equipment and installations) and then reflected by the wind turbines in the direction of the LOFAR core.

The wind turbines are planned on the outskirts of the agglomeration Stadskanaal. The joint electromagnetic interference emissions of all electrical and electronic equipment and systems in and around Stadskanaal form a broadband source of electromagnetic interference. The wind turbines will therefore be self-irradiated and are noise sources that dominate the horizon and thus come in direct sight of the LOFAR core. The fault that is "rebroadcast" by the wind turbines " is broadband (a summation of emissions from all sources of interference) and is modulated in strength by the rotating blades of the wind turbine. The rhythm of this modulation is determined by the rotation speed and the number of blades rotor blades, see the measurements taken by the AT in Annex D.
In order to determine how much of the interfering radiation is reflected by the wind turbine in the direction of the LOFAR core, the degree of reflectivity of the wind turbine must be known. A measure of the reflectivity of the wind turbine is the Radar Cross Section (RCS), a number that indicates how big the apparent surface area is that reflects radio waves. A lower RCS value means less reflection of the wind turbine. This is further explained in Appendix D. In the literature there are no, measurements and / or calculations available on the reflectivity of wind turbines in the frequency range within which LOFAR observations are carried out. Telecom Agency has therefore itself carried out measurements (see Annex D) and calculations (see Annex E) carried out on a wind turbine in order to gain more insight here [15]. Based on these measurements, and

calculations, it was decided to assume an RCS of 2000 m2 for all frequencies within the frequency range LOFAR. On the basis of these value-RCS, now the interfering radiation in the core LOFAR can be calculated as a result of the above-mentioned interference phenomenon.

The total spurious radiation from agglomeration Stadskanaal directed toward the wind farm is, as in Section 4.1, based on the requirements for unwanted emissions of devices as defined in the harmonized EMC standard EN 55011 [3]. However, the interference signal that is emitted from Stadskanaal and its surrounding area to the wind turbine is derived from a large number of individual sources, for which the cumulative interference field strength must be determined.

For an assessment of the cumulative field strength is based on the following:
The interference sources are not all equally strong: the spurious consumer devices are weaker than those of industrial plants. The interference signals from equipment situated weakened by the attenuation of the buildings in which they are indoors. In addition, the emissions from the devices are often up to the limit at specific frequencies, and weaker at other frequencies, and the fields from all sources will not add up coherently. For calculating a cumulative field strength is assumed, generated by a 10 times stronger resource as a source generating the limit of EN55011. This provides a source strength of $2.8 * 10^{-12}$ W / Hz * 10 = $2.8 * 10^{-11}$ W / Hz.

The average distance between agglomerate Stadskanaal and the wind farm is 5 km. In reality there is a variation in the distances that will effectively lead to a higher result. For distances between wind turbine and LOFAR have been taken individual values, so overall there are no big differences introduced by this simplification. On the basis of this distance, we calculate the power density [W / m2] at the location of a wind turbine, and we multiply it with the RCS value of the wind turbine (RCS = 2,000 m2). In this way a power source is obtained to determine the contribution of any individual wind turbine as a reflector of spurious signals from Stadskanaal area to the interference field strength at the LOFAR location. This value is shown in **Figure 6**.
For the calculation of the path attenuation between the interference source and wind turbines, and between wind turbines and LOFAR the 'free space' propagation is used.
For reference purposes, the expected ambient noise levels in accordance with the ITU [4] peculiar added at two different reference environments: "Rural" and "Quiet Rural". In "Quiet Rural" environment is the ambient noise level below the galactic noise; This curve is also added.
The cumulative effect of all wind turbines is calculated together in the same way as in section 4.1 and is shown graphically in **Figure 7**.

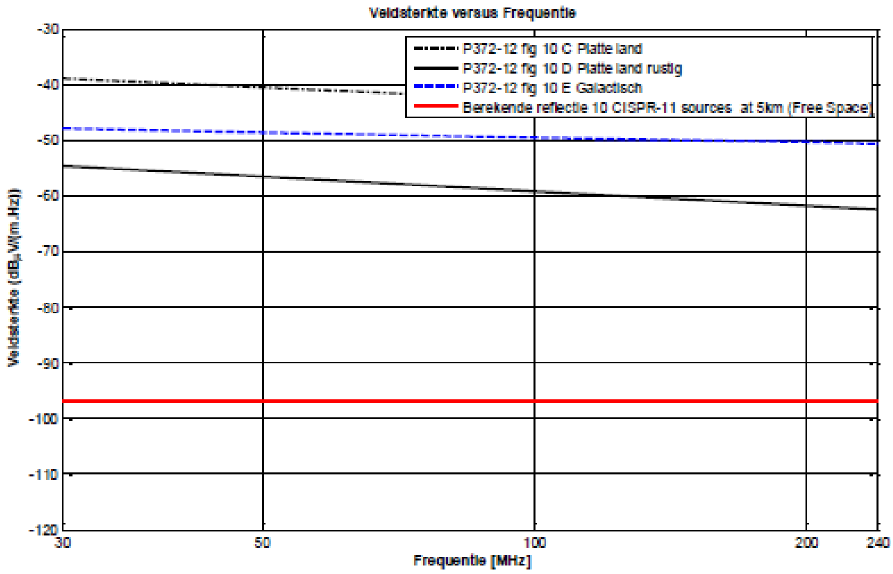


Figure 6: *Electric field strength in [dBμV / (m.Hz) at a distance of 5 km of one wind turbine which the cumulative interference signals of the agglomerate Stadskanaal reflects. This is simulated by 10 industrial sources according to EN55011 class A, with a total source strength of 2.8 * 10^{-11} W / Hz and RCS = 2000 m2. For the calculating the path attenuation between the interference source and wind turbines, as well as between wind turbines and LOFAR is used the 'free space' propagation is used*.

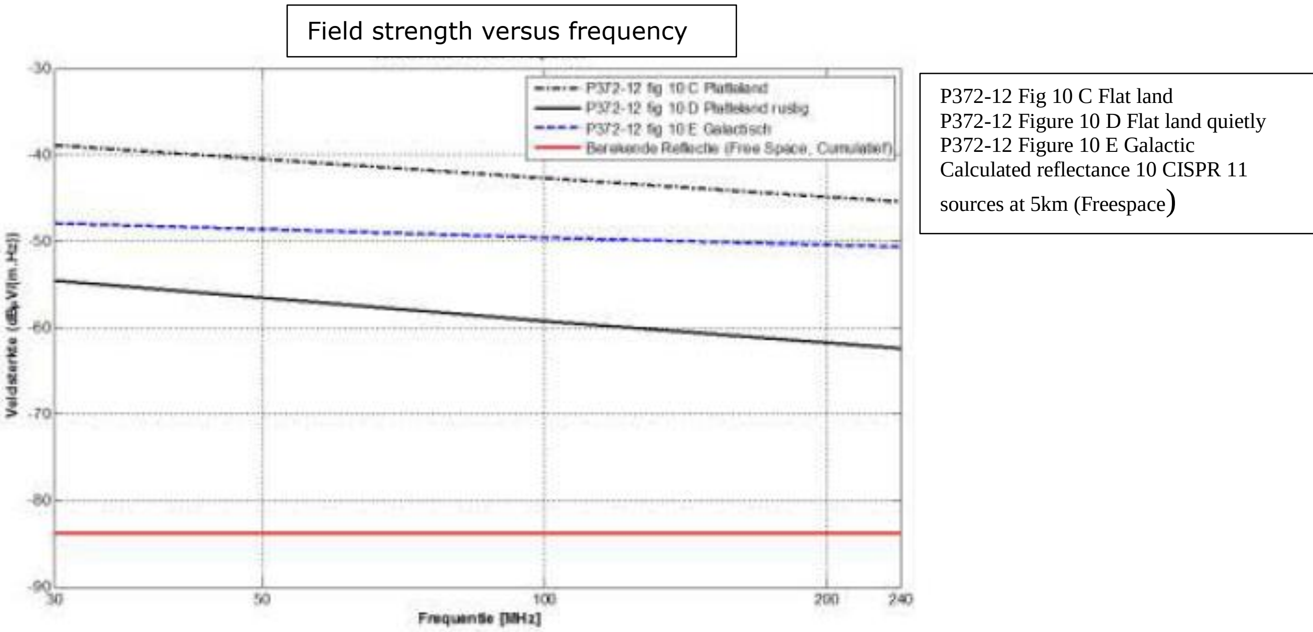


Figure 7: *Electric field strength in dBμV / (m.Hz) at the location of the LOFAR core as a result of the accumulation of all wind turbine reflections by illumination of all wind turbines with cumulative interference signals of the agglomerate Stadskanaal. This is simulated by 10 industrial sources according to EN55011, Class A [3] (5 km from the wind turbines) with a total source strength of 2.8 * 10^{-11} W / Hz and RCS = 2000 m2. For the calculation of the path attenuation between the interference source and wind turbines, and between wind turbines and LOFAR is the 'free space' propagation is applied*.

The interference field strength in the LOFAR core, coming from the first wind turbine caused by the phenomenon described here is -96 dBμV / (m.Hz), this is 42 dB lower than the value which was found in 4.1 as a result of the aura of a EMC wind turbine. On the other hand, these spurious signals are modulated in intensity by the rotating blades of the wind turbine. The rhythm of this modulation is determined by the rotation speed and the number of rotor blades, see the measurements taken by the AT in Annex D.

4.3 Reflection of unwanted emissions from the wind farm itself

In 4.1 is only assumed EMC emissions directly from the wind turbine to the LOFAR core. Reflection of EMC emissions from another wind turbine is of course also possible. This reflection will be substantially lower than the direct radiation, due to the losses that occur during the reflection which is described in section 4.2 and Annex D and E.

On the other hand, these spurious signals are modulated in intensity by the rotating blades of the wind turbine. The rhythm of this modulation is determined by the rotation speed and the number of rotor blades, see the measurements taken by the AT in Annex D.

If the wind turbines have an EMC level comparable to the standard, then the reflection will EMC of these signals through the blades of other turbines are dominant with respect to the EMC signals from other sources in the environment. This because of the relative proximity of the wind turbines and the direct path. There is, here, of course, a relationship with the level of the direct radiation from the wind turbine. If this direct radiation is made lower, the reflection of this will also be lower. It may be that in that case the EMC reflectivity from other sources is more important.

4.4 Reflection of broadcasting signals

In the development of LOFAR takes into account the presence of broadcast signals. The low and high band LOFAR are respectively 10 MHz - 80 MHz and 110 MHz - 240 MHz [2, p.7]. The intermediate FM broadcast band is not used for observation because of the strong broadcasting signals in the frequency range. However, at the time of writing this report, Digital Radio DAB + is being rolled out in the frequency range of about 183-228 MHz. This development was provided for in the period in which LOFAR was designed and built, but given the lack of interest in DAB is the likelihood of this rollout supposedly was judged very low.

DAB + is broadcast as a 1.6 MHz wide OFDM multiplexing in which a number of audio programs encoded. This transmission takes place from a smaller or larger number of synchronous channels, called a single frequency network. Around LOFAR are 4 DAB + channels in use. In Appendix C shows which DAB + stations near LOFAR use of these frequencies. See also the Radiocommunications Agency website [16] with an overview of digital broadcasting channels.

These signals from this DAB + will now already been able to be detected by LOFAR. That will be slightly stronger because the wind turbines that will reflect the signal back into full view of the channels in the direction of the LOFAR core. The reflected signal will, however, be modulated in strength by the rotating blades of the wind turbine. The rhythm of the modulation is determined by the rotation speed and the number of rotor blades, refer to the measurements carried out by the AT in Annex D. In particular, this modulation is in general by astronomers experienced as problematic.

With the distance of each individual DAB transmitter from annex C to the center of the planned wind farm is the field strength in each DAB transmitter determined on the location of this center.
With the RCS of an individual wind turbine is then determined which produces this field strength at the location of the LOFAR core. The distance from one turbine to the LOFAR core is held at 5 km. The free space propagation model is used for the calculations.

The total field strength caused by one refecting wind turbine is 40.8 dB μV / m, DAB is -21.2 dBμV / (m.Hz) according to the free space calculation. The calculations show that the transmitter in Stadskanaal is the dominant source.
For these distances, the free-space model is, however, not realistic, and the resulting values will be much lower. Without a comprehensive analysis with propagation tools it is not possible to quantify accurately the level of interference at the moment. Since the DAB frequencies are avoided by LOFAR because of the high signal levels and the field strength of the reflected signal with the calculated free space model is already located below the directly received signal, the reflected signal will not cause any problems in spite of the strength.

4.5 Blocking and deflecting desired signals

Blocking and deflecting desired signals occurs when a celestial body observed from the LOFAR core seen behind or nearly behind a wind turbine sits. This happens not only in a direct line, but also when the rotor blades cut through the Fresnel zones [17]. The periodic interruptions by the turbine blades are difficult to distinguish from phenomena that need to be observed. Therefore, measurements on a celestial body in the time domain may be unusable when this body is located behind the turbine, at a low angle to the horizon.
The energy of an object to be observed does not only travel in a straight line between LOFAR and the object. This energy travels within so-called Fresnel zones. The radius of the zones is dependent on the frequency and can be calculated as follows.

$$F_n = \sqrt{n\lambda d}$$

Where n is the number of the Fresnel zone, λ the wavelength and d is the distance between the super LOFAR mound and the nearest wind turbine. With the Knife edge diffraction model it is possible to calculate the additional attenuation that arises from diffraction. In this model, it is assumed that a wall which is extremely thin, however, with an infinite width is (partly) located in the visibility path. In **Figure 8** shows an approximation of this diffraction damping follow Lee [18], page 123 and 124 of formulas 4-12 to 4-24, to display as a function of the Fresnel zone. The calculation method is made up of a number of formulas in which loss is based on the classic knife edge diffraction method. Lee has the simplified calculation method by taking on a graph (4-7) from which this loss is easy to read.

The turbine blade of a wind turbine is to some extent comparable with such a wall, with the difference that this is very narrow. If we assume a width of 1 meter for the wind turbine vane tip and determine that when the diameter of the first Fresnel zone highest frequency which can be done with LOFAR measurements is about 140 meters, it can be reasonably assumed that the damping due to the wind turbine tip is 20 dB is lower or more, based on the knife edge diffraction model is calculated. It, therefore, seems to be a conservative assumption that if the first Fresnel zone remains free (n = 1), the wind turbines do not constitute a troublesome obstruction.

The sensitivity of LOFAR decreases as the measuring objects are closer to the horizon. Measurements below 5 degrees relative to the horizon are therefore of less importance for ASTRON. Based on this data and the tip of a wind vane up to 190 meters high, can be determined to what extent measures can have wind turbines affect the measurements LOFAR. In **Figure 9** this is shown.

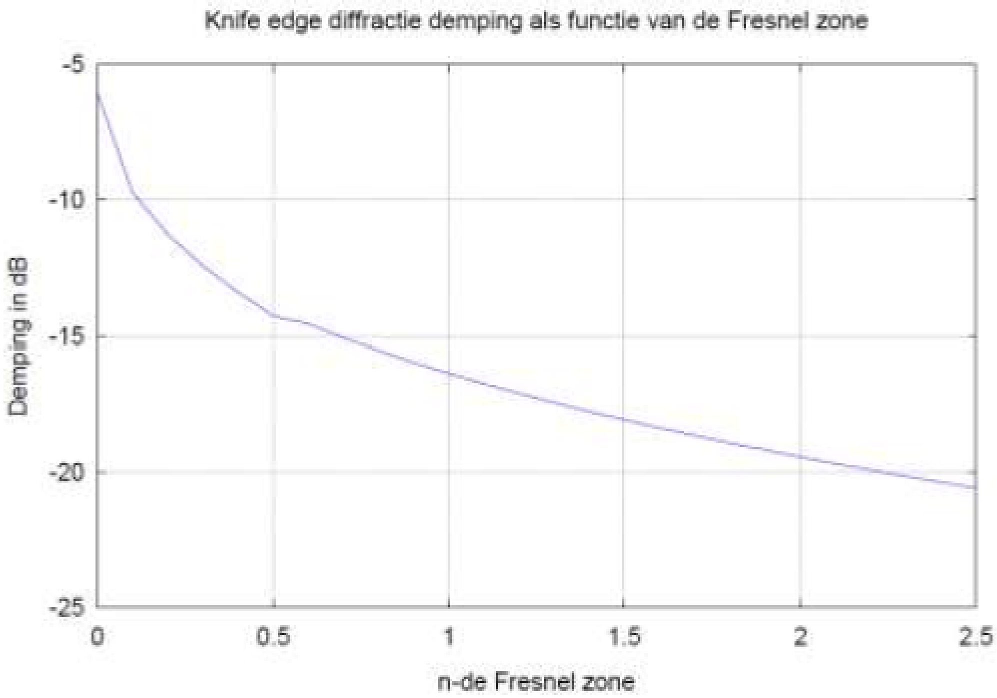


Figure 8: *Knife edge diffraction as a function of the Fresnel zone [18]*

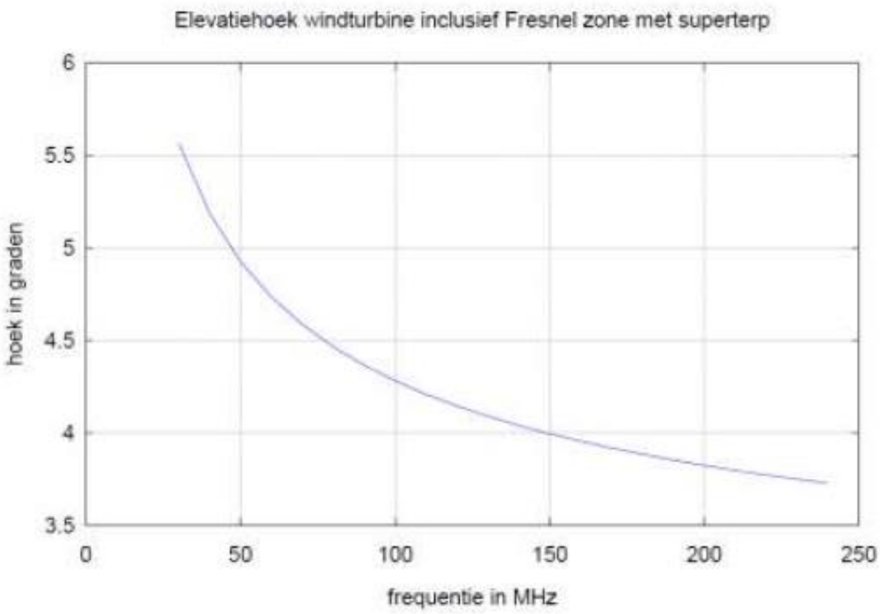


Figure 9: *Observation angle (relative to the ground plane) such that no blocking and deflecting effects are to be expected, this as a function of the frequency.*

On the basis of **Figure 8**, it can be expected that blockade or deflection of the desired signal by wind turbines will not or hardly occur.

ASTRON is planning to investigate this effect by doing an experiment with the side-receiving station RS 508 located in Nieuwolda next to the Hondshaltermeer. Seen from there is roughly in the north a group of wind turbines, and each day the strong star and radio source Cygnus A moves behind this group of turbines. So can then be determined whether the first, second or even higher Fresnel zones are affected by wind turbines such that they should remain free. These experiments have not yet been performed at this moment. For now it is assumed in this report that emanating from the second Fresnel zone is sufficient.

4.6 Reflecting on signals from space

Reflecting and scattering signals from space by wind turbines could lead to come into the picture of a star, mirrored in the wind turbines. The "mirror image" of the stars is thus seen from LOFAR at a fixed point on the horizon and is only a problem if main beam or side lobes are directed toward. Moreover, these reflected stars are weakened in relation to the actual stars. These mirrored stars however have been given an amplitude modulation frequency of the turbine blade. By ASTRON this effect is not seen as a problem to be expected. Further research therefore has not taken place by AT.
Also, there is still no attention given to the potential effects of wind turbines by reflected signals which are transmitted by satellites.

4.7 Discharge by friction phenomena

The extent to which discharge occurs due to friction phenomena is directly related to the design of the wind turbine, and is likely to be strongly dependent on the weather. Here, special attention will be needed for in case of a type-selection. It is not possible to obtain revealed details of the extent of this impact. It is recommended that if it is decided to place wind turbines, there is further research into this effect by wind turbine manufacturers. The size of the discharge, if these prove to occur frequently. Electrostatic discharges are very short and have a high energy level. Exact acceptable limits are therefore difficult to estimate. An initial step may be a limit in which the maximum pulse does not exceed the EMC average level of the wind turbine.

4.8 Interfering signals that spread across the grid

The design and method of installation of the wind turbines will have to be aimed at interference signals that may occur on the power grid to suppress as much as possible. These interference signals are generated by the generator and injected into the cabling, that will function as a junk antenna. The total emission levels of all the wind turbines including the radiant wiring will have to remain under the EMC level. The AT expects that this does not have to provide basic technical problems.

4.9 Overview interference mechanisms and their individual contributions to EM environment

The interference mechanisms as discussed in paragraphs 4.1 to 4.8 are summarized below in tabular overview:

Table 1: *Overview of the contribution of each of the interference mechanisms to the disturbance of the electromagnetic environment of the LOFAR core.*
ad1) -42 dBμV */ (m.Hz) is determined on the basis of "free space" propagation*
ad2) -84 dBμV */ (m.Hz) is determined on the basis of "free space" propagation*
*ad3) is negligible compared to the EMC radiation (1), but fully modula*ted

Bijdrage verstoring EM-milieu per stoormechanisme Veldsterkte in dBμV/(m.Hz)	par.	LOFAR frequenties "Low Band" 30 MHz	80 MHz	"High Band" 110 MHz	240 MHz	Ge-modu-leerd*
Referentie omgeving (ITU "Quiet Rural")		-55	-61	-67	-62	Nee
Galactische ruis (ITU)		-48	-51	-56	-51	Nee
1. EMC uitstraling (alle windmolens samen)	4.1	-42				Ja
2. Reflecteren stoorsignalen uit de omgeving (door alle windmolens)	4.2	-84				Ja
3. Reflecteren van ongewenste uitstralingen vanuit het windturbinepark zelf	4.3	verwaarloosbaar t.o.v. 1.				Ja
4. Reflecteren van DAB+ omroepsignalen	4.4	n.v.t.		n.v.t.		Ja
5. Blokkeren en afbuigen van gewenste signalen	4.5	verwaarloosbaar				Ja
6. Reflecteren van signalen uit de ruimte	4.6	niet gekwantificeerd				Ja
7. Ontlading door wrijvingsverschijnselen	4.7	niet onderzocht				Nee
8. Stoorsignalen die zich verspreiden over het elektriciteitsnet	4.8	niet gekwantificeerd				Nee

* gemoduleerd door de rotatie van de rotorbladen van de windturbines

The values calculated under points 1 and 2 of **Table 1** are performed based on the "free space" propagation that indicates a "worst case" result. In Chapter 5 of this report it will be corrected by calculating the modified Hata propagation model [14].

In Chapter 5 is assessed to what extent it is likely that the performance of the LOFAR receiving system will be affected.

5 Robustness of LOFAR for disturbance of the environmental EM.

By using the various mechanisms of interference from Chapter 4 wind turbines can introduce a change of the EM level at the location of the LOFAR core. In this chapter, the effects of this change in the EM environment for the "performance" of LOFAR are mapped to different modes of perception.

To be able to make an estimate of the "robustness" of the LOFAR system for the EM radiation, the Agency must dig into the LOFAR receiving system. Based on a literature study, data from ASTRON and personal accounts by it, is as good as possible the sensitivity of LOFAR measurement system and the robustness to interference signals distilled for different types of observations with LOFAR. The calculated levels of robustness have been verified by ASTRON and converted by the agency to the same unit dBµV / (m.Hz) as the disruption of the EM environment anticipated in Chapter 4. In this way, the minimum sensitivity of the array, can be compared with the interference signals caused by wind turbines. In assessing the coexistence of LOFAR and the planned wind farm, the Agency is based on the results of Chapter 4 (change of the EM environment to be expected) and LOFAR robustness levels for interfering radiation from **Table 2** of this chapter.

5.1 The receiving capacity of LOFAR for weak signals from space

LOFAR is a special radio receiver system which aims to receive signals from space and process them. These signals are generally very weak. The high sensitivity of the LOFAR array, is achieved mainly with the core. The environment of the core is characterized by a low ambient noise level. This has been of great importance in the choice of the location for the LOFAR core.

In the bands in which LOFAR works (from 10 MHz to 90 MHz (lower band) and 110 MHz to 240 MHz (high band)), the ambient noise of the core dominated by galactic noise (see Figure 10). The galactic noise also comes from space, especially from the Milky Way, which is in many cases much stronger than the signals of interest.

LOFAR applies different methods for filtering desired signals from noise. These methods may relate to the direct reception with the antennas and preamplifiers, but also at the digital operations that occur later in life. Depending on the field of research, the reception-processing technique, and is set so that the desired signal and the noise is lost as much as possible.
For example, the galactic noise, which over the whole sky forms a vast gradual source over the whole sky, is filtered away by means of cross-correlation methods in the making of sky cards with a long base line. That long baseline is created by using widely separated antennas. That way, small details are brought to attention in the sky cards. Selecting a short baseline makes extensive structures visible and makes small details disappear. The objects in space that are observed by ASTRON Research will follow a path like the sun, through the rotation of the earth. Rise in the east and setting in the west. When measured with LOFAR these

Structures are followed by iteratively adding in small time differences in the received signals in an antenna, and thereby to focus an observation beam, and to follow the path of the object. This way long measurements can be made to an object so that unintended signals can be averaged out as good as possible in time.

The performance of the array, is such that the said signals can be detected with levels in the order of magnitude of -164 dBµV/ (m.Hz). This is achieved by reducing the so-called 'thermal noise' to a level lower than that of the where emissions to be taken. The thermal noise is caused by noise in the LOFAR system itself but also includes the not filtered out (interference) emissions. The different possible thermal noise levels of the array, have been provided by ASTRON, and shown in **Table 2**. They are roughly calculated by dividing the ambient noise by the number of physical antennas per LOFAR station. Then you have the noise per station. The noise of the observation can be in turn be determined by dividing the noise per station by the number of stations involved in measurement, and the square root of the product of time and bandwidth. The division by the root form an effective averaging. Especially with long integration times the thermal noise can get very low levels.

In the context of the Epoch of Reionization (EOR) research, measurements at a frequency of 150 MHz in blocks of 1000 hours can take place, in a bandwidth of 10 MHz with the entire core. Here, a thermal noise level of -164 dBµV / (m.Hz) can be derived. For making sky maps is generally the whole core is used with 2 MHz bandwidth. At a frequency of 50 MHz means that a thermal noise of -137 dBµV / (m.Hz). In order not be bothered the noise level should remain 10 dB below that. When they are of the same order of magnitude scientific value is lost.

Table 2: The critical noise floor for different measurements.

Type of measurement	Typing	Research Areas (See 2.2)	Time [Hours]	Critical noise floor (dBµV / (m.Hz))
Generic imaging	Imaging	-Survey of the low-frequency sky - Transient Radio Sky - Magnetic fields in the universe - Solar physics and space weather	10	-137
EoR	Imaging Long integration t	- Epoch of reionization	1000	-146
Buffer board dump	Imaging with short integration time, effect afterwards	- Transient Radio Sky - Astro particle physics	a few seconds	n.a.
Measuring Pulsar	Conduct research rotating stars: detecting fluctuating signals	- Pulsar studies and surveys - Solar physics and space weather	10	-146

The super mound includes a fourth portion of the number of stations of the core, six of the 24, and hence measurements are therefore of a 6 dB higher thermal noise level. However, the shorter baselines give the Super mound measurements more sensitivity to interference again.

For measurements of pulsars applies, to noise sources with an amplitude modulation and a frequency similar to the pulsar which is measured, a similar requirement as EoR research. This is because according to information from ASTRON these signals must remain a factor of 10 below the noise. However, as a source of interference does not include amplitude modulation, the signal can simply be counted in the surrounding noise.

5.2 Interference suppression by LOFAR itself

The possible use of the available 'built' interference-suppressing measures LOFAR depend on the 'type' perception.

The phased array concept (in which use is made of several individual antennas) makes it possible to have a 'look' or main beam to address a place in the room without a physical antenna to suit. The object to observe describes a similar path as the sun in the sky. If one is directed for a long time thereafter continues to the horizon disappears from the main beam. Most terrestrial interference sources and also wind turbines, which are on the horizon, by definition, then disappear from view of the main beam. However, contains the antenna direction diagram of LOFAR antenna contains, next to the main beam also called side-lobes. A part of these side-lobes can be directed by measurements on the horizon. The interference signal affects in this way, albeit weakened, the measurement. This weakening is, according to ASTRON least approximately 15 dB. An average estimate is 25 dB. The elevation angles of the side-lobes are frequency dependent and, among other things depending on the wavelength and positioning of the individual antennas. The overall result is complex and difficult to predict. There also occurs a further 10 dB attenuation at as a result of the behavior of the individual antennas [19]. Signals from the horizon are at a small angle with the earth's surface within and thereby receive this extra attenuation. This means an average total attenuation for the side of the incoming signals of 35 dB.

Also, problems may arise with EM disturbance from wind as the observation LOFAR should take place in a limited time while the main beam remains facing the horizon. As the observation times are shorter averaging of the interference signals becomes more difficult.

In addition, in time domain measurements, such as, for example, which is done when measuring on pulsars, the amplitude modulation of the interference signal is of interest as well. Due to reflections against the rotating blades of a wind turbine arises such an interference signal that varies as a function of the time in amplitude. If this modulation is similar to the pulse frequency of a pulsar, then it is difficult to distinguish between the desired pulsar signal[14] and the modulated interference signal. Such signals must then also have a very low level, to have no influence a very low level on the measurement. When creating images of the sky where the desired signal is constant, especially the average strength of the interference signal is of interest.

Depending on the nature of the interference signal and on the type of measurement (see **Table 2**), a false signal can influence the measurement results in two different ways.

[14] This is true for about 30% of the pulsars.

- In the first case, the interference signal constitutes only an extra contribution to the (ambient) noise. That translates ultimately into higher background noise in the measurement example and more blurred images or maps of the sky. By measuring longer this noise contribution can usually be relatively lower.

- In the second case, the interference signal does not advance to be distinguished from the desired signal to be measured. It is then usually admitted through a side lobe of the antenna system, resulting in strong attenuation, but the influence cannot be reduced as noise by measuring longer or to use more antenna fields.

Longer observations
Most measurements come down to the making of a celestial map, making an image ("imaging" in the **Table 2**) of a smaller or larger structure in the universe in a certain frequency band. The sensitivity falls to interference signals in that case falls in the first category. In order not to be bothered, the level remain 10 dB under the existing thermal noise. When they are of the same order of magnitude the scientific value is lost.

There are, however, boundaries at relatively lowering the noise contribution of sources of interference, however, by measuring longer sit or boundaries. A rough averaging, because it is dependent on the used frequency band and base line length, ensures as a result, for a 10-dB suppression by a continuous observation time of 10 hours.

Therefore, we expect an additional adjustment of 10 dB noise suppression for the long dwell time.

Given that this suppression is a consequence of the smearing of the point spread function during a long observation, this plays no role in this suppression pulsar measurements. For pulsar measurements exceeding the lower limits required by the disruption of the EM environment derived in this report will therefore be 10 dB higher.

Pulsar measurements
At pulsar measurements, a "total power measurement" is carried out instead of working with interferometry, with a group of stations located relatively close together, such as the Super mound or the entire core. Typical integration times are 1 to 10 hours. But if a spurious signal has an amplitude modulation, such as in a wind turbine can occur has to be estimated a similar sensitivity as a 1000-hour imaging measurement for a 10 hour measurement to a pulsar with a corresponding low noise floor. If a disturbance has no amplitude modulation, or frequency is different enough from the pulsar frequency, the signal can simply be counted as increases in ambient noise. This measurement then falls into the first category.

In the further digital processing, it is possible in many cases in order to remove strong interference signals that are defined in time or in frequency from the measurement data. This can be done by hand, but there are also algorithms for. A loss of 8 to 10% of the measurement data is occurring according to ASTRON, every now and then.

5.3 Current EM local environment LOFAR (without wind turbines)

LOFAR is currently functioning as a tool of international first-class [20], despite the fact that the environment now is not trouble-free. On some already occurring interference possibilities are discussed here.

Current EMC emission in the vicinity of LOFAR
The LOFAR core is 2.8 km from the village of Buinen. Any electrical device operating on a floor or attic can be blasting the LOFAR core can (possibly with damping when used in buildings). Within 5 km of the LOFAR core there are more residential areas, in which there must be devices on a floor or attic. LOFAR seems to have no excessive problems for the operation of their system. That means LOFAR is apparently able to count these disruptions out. [6] This is mainly due to the properties of the LOFAR system that listens in a wide spectrum over longer periods. But also adequate detection methods, strong filters, receiving high linearity and low height of the antennas contribute to this. [7] Yet there regularly occurs some EMC interference and this can cause an increase in noise observations. Regular EMC interference is not spatially coherent source because it is too close and in this sense out of focus. In the case of the most sensitive measurements ASTRON indicates thus in cases having to discard observations. This suggests that there occasionally devices are present in the area that produce less than one to several MHz distortion around the limit. The exact cause of this, however, is due to the complexity of the required analysis by ASTRON not yet been fully mapped.

Wind farms at 20-30 Km (Rütenmoor and Heede, Germany)
For example, there are already wind farms behind Ter Apel and Stadskanaal in Germany at distances of approximately 20 to 30 km from LOFAR all wind farms. These wind turbines are already causing a (theoretical) impact on the EM environment locally LOFAR. ASTRON does not seem to be having problems, however from these wind turbines. How can we explain this? [15]
In the determination of the change of the EM environment on the spot of the array, as a result of wind farms at greater distances, we run against the following uncertainties: The application of conventional propagation models (such as Hata [14] ITU-R Recommendation P.1546-5 [21]) in the determination of the attenuation of an interference signal from a wind turbine which is a distance greater than about 10 to 15 km under a very low angle (as compared to the ground plane) is incident on the LOFAR antennas is associated with uncertainties. The propagation models turn out not to be validated for calculating field strength values at low altitude above a specific surface area (where the LOFAR antennas are positioned) and for longer distances. This coupled with the uncertainty about the dampening effect of the LOFAR antennas for receiving interference at very low incident angles (<5 degrees, and in the longer distances), makes a theoretical prediction unreliable. Measurements as specified in section 6.1.4 could provide more clarity about the actual interference field strength caused at the LOFAR location due to wind farms at longer distances.

[15] For this not suggesting that these existing wind farms or wind turbines in that area would have the same characteristics as the planned wind farm in Drentse Monden and Oostermoer. There has not been studied by the AT to.

5.4 Expected EM local environment LOFAR (wind turbines)

The electromagnetic environment can be represented by the values as shown in Figure 10. various said levels are indicated. There are a number of known levels, which are taken directly from ITU recommendations and several levels (from Table 2), as specified by ASTRON for the coexistence of LOFAR and Drentse Monden and Oostermoer of interest.

ITU-R Recommendation P 372-12 [4] shows the expected median noise levels for a number of environments.

In addition, ITU-R Recommendation 769-2 RA [22] provides protection criteria for radio astronomy measurements. It is noteworthy that since the adoption of these criteria have taken place the necessary technology improvements so that LOFAR measurement deeper into his bands than these criteria. The protection criteria according to ITU-R RA 769-2 is therefore no longer sufficient for LOFAR.

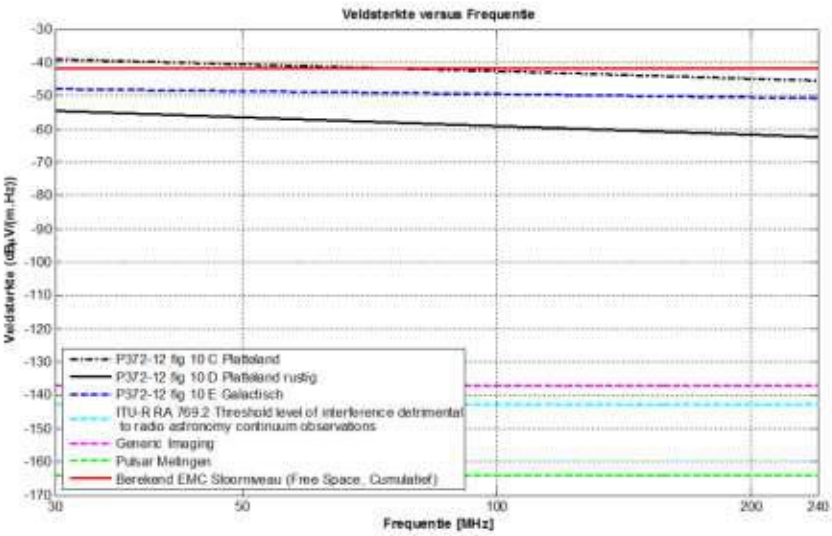


Figure 10: Overview of the level of interference as a result of the EMC emission of wind turbines (red line) and the different critical levels for performing radio astronomy measurements [22].

There are several effects which are considered to cause a reduction of the signal on the LOFAR core. The following calculation can be made on the basis of Figure 10:

A cumulative interference signal on the LOFAR core
on the basis of free space calculation according to section 4.2: - 42 dBμV / (m.Hz)

A more Realistic propagation model instead of Free Space: -10 dB
See Annex A.
Correction for practically radiated EMC interference
Turbine, see 4.1: [16] -10 dB

[16] There are several conditions that can lead to a lower and lower interference signal. They sometimes occur but may be limited charged. One should think of a turbine that does not have a whole

Attenuation by low irradiation in it LOFAR antennas, see 5.2	- 35 dB
Noise reduction by longer observations, see 5.2	- 10 dB
Still needed to cause no deterioration of LOFAR -164 dBμV / (m.Hz)	- **57 dB**

Compared to the sensitive lower limits that LOFAR needs for its observations means 57 dB (67 dB for pulsars) a significant overshoot. This makes a fair coexistence unlikely.

band disturbing but in a limited band and not the limit. A turbine does not always run in the circumstance in which it causes the most disruption and sometimes stands still.

5.5 LOFAR and its mitigation capabilities

LOFAR is designed from the outset with a number of built-mitigation techniques for the known noise and interference sources in mind. It does not take into account wind turbines placed in sight of the LOFAR core. This is among other things described in Boonstra [5] which describes how already certain mitigation methods are considered in the design phase. This includes, besides the above-described principle of beam-forming with spatial averaging, but also the choice of the most interference-free frequency (sub-) bands, long integration times and noise averaging.

In the thesis, "Algorithms for Radio Interference Detection and Removal" of AR Offringa of 22 June 2012 [6], it is believed that, under certain preconditions RFI signals can be averaged over the measurement bandwidth. To what extent do EMC signals from wind turbines fit into the conditions as stated in the thesis is not immediately clear.

LOFAR is a software telescope. That is, the instrument for a major part based on the, after the digitization, processing of data using computers and software of all the received signals into something to slightly astronomically useful.

With this software operation a lot is possible, but that is already happening. To forecast further mitigation possibilities in LOFAR itself, by applying improved algorithms, an in-depth knowledge of the system is needed.

ASTRON is the only organization that has the knowledge and ability to do further research for this. An assessment on the possibilities of further mitigations on the side of LOFAR is therefore not possible in the context of this investigation.

6 Additional measures to suppress interference signals

6.1 Mitigation possibilities and solutions

As seen in Chapter 5, there are at least 57 dB worth of mitigation measures needed to prevent deterioration of LOFAR for certain types of research. This chapter will examine to what extent this mitigation is available.

There are several conceivable mitigation techniques to reduce the impact of the placement of wind turbines in the vicinity of LOFAR. Given the sensitivity of LOFAR to disruptions, likely only a combination of mitigation techniques may provide a solution. In the following sub-paragraphs various options are displayed.

6.1.1 *Physical shielding of Wind turbines*

One mitigation technique would be the utmost physically shielding the wind turbines for interference seen from the LOFAR core, without making a sharp edge. This could be an overgrown shore. The closer such a shore is positioned at the LOFAR core, it may be the lower. But he must also bring further away portions of the core placed out of sight. The attenuation of an earthen wall with vegetation is not sufficiently known in the frequency bands of LOFAR. There is more known and more research around 3.5 GHz (far beyond the band LOFAR) but that has not yet led to practical implementation. Because pf the measuring wavelengths between 1 and 10 meters are an earthen wall would have to be tens of meters high.

6.1.2 *The wind turbine design*

With regard to the wind turbine design are three aspects of great importance. A low level of radiated EMC, a non-periodic fluctuating EMC level and a low reflectivity.

A low radiated EMC level can be achieved, inter alia, by placing the converter electronics as much as possible in the base of the wind turbine mast. EMC experts from the wind turbine industry indicate that interference levels are achieved, substantially under the limit. Generally around 25 dB.

Due to a good EMC design of the wind turbine, the fluctuation of interfering radiation in the time as a result of the wick rotation can be minimized.

The reflectivity can be expressed as radar cross section, RCS. Measurements show that the RCS is a determining factor in the failures of a periodic nature. In general provide smaller and lower turbines provide for a lower RCS. This could be considered in a specification.

6.1.3 *Coordination between ASTRON and the operators of the wind farm*

Through coordination between ASTRON and the operators of the wind farm, mitigation can be optimized. Good weather forecasts can help. One of the mitigation options for the coexistence of the wind turbines and LOFAR is the exchange of information and coordination of use. In practice, the turbine mostly works not at full power and is regularly still. Besides standstill little wind there is limited downtime for planned and unscheduled maintenance. During these periods, possibilities will be improved to carry out measurements on pulsars which have a periodicity in the range of the rotation time of the blades of the wind turbines as these are in operation. This does not mean that all the disruptive effects of wind turbines are gone.

Information exchange between ASTRON and the wind farm operators can help to form a picture of expected downtime based on turbine specifications and forecasts. Modern turbines have sensors that actual production figures are available. This can be fairly detailed data from sensors at the turbine, for example, the frequency at which the blades rotate, and the direction from which the wind comes. These data can help in the software noise filtering taking place in LOFAR.

6.1.4 *Changing the configuration of the wind farm*

The configuration of the wind park has an impact on the level of the interfering radiation which is generated on the LOFAR location. In general, that, as the distance is increased and the number of wind turbines is reduced, the interference is smaller. As the angle of incidence of the interfering radiation (relative to the earth) is smaller, the more LOFAR antennas will dampen the interfering radiation. This lower angle of attack can be achieved by lowering the wind turbines in height, or to increase the distance. Also it helps to place it in the design of the wind turbine, the potential sources of interference layer in the foot of the mast.

If the wind turbines are placed at a larger distance the interference effect will reduce. There has been no investigation by the agency to the minimum distance that must be maintained between wind turbines and LOFAR to avoid unacceptable disturbance of the LOFAR system.
However, if it is assumed that LOFAR experiences no wind farms that are currently operational, the corresponding distance between LOFAR and the respective wind turbine parks can be used as an indicative 'safe' distance. The minimum distance at which LOFAR encounters no distortion from wind turbines would have to be somewhere in the distance range of 15 km to 30 km. For this "safe distance" to be determined within this distance range is essential that greater clarity is obtained on the following aspects:

- The propagation characteristics (attenuation) of interfering signals within this range of distance, assuming a realistic soil type and morphology combined with

- Information about the additional attenuation which occurs because these spurious signals, are ‘seen’ by the LOFAR antennas (that are placed low to the ground plane) under a very low angle (relative to the ground plane)

- Quantitative information about the actual direct radiated EMC characteristics from wind turbines.

- Quantitative information on the reflection characteristics of wind turbines

The application of conventional propagation models (such as Hata [14] and ITU Recommendation P.1546-5 [21]) in the determination of the attenuation of an interference signal from a wind turbine which is a distance greater than about 10 to 15 km under a very low angle (relative to the earth's surface) is incident on the LOFAR antennas involves uncertainties.

Even in the circumstances in which these prediction models have been designed, it should be taken into account with a standard deviation of around 10 dB. The propagation of these distances are not validated for calculating field strength values at low altitude over a specific surface area (where the LOFAR antennas are positioned). This coupled with the uncertainty about the dampening effect of the LOFAR antennas for receiving interference at very low incident angles (<5 degrees) a theoretical prediction to be too inaccurate.

A jointly with ASTRON executed measurement campaign is expected to provide more reliable information on the above aspects and can lead to greater clarity and (possibly) consensus on keeping to a "safe" distance.

6.2 Conclusions on mitigation

The above is an overview of possible mitigation measures. The question now is how much these measures would yield total to negate the adverse effects on the EM environment of wind turbines. An expert's assessment of the combined measures is as follows.

With regard to the earthen rampart the uncertainties are too large to bring them to a positive effect into account.

Regarding the wind turbine design regarding EMC aspects gives the wind turbine industry that 25dB should be possible under the limit. For the medium / short term is an estimate of 15 dB a safe estimate. If, however, in the wind turbine itself, and the corresponding installation innovative solutions can be found, for example, by being able to place the electronics in the base of the tower, may perhaps be attributable to the benefit gained. That should be studied in conjunction with the wind turbine industry.

Regarding the coordination of LOFAR in the wind farm, the Agency sees the effects are not as substantial. It concerns only a part of a solution to a portion of the measurements.

It is concluded that at this point it would be a safe estimate that a total of 20 dB can be achieved by applying mitigation measures, of which improving the EMC of the wind turbines provides the most important contribution.

7 Conclusions

AT has, requested by the Minister of Economic Affairs, performed a study of the effects of the proposed location of the wind farm Drentse Monden and Oostermoer for radio astronomy receiving station LOFAR ASTRON. The presence of wind turbines in the vicinity of the array, causes changes in the electromagnetic environment on the spot. The LOFAR system has a certain degree of resilience for these changes, but if they are too big changes which will manifest itself as a fault in the LOFAR receiving system with a degradation of the reception potential as a result.

The main interference mechanisms prove to be the "EMC appearance of the wind turbines themselves" and to his "reflections of other noise sources using wind turbines".

The investigations into Pulsars and "Epoch of Reionization" require a sensitivity of LOFAR system of -164 dBμV / (m.Hz). In a generated EM interference level above or comparable to this value observations here will be affected by this and be lost as scientific value. The level of electromagnetic interference caused by the wind farm exceeds this level spot LOFAR 57 dB (and pulsar measurements 67 dB).

There are a number of conceivable mitigation actions that might decrease the disturbance of the EM environment as a result of the wind turbines. Most profit can be achieved most profit by reducing the EMC emission from the wind turbines themselves. However, the overall effect of these measures, which we assess at 20 dB is not sufficient to eliminate the 57 dB excess.

The internal mitigation potential of LOFAR itself is inadequate to eliminate such spurious emissions because it is likely that this potential is already fully deployed.

Conclusion:

Different interference mechanisms have been investigated by the agency. The types of distortion "EMC radiation from the wind turbines" have a major disruptive effect as a result. The level of this former effect is such that even with mitigation measures it will lead to degradation of certain types of observations as to pulsars and "epoch of reionization". For the other investigated mechanisms, it is likely that its effect is limited and / or can be solved by LOFAR.

8 Recommendation regarding effect of change configuration windfarm

The configuration of the wind park has an impact on the level of the interfering radiation which is generated on the LOFAR location. In general, that, as the distance is increased and the number of wind turbines is reduced, the interference is smaller. As the angle of incidence of the interfering radiation (relative to the earth) is smaller, the more LOFAR antennas will dampen the interfering radiation. This lower angle of attack can be achieved, in particular, by lowering the wind turbines in height, or by increasing the distance. Also it helps to place it in the design of the wind turbine, the potential sources of interference layer in the foot of the mast. The latter would also may have an additional beneficial effect on a reduction of the EMC direct effects from the wind turbine.

If the wind turbines are placed at a larger distance will reduce the interference effect will be reduced. There has been no investigation by the AT to the minimum distance that must be maintained between wind turbines and LOFAR to avoid unacceptable disturbance of the LOFAR system.

However, if it is assumed that LOFAR experiences no wind farms that are currently operational would be the corresponding distance between LOFAR and the respective wind turbine parks can be used as an indicative 'safe' distance.

From Chapter 7 of this report shows that the plan Drentse Monden and Oostermoer, based on the planned constellation of Figure 3 will lead to failure. The planned wind turbines are located at distances between 4.5 km and 15 km from the LOFAR Super mound. The existing wind farms just over the border in Ter Apel and Bourtange are located at distances of approximately 20-30 km from LOFAR. It concerns parks of about 30 wind turbines.

Assuming that existing wind farms currently don’t cause interference on LOFAR, it can be assumed that these parks are on a "safe" distance. The minimum distance at which no distortion LOFAR encounter more wind turbines would have to be somewhere in the distance range of 15 km to 30 km. It should be noted that AT has done no research into the exact EMC radiation (direct and indirect) of the park and surrounding area. In addition, this group of wind turbines different characteristics than the planned wind farm in Drentsw Monden and Oostermoer. For this "safe distance" to be determined within this distance range is essential that greater clarity is obtained on the following aspects:

- The propagation characteristics (attenuation) of interfering signals within this range of distance, assuming a realistic soil type and morphology combined with

- Information about the additional attenuation which occurs because these spurious signals, under a very low angle (relative to the ground plane) in the layer arranged inside come LOFAR antennas.

- Quantitative information about the actual direct radiated EMC characteristics from wind turbines.

- Quantitative information on the reflection characteristics of wind turbines

The application of conventional propagation models (such as Hata and ITU recommendation P-1546-4) in the determination of the attenuation of an interference signal from a wind turbine on a distance greater than about 10 to 15 km at a very low angle (relative to the Earth's surface) is incident on the LOFAR antennas involves uncertainties. The propagation may not be suitable or have not been validated for calculating field strength values at low altitude above a specific surface area (where the LOFAR antennas are positioned). This coupled with the uncertainty about the dampening effect of the LOFAR antennas for receiving interference at very low incident angles (<5 degrees) a theoretical prediction to be inaccurate.

A jointly with ASTRON executed measurement campaign is expected to provide more reliable information on the above aspects and can lead to clarity and (possibly) consensus on keeping to a "safe" distance. Regarding the EMC behavior of wind turbines is the exchange of knowledge with the promoters / operators of wind turbines desirable.

ATTACHMENTS

A. Modified Hata model & freespace model

The propagation models used in this report are free space, Hata and modified Hata.

The free space model is a model in which factors such as reflections, "shadowing" "Multipath" and other topology are not considered related securities.

The calculation is very simple $$E = 5{,}48 \cdot \frac{\sqrt{P_{e.i.r.p}}}{R}$$ where E is the field strength in V / m,

P is the radiated power in W e.i.r.p. and R is the distance in meters.

The Okumura Hata model is a model developed by the Japanese and Okomura Hata This is the original model often just Hata model is called [23]
The Okumura Hata model is an improvement of the Okumura model but has a limited frequency range and does not work with distances of less than 1000m.
In using an "excess of loss" and a height adjustment for the transmitter extra cushioning compared to calculate the free space model. In this report, this frequently used method.
Incidentally, one must also in these situations for the applicable more realistic prediction models, taking into account a standard deviation of around 10 dB.

To give an example, in an aerial height of 100m at a frequency of 200MHz and a distance of 5 km is the "excess of loss" 23 dB and height adjustment 2dB on the radiated power.
This results in an approximately 10 dB lower than that calculated field strength with the free space model.

For a wider frequency range is the 'modified Hata' or 'extended Hata model developed with different versions in circulation. Here is the variant from ERC report 68 used [14].

B. Estimation of current interference and noise level

LOFAR [2] has been developed for the area where it is today and functions well. The core is between Exloo and Buinen at a selected location. For the low LOFAR show for this location galactic noise seems to be dominant. For the high band applies that the noise is half system noise and half galactic.

The table shows some values for galactic noise according to ITU-R 372-12 [4]

Frequency [MHz] median	dBμV / (m.Hz)
10	-49.9
30	-51.3
100	-52.9
300	-54.3

C. Overview of DAB + stations near LOFAR

Near LOFAR next DAB + channels can be detected.

location	Height [m]	P erp [kW]		NPO
Smilde	210	1		channel 12C
Stadskanaal	79	0,7		226,592 – 228,128 [MHz]
Emmen	60	8		
Groningen	132	0,3		
Dedemsvaart	51	6,5		
Winschoten	58	4		

location	Height [m]	P erp [kW]		Rural commercial
Smilde	255	10		channel 11C
Emmen	55	0,4		219,584- 221.120 [MHz]
Hoogezand	90	2		

location	Height [m]	P erp [kW]		No nationwide commercial + regional audience
Smilde	253	3,5		channel 6B
Hoogezand	82	25		182,880- 184.416 [MHz]

location	Height [m]	P erp [kW]		MTV NL
Smilde	70	0,01		channel 11C
Emmen	55	0,8		191,584- 193.120 [MHz]

D. Measurement of the reflectivity

In the literature there are no or virtually no, measurements to be found on of the reflectivity of wind turbines in the frequency range over which measurements are carried out with LOFAR. Agency Telecom therefore itself has executed measurements of a wind turbine in order to gain more insight here. As a measure for the reflectivity of the wind turbine is the Radar Cross Section (RCS) is selected, a number that indicates how big the apparent surface area is that reflects radio waves. RCS A lower value means less reflection of the wind turbine.

It is measured on a wind turbine with a hub height of 136 meters and a blade length of 50 meters near Lelystad [15]. The results of these measurements can be used to estimate the expected reflectivity of a single wind turbine in Exloërveen.

The RCS of the wind turbine was determined at frequencies between 50 and 60 MHz, is between 200 and 280 MHz and around 600 MHz. To this end, a pulse-shaped signal was broadcast with precise characteristics at the selected frequency and the reflected pulse received by the wind turbine at a different location and measured. In the area of multiple wind turbines were present, but the proposed wind turbine could be measured separately by the use of the duration of the transmitted signal to the wind turbine and from the wind turbine, and to the measuring receiver.

A large number of measurements was performed during three measurement sessions in April, May and June 2016. This is to prevent that the measured values are dependent on a specific measuring distance, a specific position in the landscape, or a particular orientation of the wind turbine as a result of the instantaneous wind direction. The measured values are given in the table below.

Measured RCS values		
50-60 MHz *	11-12 dBm^2	12-16 m^2
200-280 MHz	24-33 dBm^2	250-2000 m^2
600 MHz	28-29 dBm^2	600-800 m^2

Table E.1: By AT measured reflectivity of a wind turbine. [15]

As can be seen, the RCS measured is not constant: it varies changed when the orientation of the wind turbine changed and also when another position is chosen in the field. The variation of the RCS values is much larger than the uncertainty of measurement.

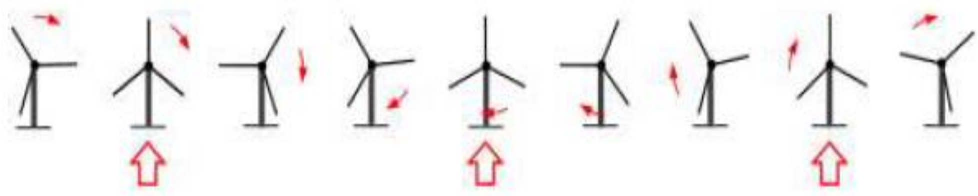
The RCS measurements made at 50-60 MHz, marked with an asterix (*), make use of an antenna fabricated for this study which is arranged close to the ground. For this antenna no external calibration is available, and data are based on values obtained by simulation. The value for 50 MHz-60 MHz can therefore still contain a systematic error.

Taking into account the foregoing observations, there is in this study decided to obtain additional information on the basis of literature and own calculations (see Annex E). Eventually was chosen for this study to keep an RCS value of 2000 m2.

Periodic variation of the reflectivity

The measurements show that the reflectivity of the wind turbine is dependent on the position of the rotor blades. As a result, a constant radio signal in the environment of the wind turbine - whether it concerns a spurious signal or the signal from a scheduled transmitter - are reflected and thereby importing the periodicity of the rotor blades.

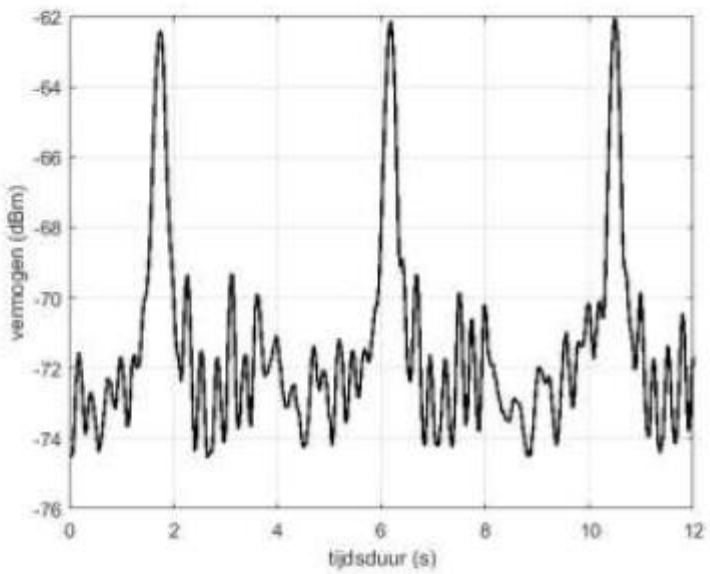
The wind turbine with three blades, which is measured during measurements made one revolution every 15. Because of this, a reflection occurred every 5 seconds a reflection. This is illustrated in the image below, taking as an example the maximum reflection occurs at a wick in the highest position.



The reflectivity of the wind turbine is dependent on the position of the rotor blades. The here drawn position of the rotor blades in which reflection occurs is only an example. It also appears that another (recurring) rotor position maximum reflection.

In most cases, the reflection occurred when one of the rotor blades was located at the highest position, but on some occasions the reflection performed precisely in a different position of the rotor blades on it. The orientation of the wind turbine as a result of the instantaneous wind direction plays a role. So both wind direction and wind speed to determine the periodic variation of the reflected (potentially interfering) signal.

The values them in the table in the previous section have occurred during the brief limits. In between is the value of the reflected signal is at least 10 dB lower, that is to say a factor of 10 in terms of power. The size of this minimum could not be measured precisely with the equipment used. The reflections show a short duty cycle, that is to say the peaks in the signal are short-lived compared to the periodicity. Therefore, the wind turbines in a wind turbine park will not all exhibit a maximum reflection at the same time.



A detail of one of the reflectance measurements on a wind turbine, such as described in [15]. The regular reflection can clearly seen. The repetition frequency of the reflection is dependent on the number of rotor blades and their rotation speed. The reflection is in each case of short duration and occurs at a very specific position of the rotor blades.

The repetition frequency of the reflection is dependent on the number of rotor blades and the rotational speed of the rotor. The speed of revolution is dependent on the available wind speed, but is also regulated by the wind turbine itself.

Modern wind turbines with a capacity of between 1 and 5 MW have a maximum rotational speed about 16 rpm. For wind turbines with three rotor blades is the time between two reflections is 1.25 second or longer.

Radar Cross Section (RCS) is a technical factor that indicates how strongly an object reflects radio waves. The unit of this factor is square meter (m2).

It is important to realize that this area measure has no direct relationship with the physical dimensions of the reflective object. A small object can have a large RCS, if the radio waves reflect well. And a large object may have a small RCS when the radio waves reflected poorly. In comparison, a small mirror will reflect more light than a large matte black wall.

The RCS of the rotor blades of a wind turbine strongly depends on the position of the rotor blades. Compare this with a rotating mirror which catches sunlight falls: we see the reflection of light only when the position of the mirror is just right.

.

E. Calculation of the reflectivity

In order to get additional (indicative) information about the Radar Cross Section of (the vanes) of wind turbines with the calculations Numerical Electromagnetic Code [24] were implemented in a simplified structure in which a vertical wire equal to 2 x a constructed wick (length is from 50 m) is observed in the free space. (The rotor blades of wind turbines comprise a conducting wire that acts as a lightning conductor and thus forms a potential reflector).

The Radar Cross Section (in the direction perpendicular to the wire) of the following configuration has been studied at the frequencies 50 MHz, 100 MHz, 150 MHz and 200 MHz: straight vertical wire into the free space with a length of 100 meters and a beam of 0.01 cm which is irradiated with a plane wave (E-field component parallel to the wire). The results of the simulation are as follows:

Frequency MHz	RCS in [m2]
50,00	1347
100,00	1676
150,00	2056
200,00	2389

In Figure E1 is the back scatter cross section, reflectance in the direction perpendicular to the wire, for different angles of incidence of a plane wave on the thread shown at 50 MHz in the above-described configuration. At 90 degrees, the back scatter cross-section is equal to the radar cross section, and do 1347 m2.

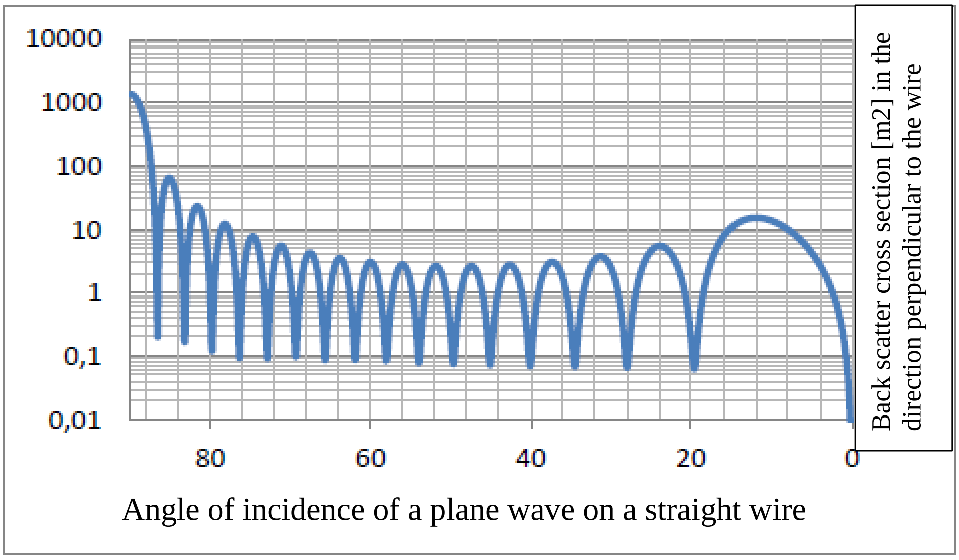


Figure E1: Back scatter cross section [m2] for the reflection direction perpendicular to the wire, for different angles of incidence of a plane wave with the thread @ 50 MHz, wire length 100 m, diameter 0.02 m, in 'free space'.

F. Bibliography

[1] "The wind farm Drentse Monden and Oostermoer" http://www.drentsemondenoostermoer.nl (weblink of 2016-05-02).

[2] MP Haarlem, et al, "LOFAR: The low-frequency array.", Astronomy & Astrophysics, Vol. 556, A2, pp. 1-53, 2013.

[3] "Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement", BS EN 55011: 2016, NEN, Delft, 2016.

[4] "Radio Noise", ITU-R Recommendation P.372-12, International Telecommunication Union, Radiocommunication Sector, Geneva, Switzerland, in 2015.

[5] AJ Boonstra, "Radio Frequency Interference Mitigation in Radio Astronomy", doctoral thesis, University of Technology, Delft, 2005.

[6] AR Offringa, "Algorithms for Radio Interference Detection and Removal", writes trial, University of Groningen, 2012.

[7] Offringa AR, et al, "The LOFAR radio environment", Astronomy & Astiophysics, Vol. 549, January 2013. http://www.aanda.org/articles/aa/abs/2013/01/aa20293-12/aa20293-12.html

[8] "The wind farm Drentse Monden and Oostermoer - Environmental Impact Assessment", Pondera Consult Hengelo, September 8, 2015. https://www.rvo.nl/sites/default/files/2015/09/2015%2009%2011%20MER%20Hoofdrapport%20DDM-OM%20-versie%2008%2009%202015%20definitief-%20versie%20website .pdf

[9] K. Frolic, Mr. Watson, "Drentse Monden Wind Development - LOFAR Technical Impact Assessment", Pager Power, Sudbury, United Kingdom [commissioned by the Ministry of Economic Affairs] in April 2015.

[10] A. Mulder, C. Thick-Faber, EMA Smaling, "Modified motion of the member Agnes Mulder et al (tvv 30196, no. 414) on account of the investigation of LOFAR in placing windmills" Sustainable development and policy, the House of Representatives, Kamerstuk 30196, Nr. 429, The Hague, March 8, 2016.

[11] LOFAR website http://www.lofar.org (weblink of 2016-05-02).

[12] website plan Drentse Monden and Oostermoer, http://www.drentsemondenoostermoer.nl/ (link of 2016-05-02).

[13] "Council Directive 2014/30 / EU of the European Parliament and of the Council of February 26, 2014 on the harmonization of the laws of the Member States relating to electromagnetic compatibility", Official Journal of the European, L96 / 79, March 29, 2014.

[14] "Radio Monte Carlo Simulation Methodology for the use in sharing and compatibility studies between different radio services or systems" ERC Report 68 European Radio Communications Committee (ERC), European Conference of Postal and Telecommunications Administrations (CEPT), Baden, June 2002.

[15] L. Colussi, "Determination of the radar cross section of wind turbines - Phase 1," draft report version 0.6, Radiocommunications Agency, Amersfoort, June 8, 2016.

[16] Website Radiocommunications Agency, list of digital broadcasting transmitters in the air or will soon be, http://appl.agentschaptelecom.nl/ DAV / index.html (link 2016-06-21).

[17] A. Fresnel, "Auszug aus einer Abhandlung über die Reflexion of Light," Annalen der Physik, Vol. 1, Nr. 1, pp. 255-261, 1833.

[18] WC Lee, Mobile Communications Engineering, McGraw-Hill, 1982.

[19] M. Krause, "Calibration of the LOFAR Antennas", Master's thesis, Radboud University Nijmegen, The Netherlands, 2013.

[20] RC Vermeulen, "The impact of the planned wind farm Drentse Monden on the scientific return of LOFAR (Scientific report)", Director Radio Observatory at ASTRON and Director ILT.

[21] "Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz," Recommendation ITU-R P.1546-5, International Telecommunication Union, Radiocommunication Sector, Geneva, Switzerland, in 2013.

[22] "Protection criteria used for radio astronomical measurements", ITU-R Recommendation RA.769-2, International Telecommunication Union, Radiocommunication Sector, Geneva, Switzerland, in 2003.

[23] Y. Okumura, "Field strength and its variability in VHF and UHF land-mobile radio service," Electrical Communication Laboratory, Vol. 16, Nr. 9-10, 1968.

[24] G. Burke, A. Poggio, J. Logan, J. Rockway, J. "NEC Numerical electromagnetics code for antennas and scattering," IEEE Antennas and Propagation Society International Symposium, Vol. 17, 1979, pp. 147-150).