International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R SM.2391-0
(06/2016)

The effects of wind turbines on fixed radio direction finders

SM Series
Spectrum management

International Telecommunication Union

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R SM.2391-0

The effects of wind turbines on fixed radio direction finders

(2016)

Summary of the Report

Notwithstanding the requirements of the ITU's Spectrum Monitoring Handbook, which calls for a minimum safety distance of five kilometres between radio direction finders and wind farms, no separate studies have as yet been conducted into the specific effects of wind turbines on fixed radio direction finders at various safety distances.

Annex 1 to this Report provides one study conducted on this topic regarding the influence of wind parks on radio direction finders operated at various distances and at various frequencies.

Annex 1

Example of a study of the effects of wind turbines on fixed radio direction finders executed in Germany

Summary of Annex 1

The draft version of a new regional plan proposes the designation of a wind energy priority area around the Bundesnetzagentur's radio monitoring station in Rheurdt, Germany.

This investigation has found that significant interference is caused by wind farms situated in proximity to fixed radio direction finders. Even at a distance of 4.6 km, the results show that wind farms cause unacceptable bearing deviations and interference levels.

Specific interference varies considerably depending on the distance and position of the wind farm as well as the wavelength. In the case of long-wave VHF frequency bands (4 m and 2 m), interference generally occurs in all directions irrespective of the specific position of the wind farm. At close proximity to a wind farm, the level of interference in the case of short-wave UHF frequency bands (especially 23 cm and 13 cm) depends on the position of individual wind turbines, while, at greater distances, the wind farm as a whole acts as a reflective surface. The bearings in these frequency bands are also subject to high levels of fluctuation.

Direction-finding (DF) errors can take the form of highly dispersed DF results in all four quadrants, a few discrete DF errors or bearings which fluctuate around a fictitious average value.

A short-wave direction finder behaves chaotically within a wind farm. Even when the wind park is situated 2.5 km away, there is only a narrow sector transverse to the wind farm in which valid bearings are theoretically possible. At a distance of 4.6 km, the situation improves to the extent that significant DF errors were identified only in the direction of the wind farm and in the opposite direction. However, the effects on the sky-wave reception of short-wave direction finders were not included in the scope of this investigation.

In all frequency bands, the DF errors identified are greater than ±20° (and, in some cases, are even rotary). Even DF errors of more than 2° prevent the timely investigation of interference on safety frequencies (police, aeronautical radio, etc.) and the efficient clarification of frequency usage, whether in the event of interference or when checking frequency occupation.

The identified level fluctuations of up to 40 dB (which equates to a 99.99% loss of signal) make calibrated field strength measurements impossible and jeopardise the potential necessary decoding of analogue and digital radio transmissions.

The investigation shows that wind turbines and fixed radio direction finders are not compatible at distances of up to at least 4.6 km. The recorded interference shows clearly that, in such circumstances, it would no longer be possible to operate a Bundesnetzagentur radio monitoring station in accordance with the relevant requirements.

Table of contents of Annex 1

Page

1 Introduction

The Bundesnetzagentur (Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway) is a separate higher federal authority within the scope of business of the Federal Ministry of Economics and Energy, and is headquartered in Bonn. Pursuant to the Telecommunications Act (TKG), its tasks include frequency regulation within the Federal Republic of Germany, monitoring compliance with the conditions of frequency assignment, investigating interference in connection with frequency usage and remedying any resulting infringements.

For this purpose, the Bundesnetzagentur operates seven radio monitoring stations throughout Germany which are equipped with radio direction-finding (DF) apparatus, and are registered with and recognised by the ITU (International Telecommunication Union). These monitoring stations can identify the direction from which a radio transmission is made relative to their location. Based on this information, the probable location of the transmission can then be determined. Of these seven radio monitoring stations, only four are equipped with additional short-wave direction finders due to the high investment costs involved and topographical requirements for the location of such equipment.

Radio monitoring station Krefeld/Rheurdt

Short-wave direction finder

The radio monitoring station at Rheurdt near Krefeld is one such location. Owing to the homogeneous environment, and also to avoid spurious emissions and (DF) errors as a result of surrounding buildings, the short-wave direction finder was constructed away from the building, is operated remotely and is sited on a flat plain used exclusively for agricultural purposes.

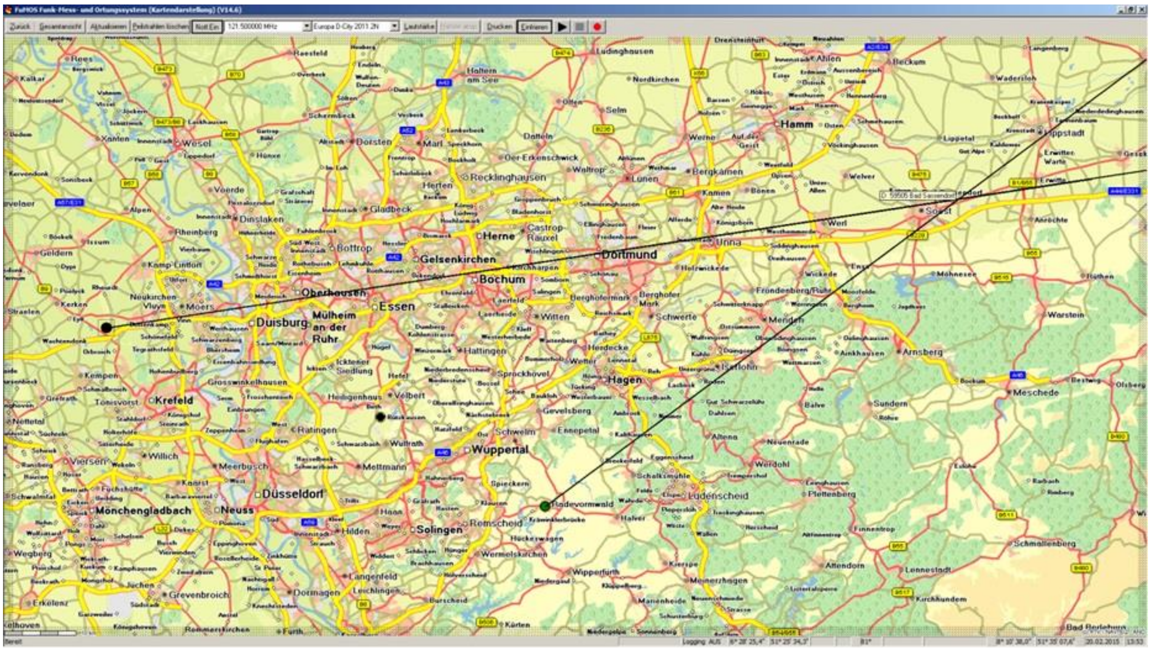
The usefulness of a direction finder, which is based on confidence in its ability to produce accurate DF results, depends on its location. It requires an "unobstructed view" of its field of reception and must not be affected by interference from surrounding structures (e.g., man-made noise from industrial or commercial areas). Wherever possible, direction finders are therefore located far from developed areas.

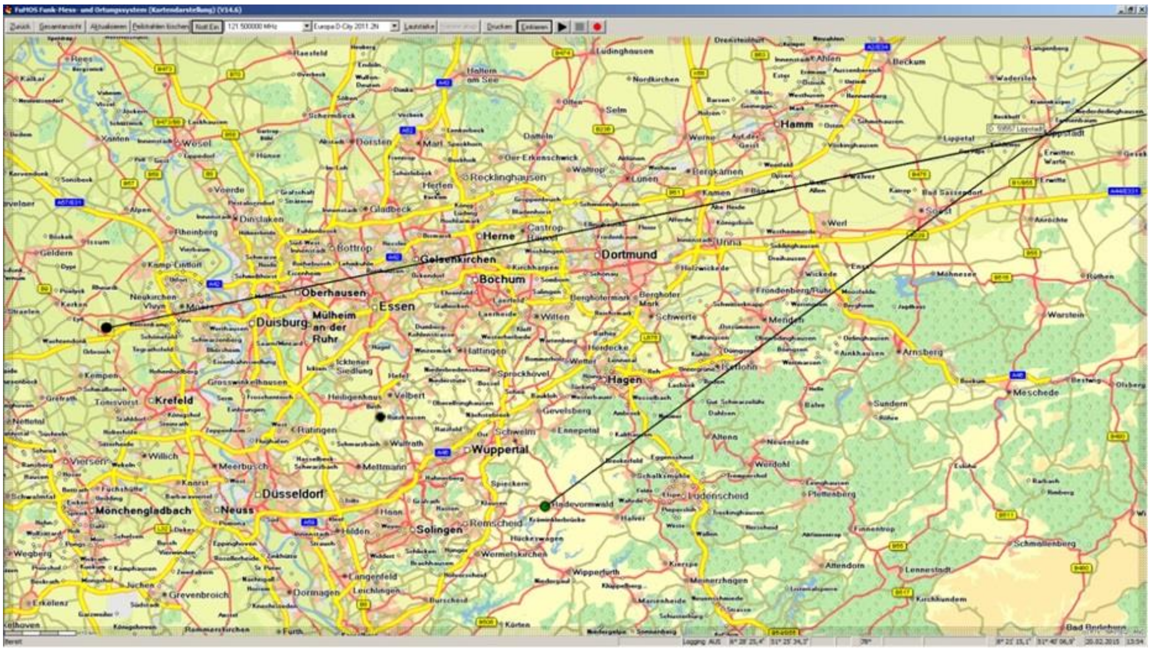
The manufacturers of DF systems define the quality of obstacle clearance required for the system to function properly and in accordance with the agreed terms. The requirements of the system operator, which are listed according to the importance of the frequency bands in question, are also taken into account. Safety services, such as aeronautical radio, police radio and emergency rescue services, have a higher priority and must be investigated much more quickly than other bands, e.g., amateur radio, where radio frequencies are used for leisure purposes only.

For the short-wave direction finder used at the location in Krefeld/Rheurdt, the manufacturer (a company called Plath, based in Hamburg) states that obstacle clearance must be maintained within a radius of 2 000 m, as represented by a cone with an elevation angle of 3° from the centre of the direction finder. This means that, within a distance of 2 000 m, buildings with a maximum height of around 105 m can be tolerated (2 000 m × tan 3° ≈ 105 m). In the case of wind farms, the maximum height of the blade tip must also be taken into account, as the rotation speed and direction of rotation influence the extent to which the swept area constitutes an obstacle to radio reception. With short-wave direction finders, clearance of around 3.8 km constitutes a "tolerable distance" where wind turbines with a height of 190 m are planned.

At a distance of 200 km, a DF error of just 3° causes a bearing deviation of 10.5 km and therefore makes it impossible to determine the location from which the transmission was made.

DF value changed from 81° to 78° from Rheurdt





Based on the example of a DF error of just 3°, the target area shifts from the city of Soest to the city of Lippstadt 10 km away.

The ITU's Spectrum Monitoring Handbook (which includes globally applicable guidelines for the erection of radio monitoring stations) therefore recommends that a distance of 2 000 m be maintained between radio monitoring stations and individual wind turbines, and a safety zone from wind farms of 5 000 m around the radio monitoring station.

This investigation was triggered by the planned designation of a wind energy priority area around the fixed radio monitoring station and receiving system of the radio monitoring and inspection service in Rheurdt, as proposed in the regional plan of the Düsseldorf regional administration. The aim of this investigation is to identify in advance the possible effects of these plans on HF and VHF/UHF direction finders and to define a critical distance from wind turbines, from which these effects can be tolerated.

2 Frequency bands

This investigation looked at all relevant VHF/UHF frequency bands. The following table provides an overview of the individual frequency bands and their key uses:

Frequency band	Wavelength	Type of radio usage
65-87.5 MHz	4 m	Authorities and organisations concerned with public safety (police, fire service, emergency rescue services), Federal Armed Forces, railways, private mobile radio (PMR), on-site paging, ancillary broadcasting
108-174 MHz	2 m	Aeronautical radio, authorities and organisations concerned with public safety, Federal Armed Forces, taxi radio, in-house radio applications, maritime mobile service and inland waterways service, amateur radio
400-470 MHz	70 cm	Authorities and organisations concerned with public safety, analogue and digital trunked mobile radio, in-house radio applications, amateur radio, mobile data services, radio astronomy
800-1 100 MHz	30 cm	Mobile communications, Federal Armed Forces, aeronautical navigation, radiodetermination, radio astronomy
1 200-1 400 MHz	23 cm	Radiodetermination (radar, GPS, Galileo), satellite communications, amateur radio
2 000-3 000 MHz	13 cm	Mobile communications, WLAN, authorities and organisations concerned with public safety, radio relay, satellite communications, Federal Armed Forces, aeronautical navigation, radiodetermination, radio astronomy, amateur radio

The specified wavelengths should be seen as indicative of the individual frequency bands.

3 Carrying out measurements

Various combinations of the following parties were involved in taking measurements:

– Darmstadt radio monitoring and inspection service

– Rheurdt radio monitoring and inspection service

– “GPS_Azimuth” software development (see § 06).

Measurements were taken during the period from 26 to 30 January 2015 and from 5 to 8 February 2015 in and around the wind farm in Haren (Ems), and reference measurements were taken during the period from 18 to 20 February 2015 in the open countryside near Kerken-Aldekerk.

4 Measurement areas

4.1 Wind farm measurements

Prior to measurements being taken, efforts were made to find a wind farm in the federal territory which meets the following criteria:

– a sufficiently large number of the latest generation of wind turbines;

– a flat landscape;

– little developed land within a 5 km radius of the wind farm;

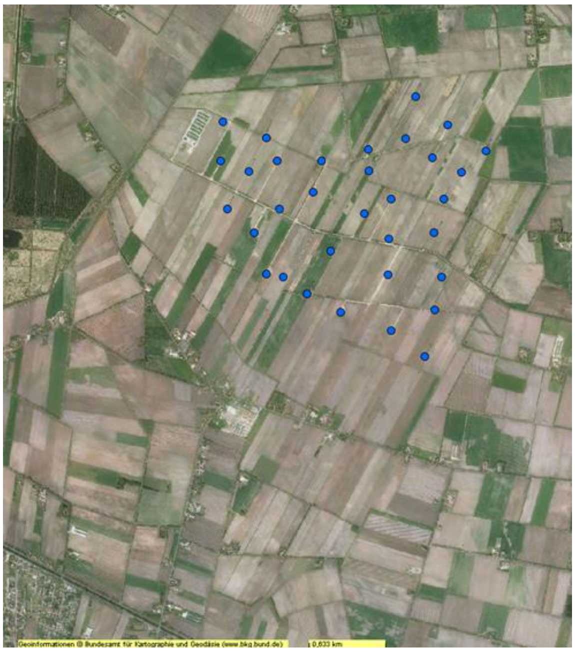
– no impact from leafy trees.

The wind farm in Haren (Emsland) was ultimately chosen, as this location appears to best meet the above criteria. The wind farm in Haren consists of 29 wind turbines, belongs to the region of the city of Haren/Ems and is situated in the district of Rütenmoor, in the immediate vicinity of the Dutch border. The cleared area, which used to be moorland, covers approximately 295 ha and is now used intensively for agricultural purposes.

Wind farm at Haren (Ems)

29 ENERCON E-70-4 wind turbines with an effective output of 2 MW and ENERCON E-66-1 wind turbines with an effective output of 1.8 MW were constructed on the grounds of the wind farm. The hub height of all turbines is identical (98 m). The turbines are equipped with state-of-the-art rotor blades (tapered tips) which guarantee improved wind energy use.

Wind farm in Haren
(blue dots represent the locations of wind turbines)



4.2 Reference measurements

The manufacturer of the DF antenna for the HF range and the antenna for the VHF/UHF range, states in its specifications that a maximum DF error of ≤2° RMS can be tolerated.

Specifications

Frequency range (in two sub-ranges)	VHF / UHF I UHF II	20 MHz to 1300 MHz 1300 MHz to 3000 MHz
Antenna type	VHF / UHF I UHF II	1 nine-element and 1 eight-element circular array
Polarization		vertical
Nominal impedance		50 Ω
DF error[1]		≤ 2° RMS
DF sensitivity[2] (see Fig. 4-1)	20 MHz to 200 MHz 200 MHz to 1300 MHz 1300 MHz to 3000 MHz	12 µV/m to 1.0 µV/m typ. < 2 µV/m typ. 2.5 µV/m to 10 µV/m typ.
Antenna factor (see Fig. 4-2)		see also Interface Description 4071.4004.01 SB
Linearity		IP2: 65 dBm typ. IP3: 30 dBm typ.
Connectors	DF1 DF2 DF3 CAL control and power supply compass connector	N-type female N-type female N-type female N-type female SJT-07GS-12-35P-014 SJT-07GS-10-35S-RF45
Power supply (by the DF processor)	voltage current	15 V DC to 18 V DC < 1.6 A
Dimensions	diameter height length of lightning protection rod	approx. 1.1 m approx. 0.45 m approx. 1.4 m with lightning protection rod approx. 1 m

[1] *On mast, in reflection-free environment. The RMS value is calculated from the DF values averaged over azimuth and frequency. On thin masts (4 m to 8 m), an additional DF error of up to 2° may occur at frequencies between 20 MHz and 40 MHz due to possible self-resonance.*

[2] *DF bandwidth 0.6 kHz, average time 1 s, DF error ≤ 2°.*

To verify this information, reference measurements were taken for the HF and VHF/UHF DF antenna in the proximity of the manned radio monitoring station on flat land used for agricultural purposes near the village of Kerken.

HF and VHF/UHF reference measurements

These measurements show that, in a homogeneous environment which is not affected by interference from structures such as wind turbines, it is largely possible to remain within the maximum DF error specified by the manufacturer of ± ≤ 2° RMS. For further details, please see § 9.1.

5 Measurement set-ups

5.1 DF vehicle

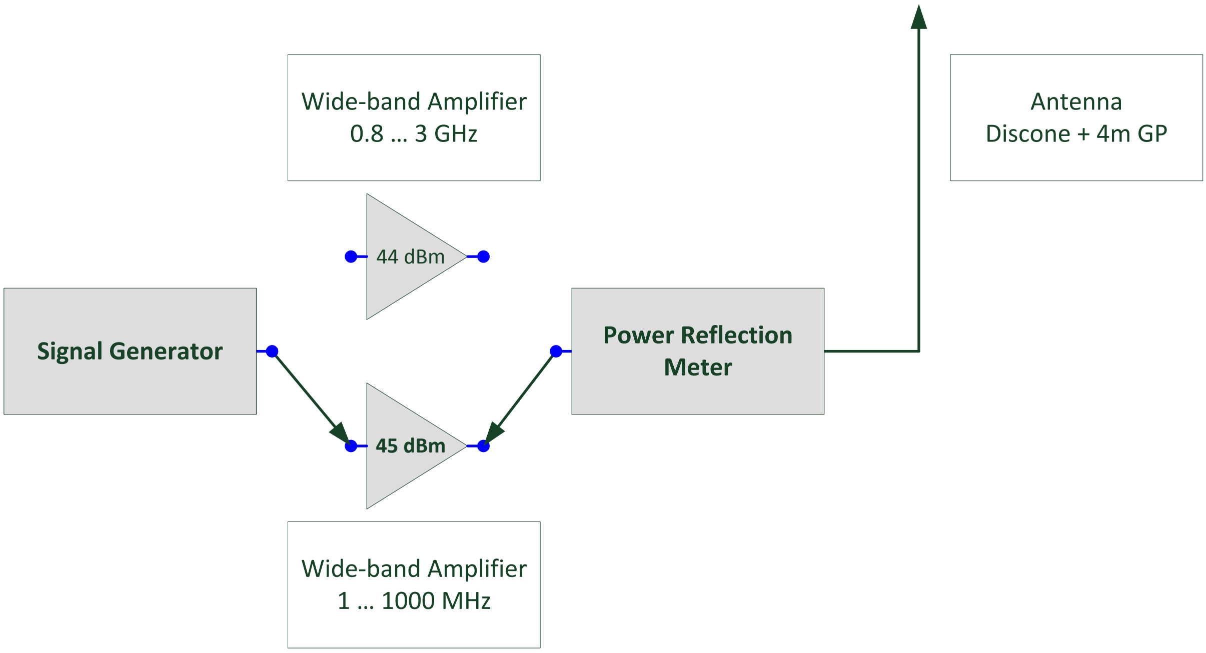
As a quasi-fixed direction finder, a Mercedes Sprinter monitoring vehicle was equipped with the DF system and the DF antennas (frequency bands 30 to 3 000 MHz and 1 to 30 MHz). The DF antennas were operated on a telescopic mast 8 m above ground.

For internal communication, portable radios and a relay terminal from the same manufacturer were used.

5.2 Transmitter vehicle

The transmission signal was generated using a signal generator and, where necessary, amplified to a transmission output of up to 25 watts using wide-band amplifiers. A transmission-enabled broadband discone antenna was used for the frequencies 146 MHz, 440 MHz, 971 MHz, 1 300 MHz and 2 400 MHz, and another ground-plane antenna for the frequency 87.45 MHz. Both antennas were installed and operated on a 10 m telescopic mast in a Mercedes Sprinter monitoring vehicle.

Block diagram VHF/UHF transmitter

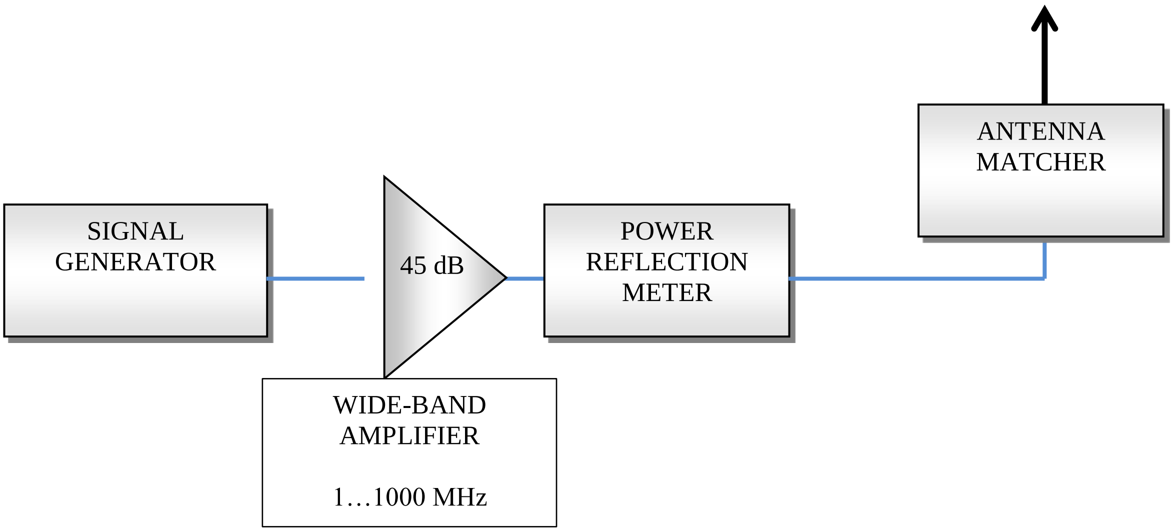


Monitoring vehicle with 10 m mast and transmitting antenna

Amplifiers

After amplification (where necessary), the transmissions for the HF range (5.46 MHz, 14 MHz and 28 MHz) were generated using an antenna tuning unit (ATU) and a vertical antenna measuring approximately 3 m in length.

Block diagram HF transmitter

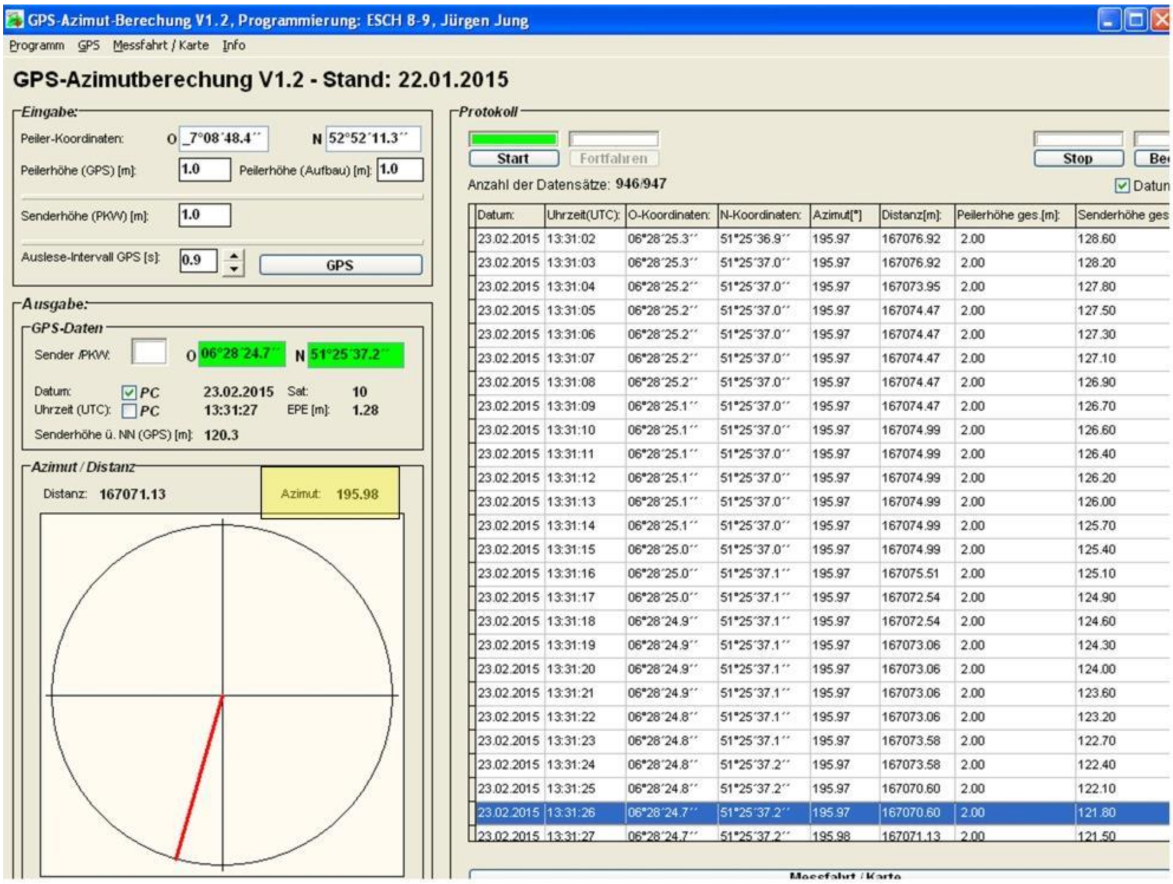


Monitoring vehicle with an HF vertical antenna

6 Calculating the bearing angle

The Bundesnetzagentur's internally developed "GPS_Azimut" program was used to calculate the azimuth from the direction finder to the transmitter (target bearing) for each location of the transmission vehicle. It automatically calculates the bearing angle based on the coordinates of the direction finder and the respective coordinates of the vehicle, as supplied by a GPS receiver.

"GPS_Azimuth" program interface (bearing angle highlighted yellow)

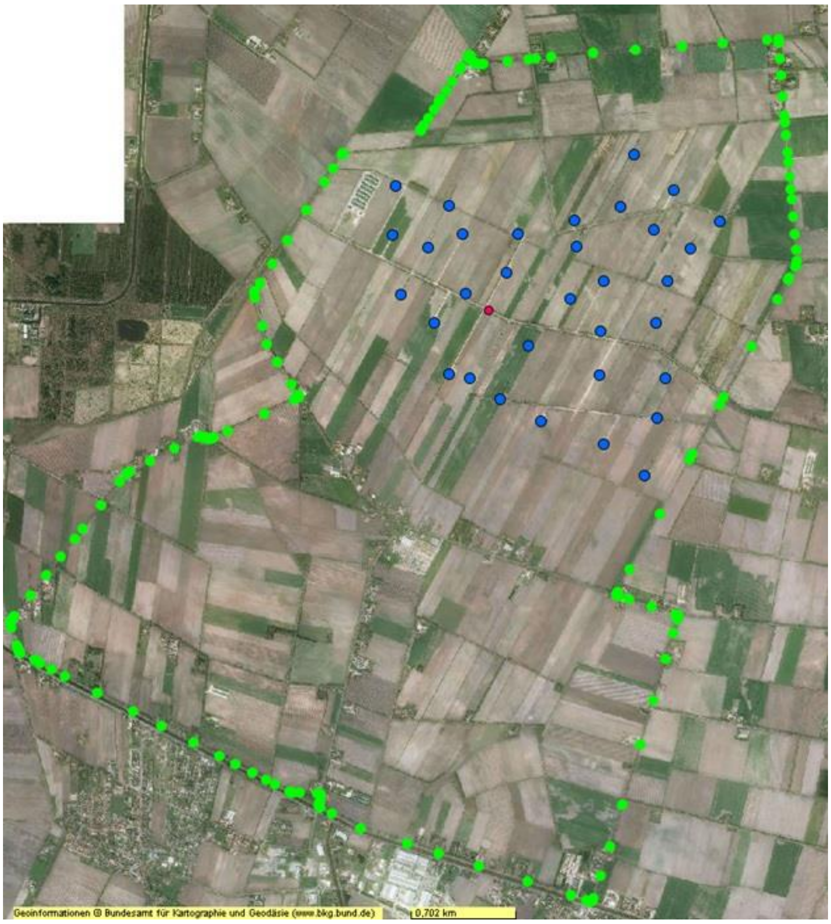


7 Direction finder locations

7.1 Direction finder 0 – centre of wind farm

The choice of location for the direction finder in the centre of the wind farm corresponds to the situation to be expected if the regional administration's intended regional plan for the designation of the "Ker_Wind_007" wind energy priority area is implemented as proposed. In this case, the direction finder is surrounded on all sides by wind turbines. The measurement results are presented in § 9.2.1.

Location of the direction finder (red dot), surrounded by wind turbines (blue dots)

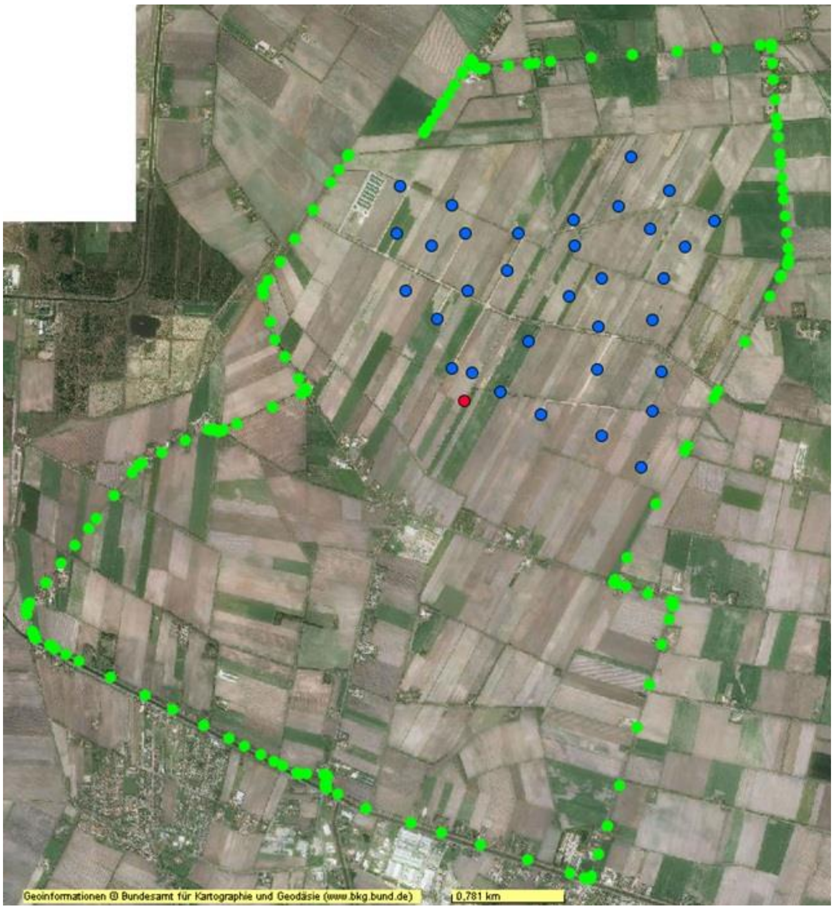


Location of the direction finder within the wind farm

7.2 Direction finder 1 – edge of wind farm

This direction finder is located at the edge of the wind farm with an unobstructed view to the south and wind turbines to the north. The measurement results are presented in § 9.2.2.

Location of the direction finder (red dot) at the edge of the wind farm (blue dots)

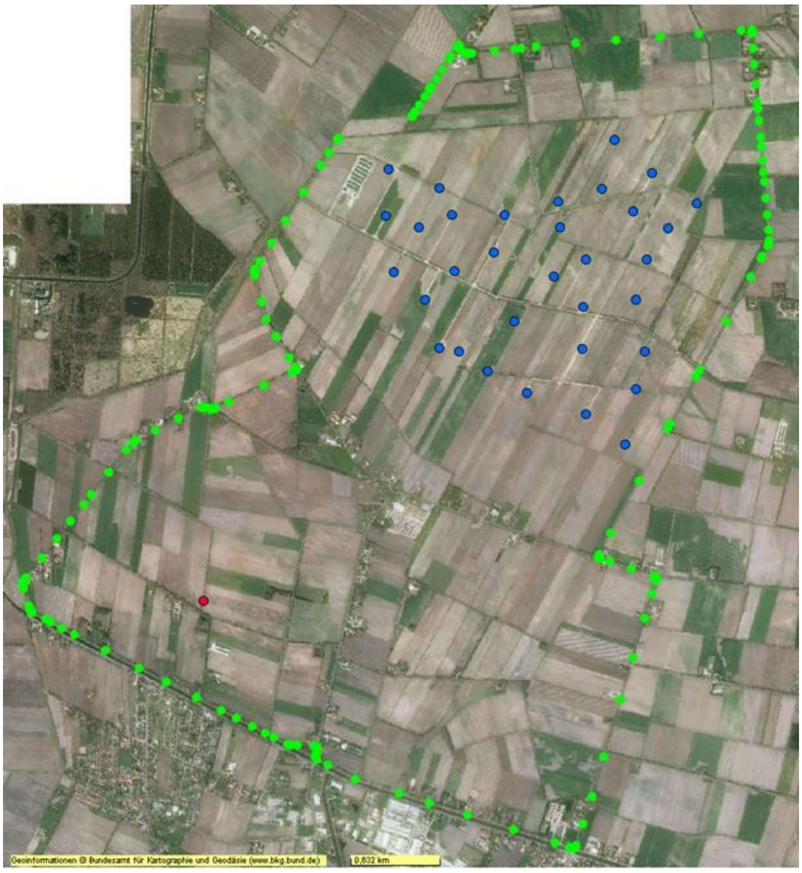


Location of the direction finder at the edge of the wind farm

7.3 Direction finder 2 – located 2.5 km away

This direction finder is located approximately 2.5 km away, with an unobstructed view of the wind farm to the north-east. The measurement results are presented in § 9.2.3.

Location of the direction finder (red dot), south-west of the wind farm (blue dots)

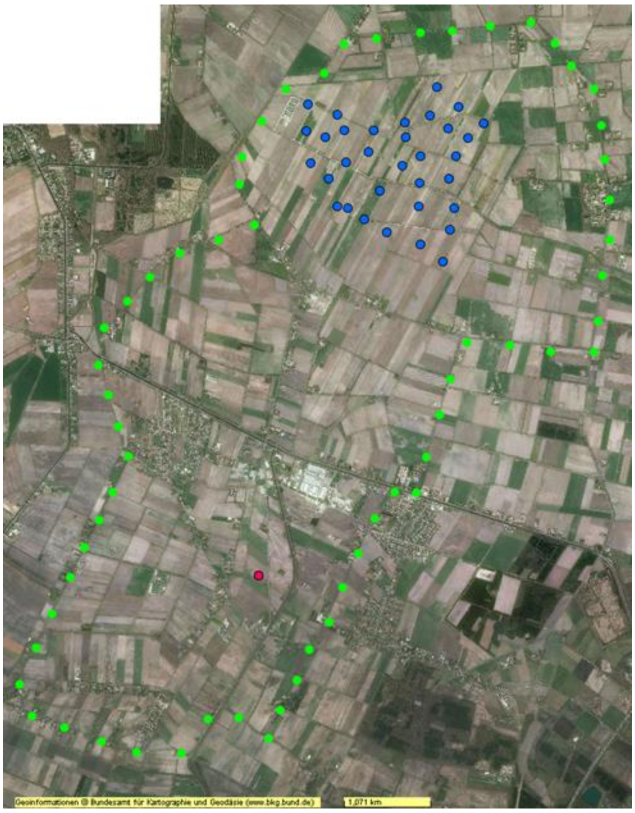


Direction finder located 2.5 km from the wind farm (visible in the background)

7.4 Direction finder 3 – located 4.6 km away

This direction finder is located farthest (4.6 km) from the wind turbines. The measurement results are presented in § 9.2.4.

Direction finder (red dot) located 4.6 km from the edge of the wind farm (blue dots) as the crow flies

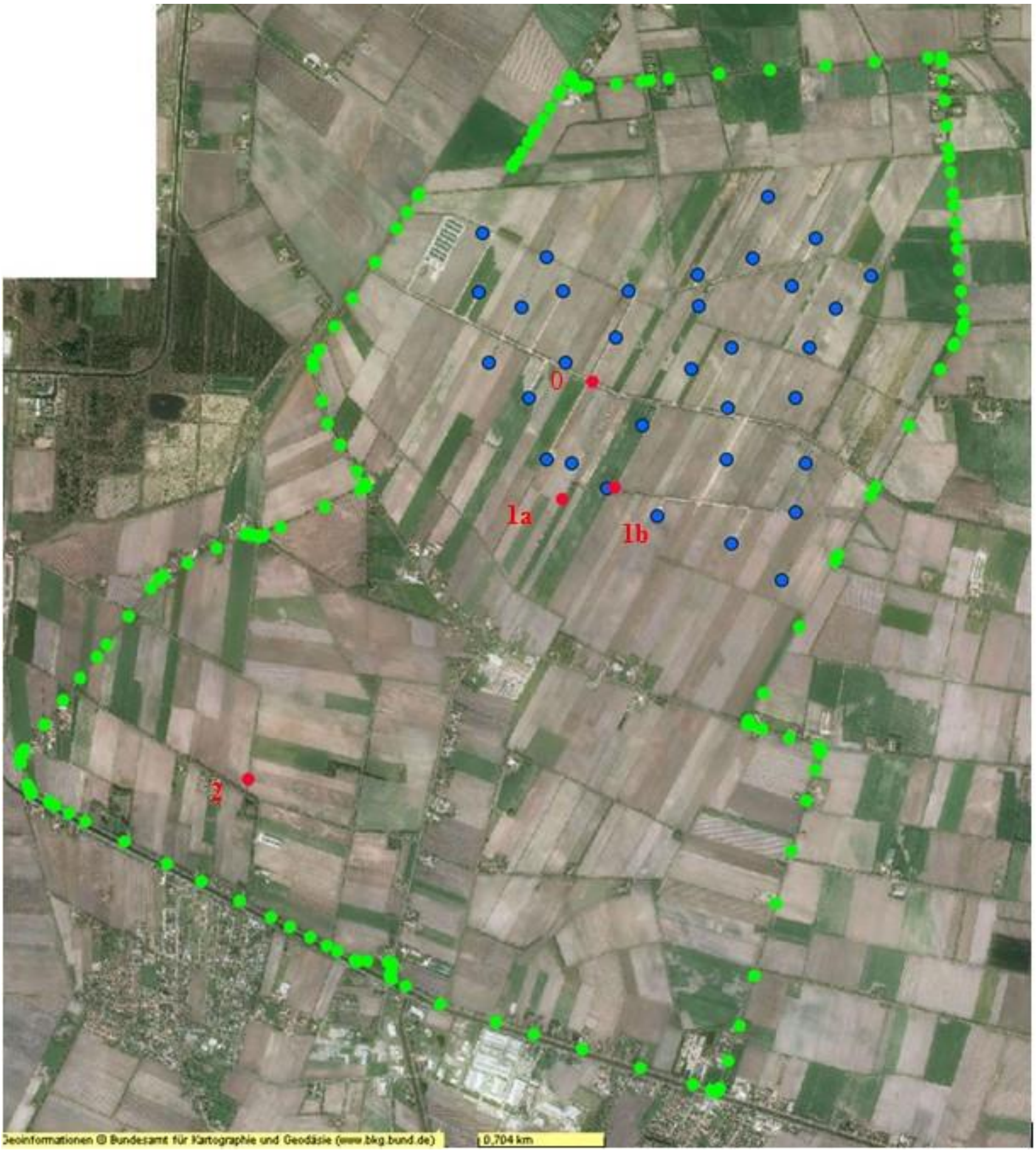


Direction finder located 4.6 km from the wind farm

8 Measurement paths

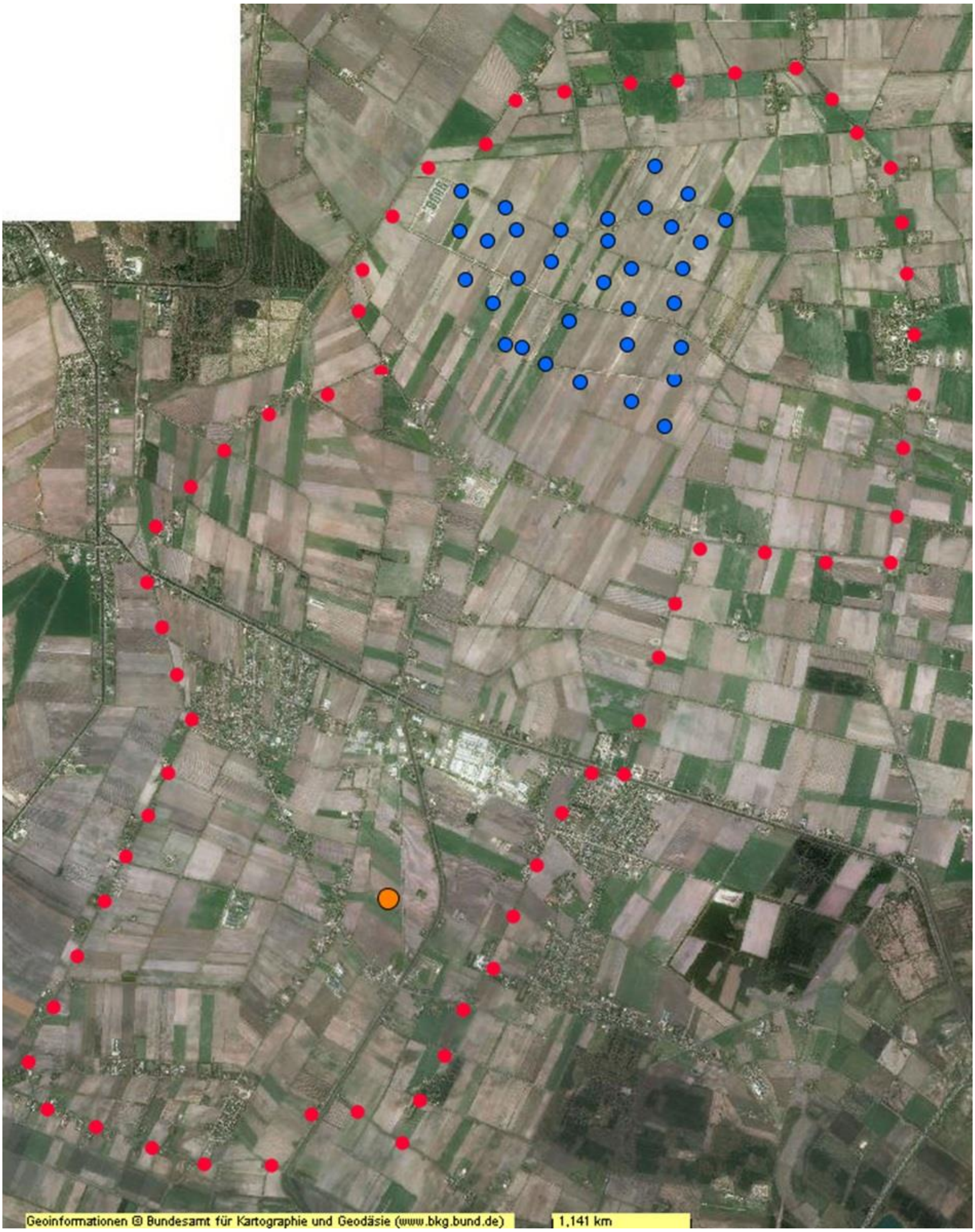
The transmission vehicle, a Mercedes Sprinter, was moved in increments of 10° around the location of the direction finder and the wind farm along the path indicated by green dots. The existing infrastructure had to be taken into consideration when planning the route. Some sections were not paved and could only be accessed using the Mercedes Sprinter's four-wheel drive option.

Transmission path (green dots) around the wind farm and direction finder locations 0-2



For direction finder location 3, the transmission path (red line of dots) had to be extended considerably to include the direction finder and wind farm within the scope of measurement.

Measurement section (red dots) around the wind farm and direction finder location 3



9 DF results

9.1 Reference measurements

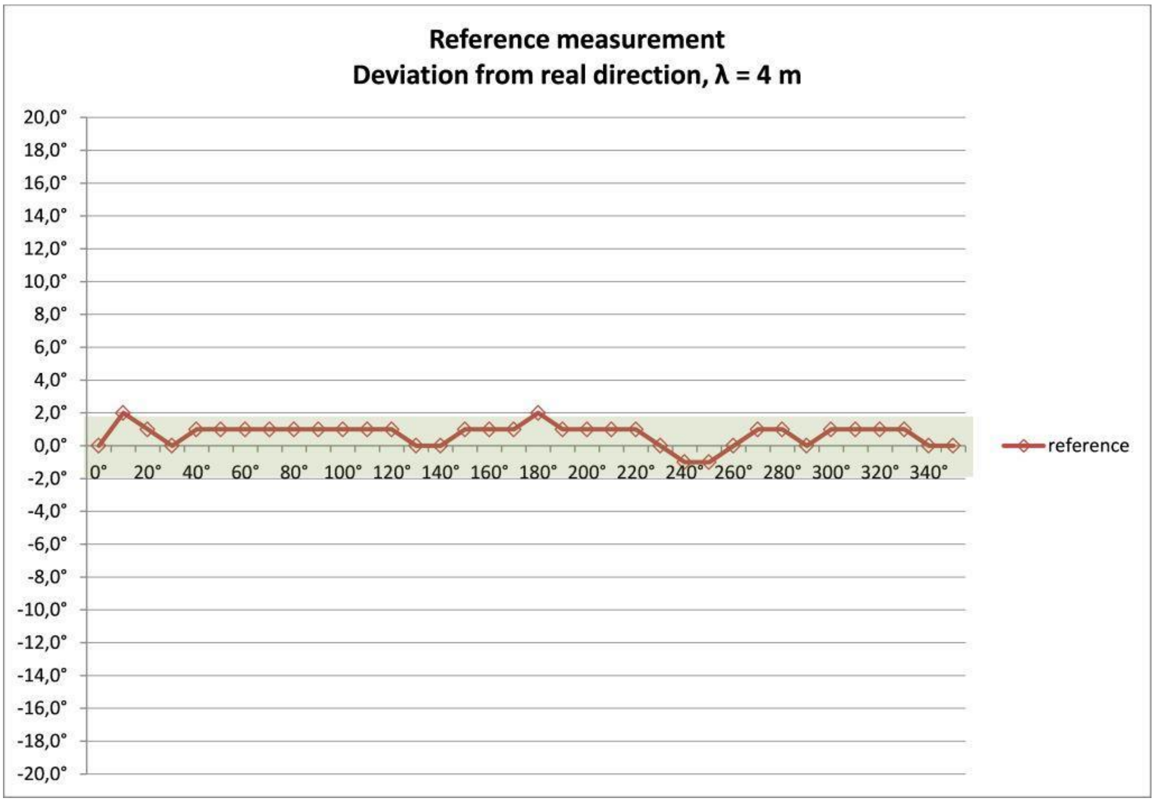
In the diagrams on the following pages, the tolerance range for the radio monitoring and inspection service's fixed direction finders is highlighted in colour. Above all, this is calculated on the basis of the DF system specifications pursuant to § 4.2 and the effects of DF errors pursuant to § 1.

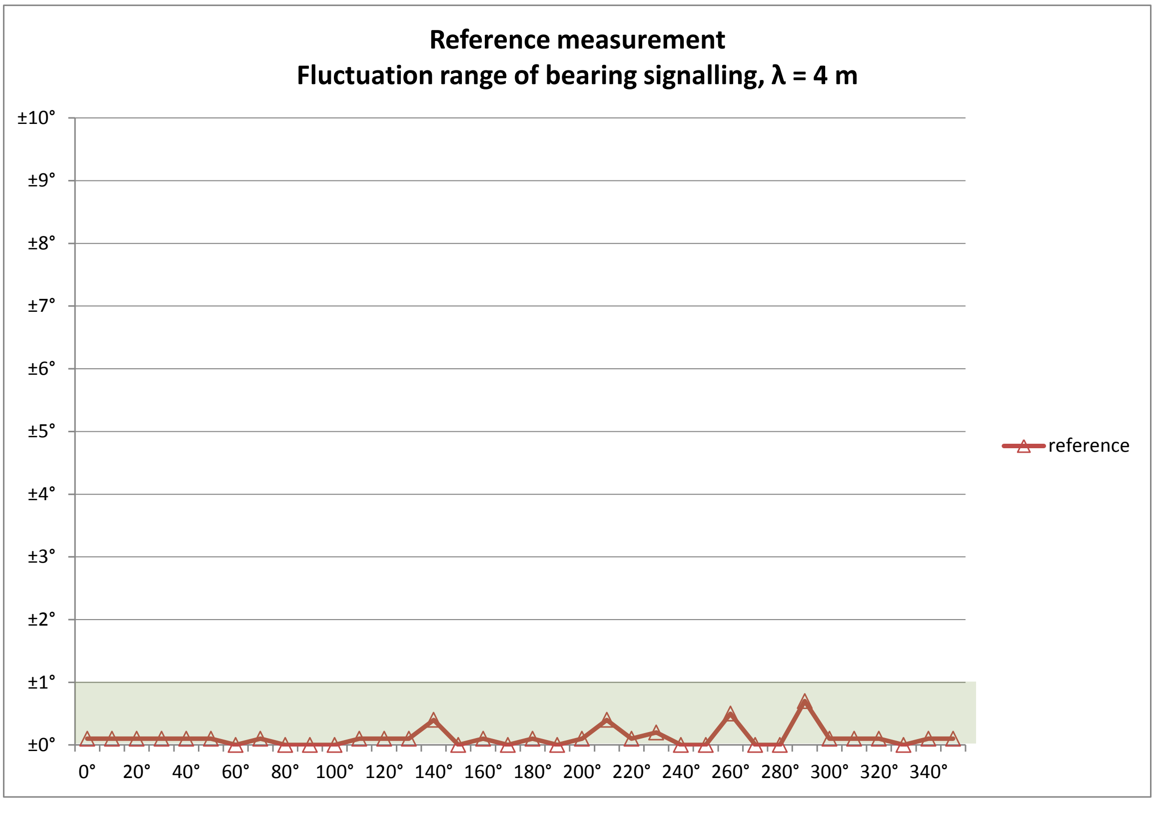
As mentioned previously, fixed radio direction finders must be mounted on masts of a sufficient height which are situated in an unobstructed setting in order to fulfil their function. With this in mind, the challenge then lay in reproducing these conditions using a portable measurement set-up such that, with limited outlay, it was possible to conduct investigations the results of which can be applied to fixed direction finders.

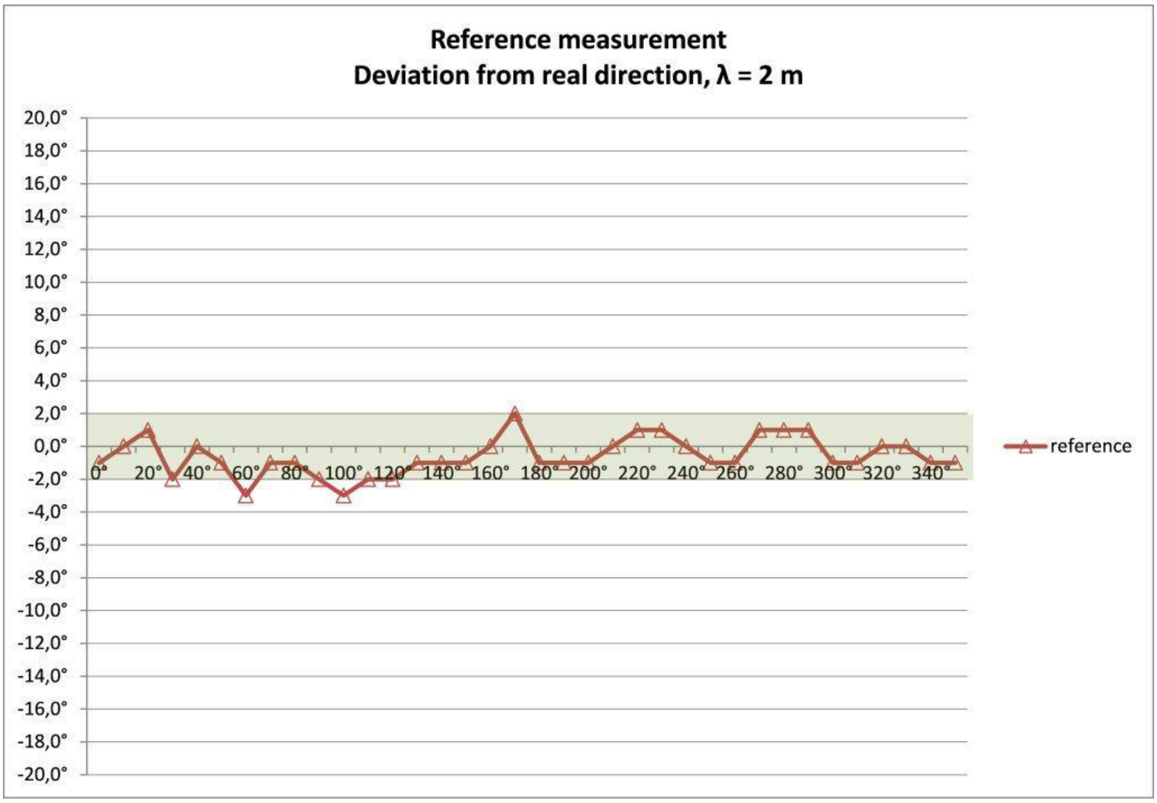
Taking reference measurements in the open countryside near Kerken

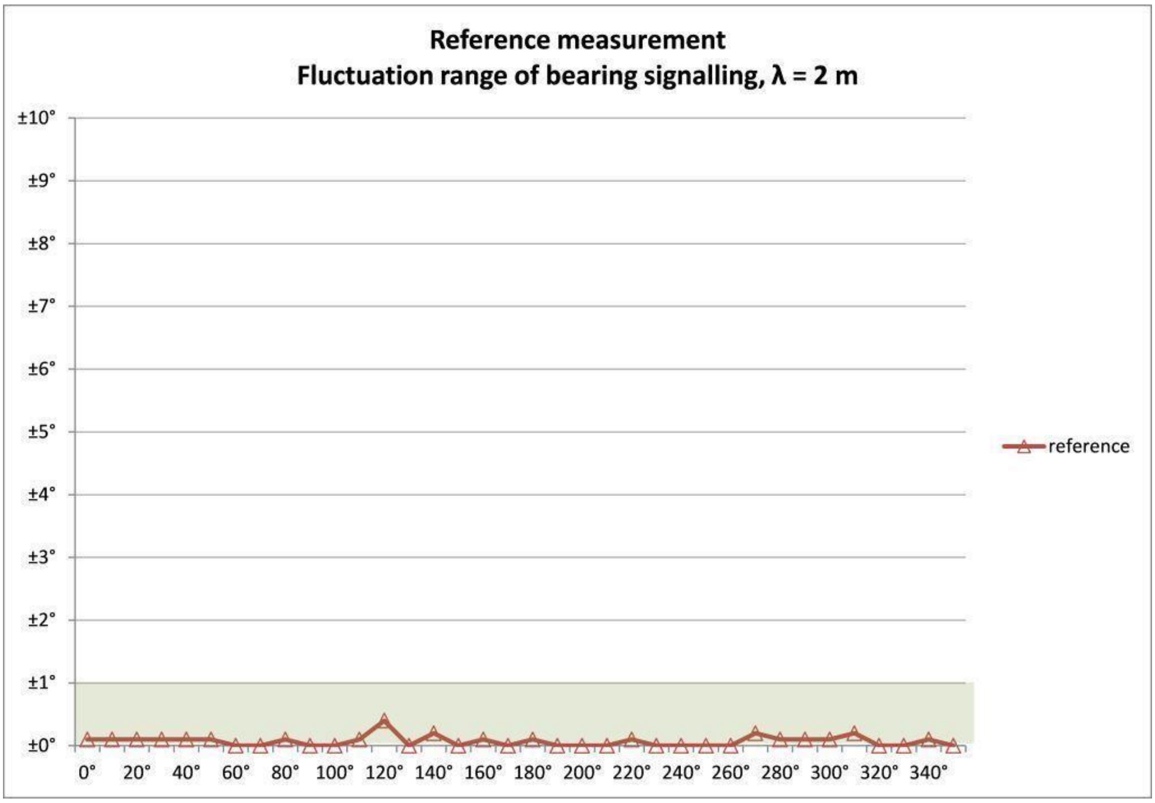
9.1.1 VHF/UHF

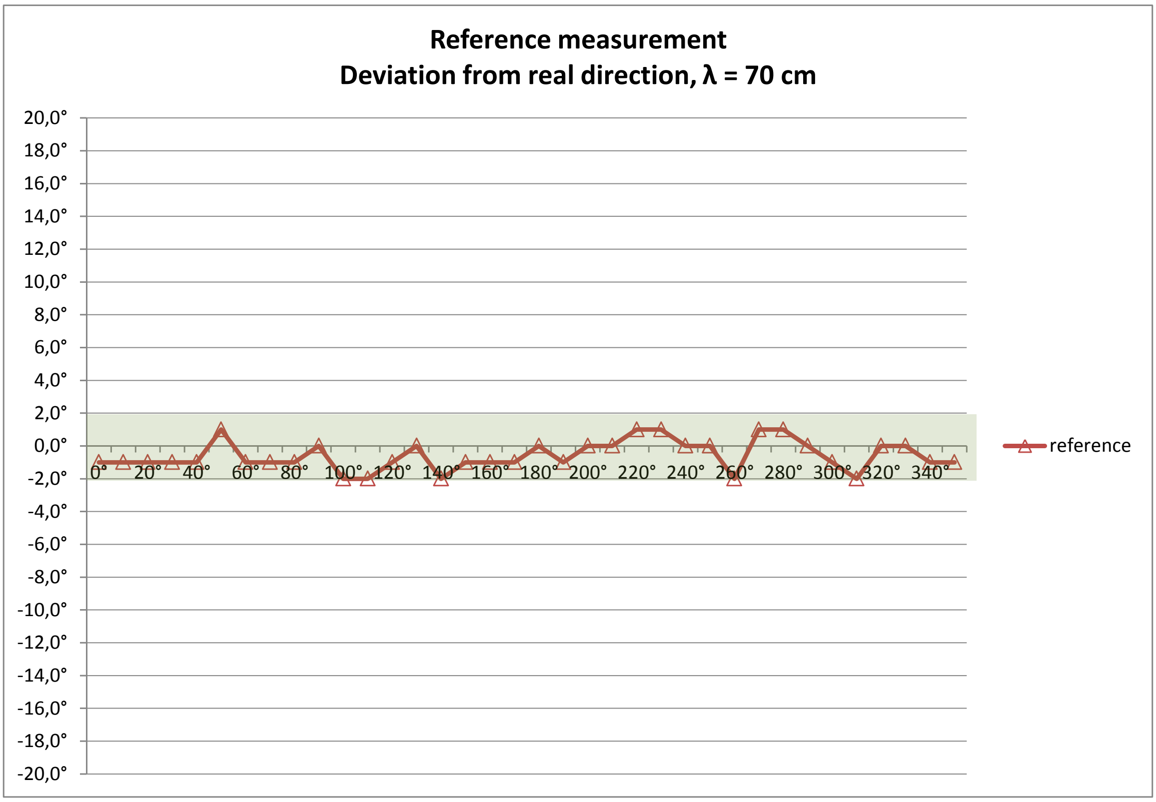
A reference measurement pursuant to § 4.2 was used to verify the measurement set-up. The results are presented below.

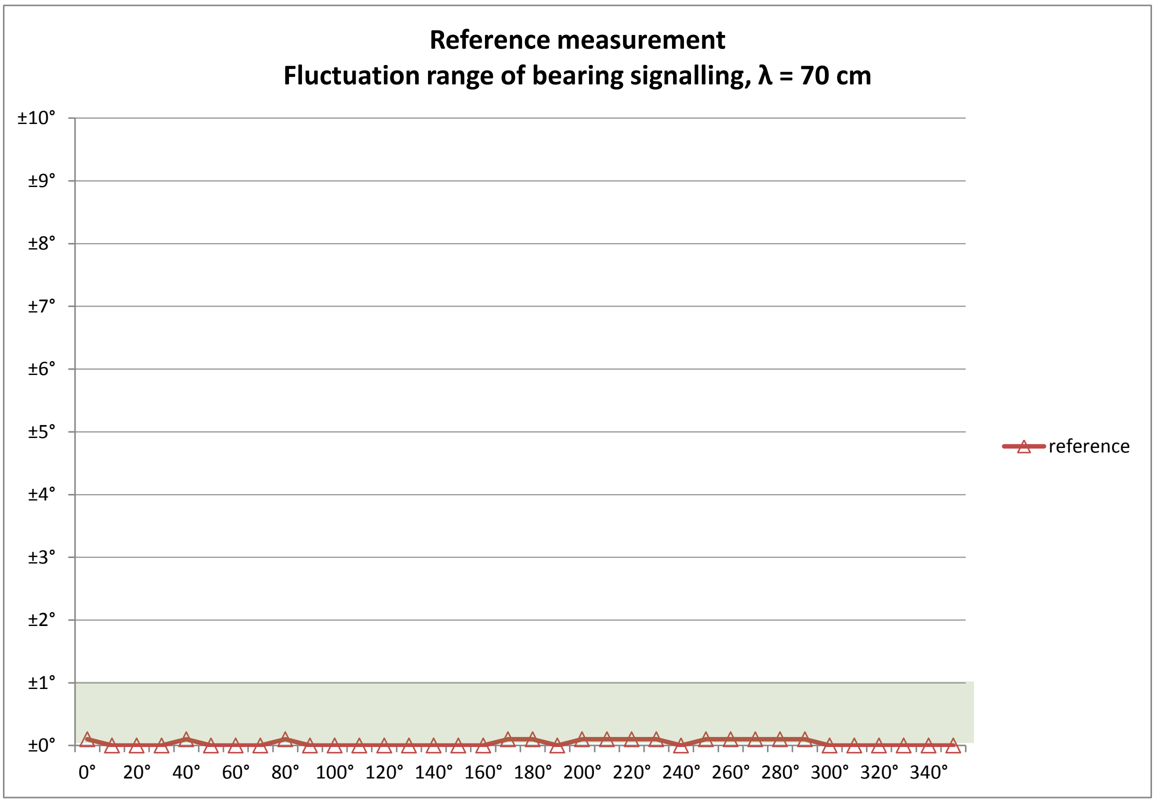


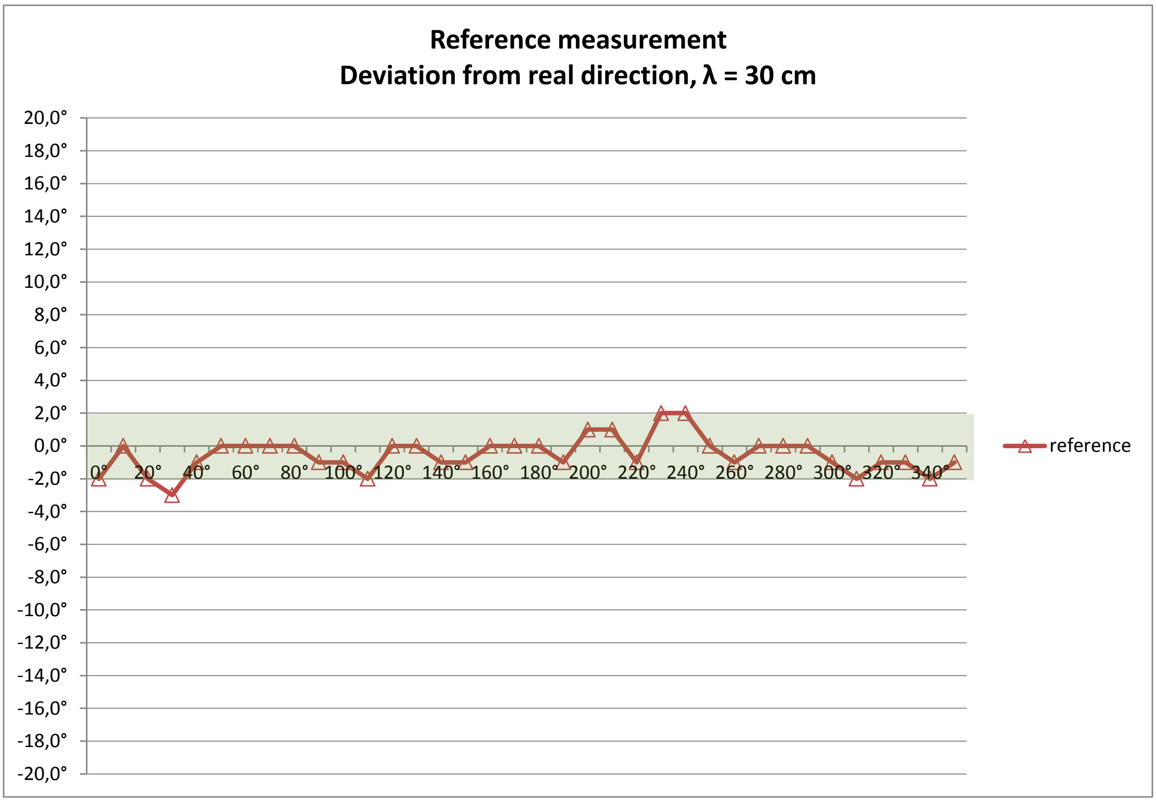


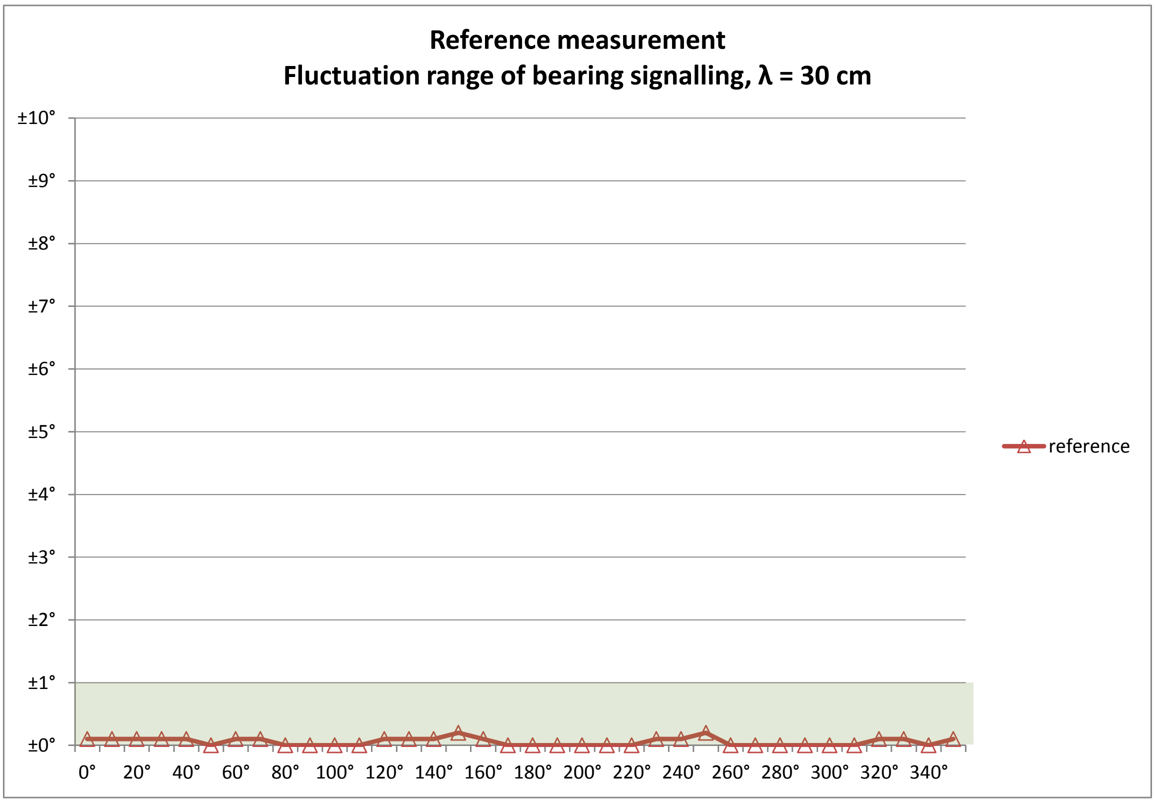

Reference measurement
Deviation from real direction, λ = 2 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference

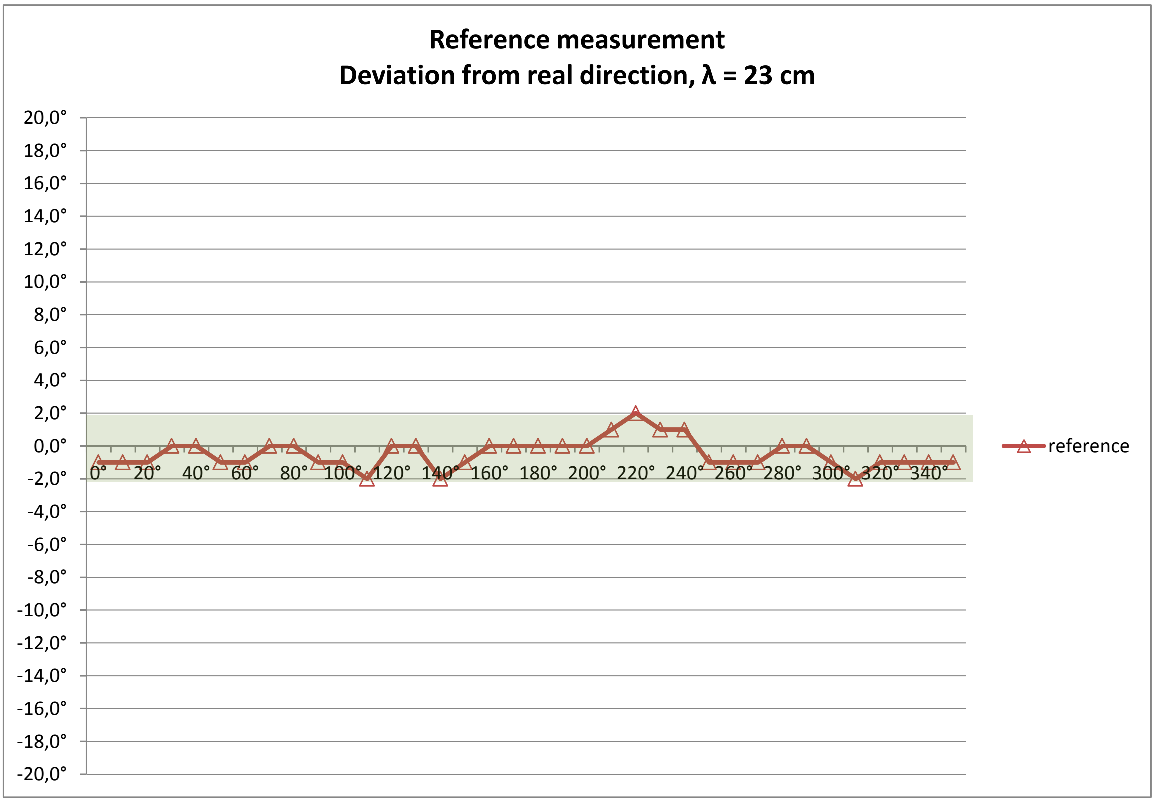

Reference measurement
Fluctuation range of bearing signalling, λ = 2 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference

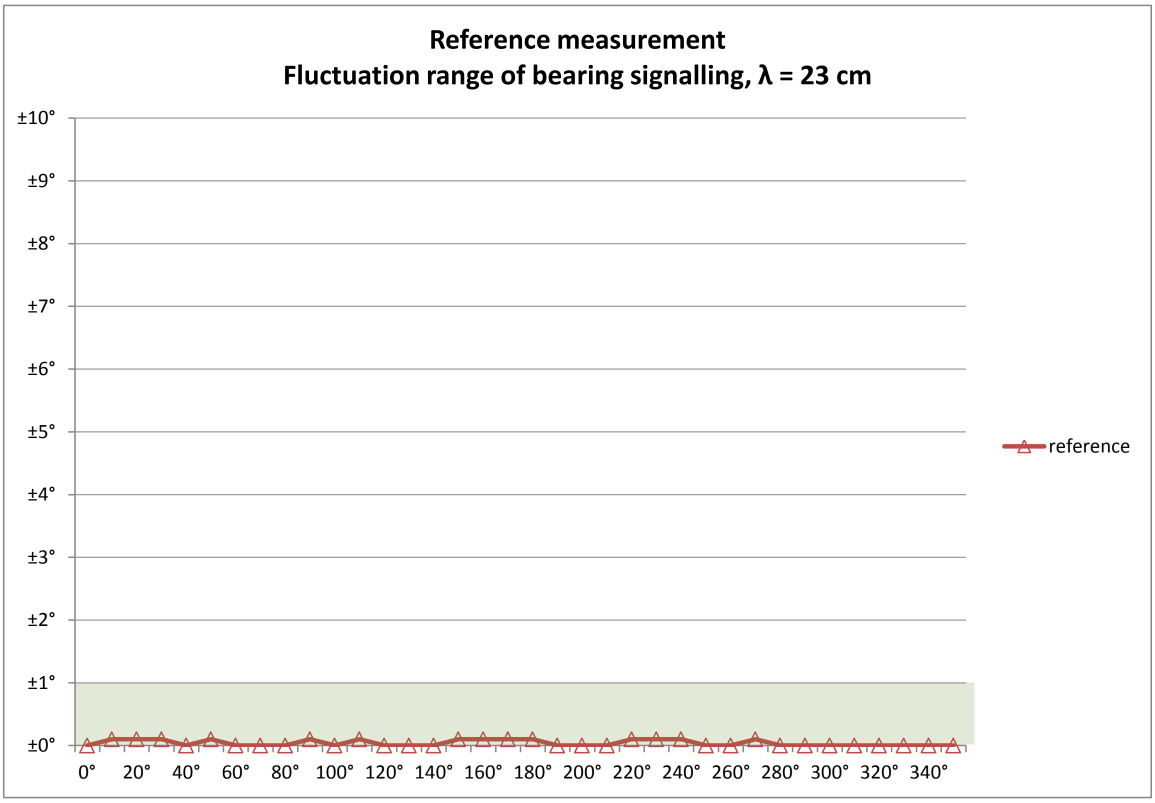

Reference measurement
Deviation from real direction, λ = 70 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference

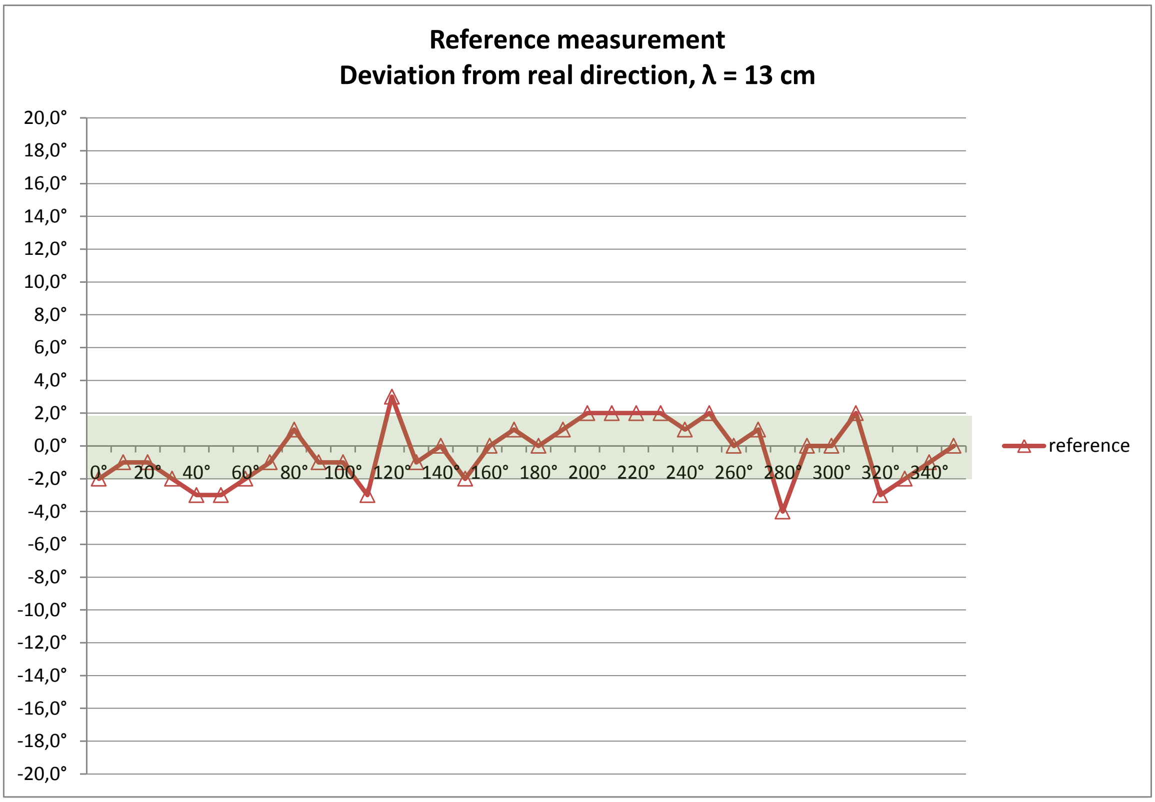

Reference measurement
Fluctuation range of bearing signalling, λ = 70 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference

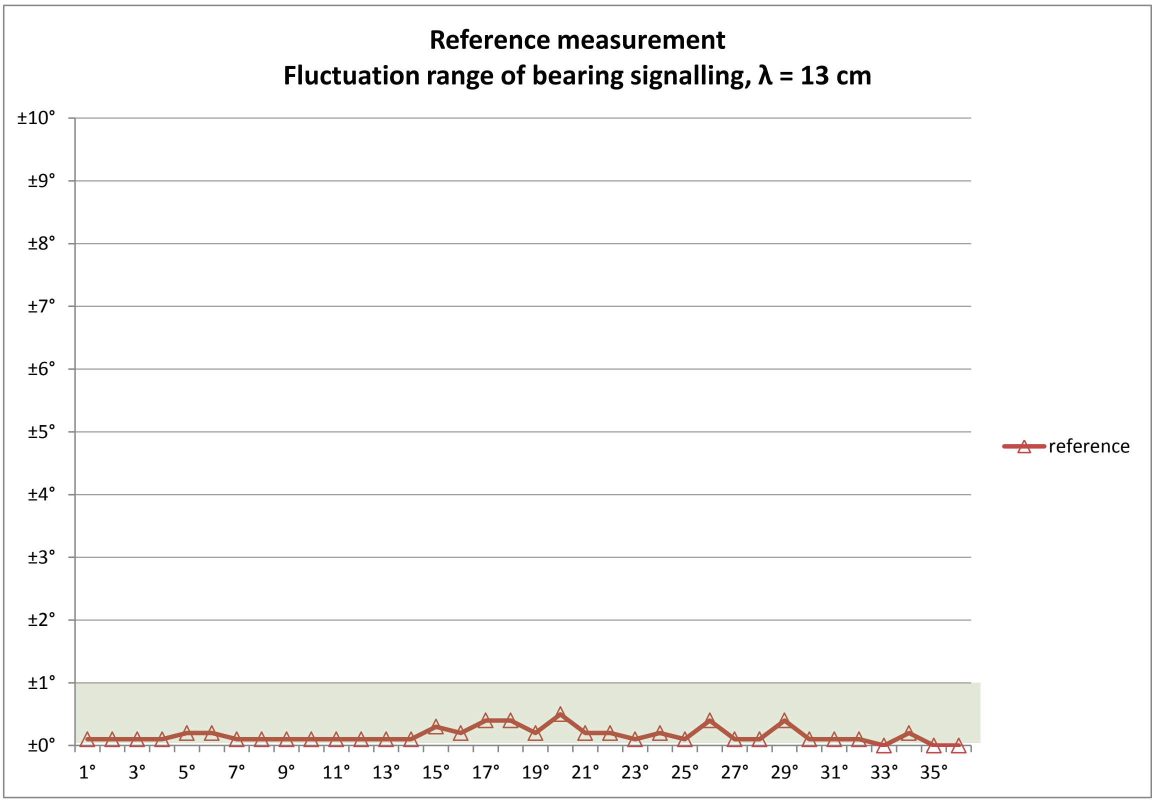

Reference measurement
Deviation from real direction, λ = 30 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference


Reference measurement
Fluctuation range of bearing signalling, λ = 30 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference


Reference measurement
Deviation from real direction, λ = 23 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
220°
240°
260°
280°
300°
320°
340°
reference


Reference measurement
Fluctuation range of bearing signalling, λ = 23 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
220°
240°
260°
280°
300°
320°
340°
reference





In the 4 m, 2 m, 70 cm, 30 cm and 23 cm frequency bands, the resulting measurements were mostly within the tolerance range for fixed direction finders. Only in the 2 m and 30 cm frequency bands was the tolerance range exceeded slightly by 1° in individual directions. Even in the 13 cm band, which is especially critical owing to its short wavelength, the tolerance range was only exceeded once by 2° and in two directions by 1°.

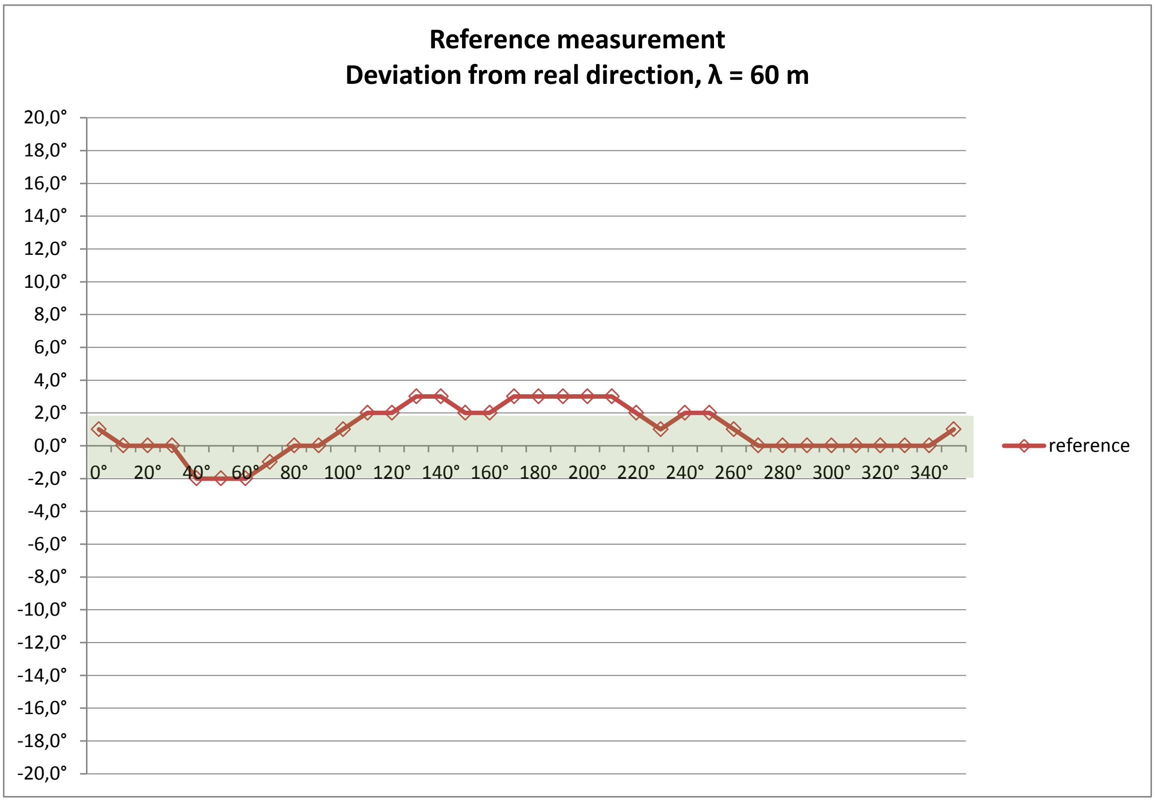
Without exception, the margin of fluctuation of bearing indications, which is important for the evaluation of DF results, is within the tolerated range.

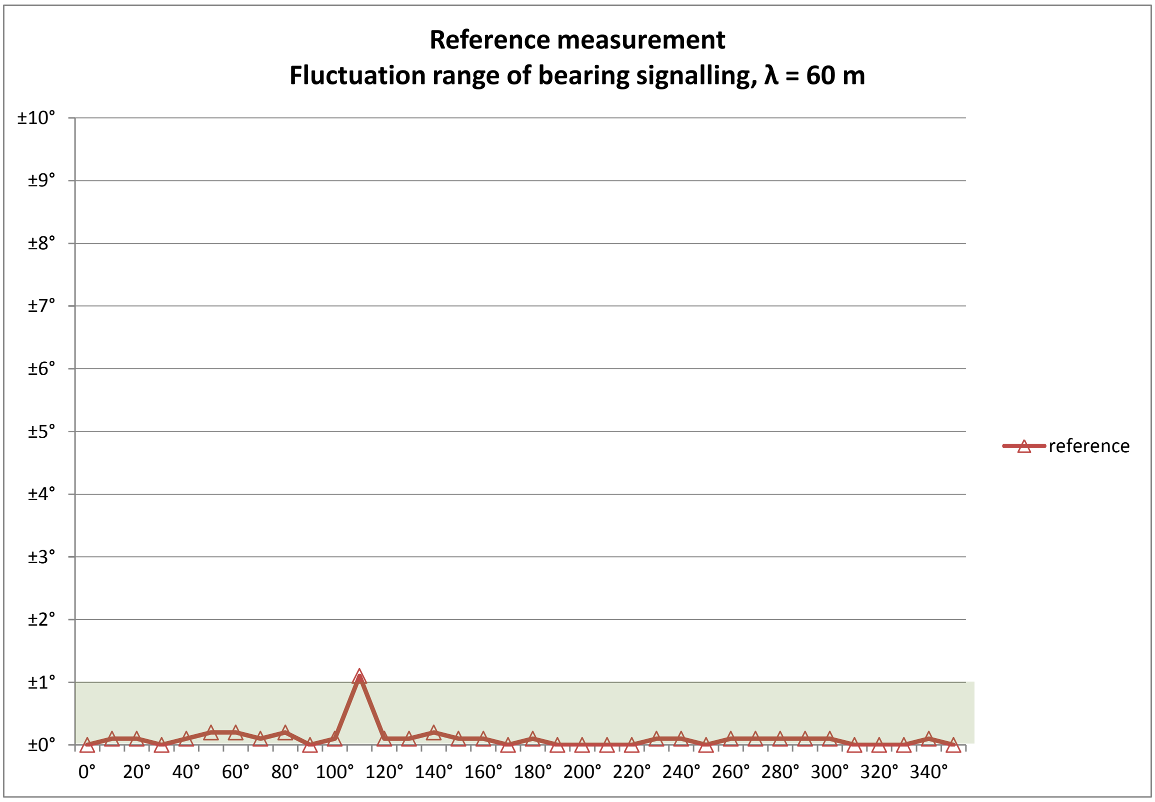
The measurement set-up can therefore be used to carry out the intended investigations.

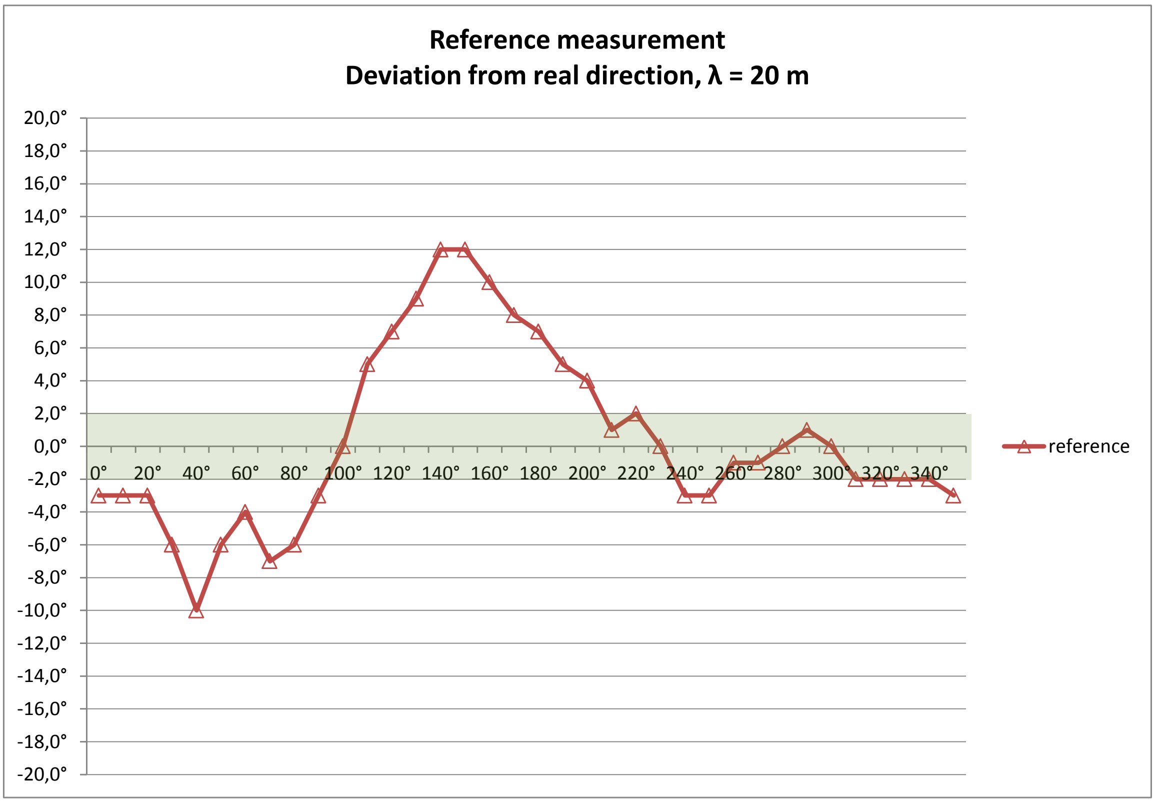
9.1.2 HF

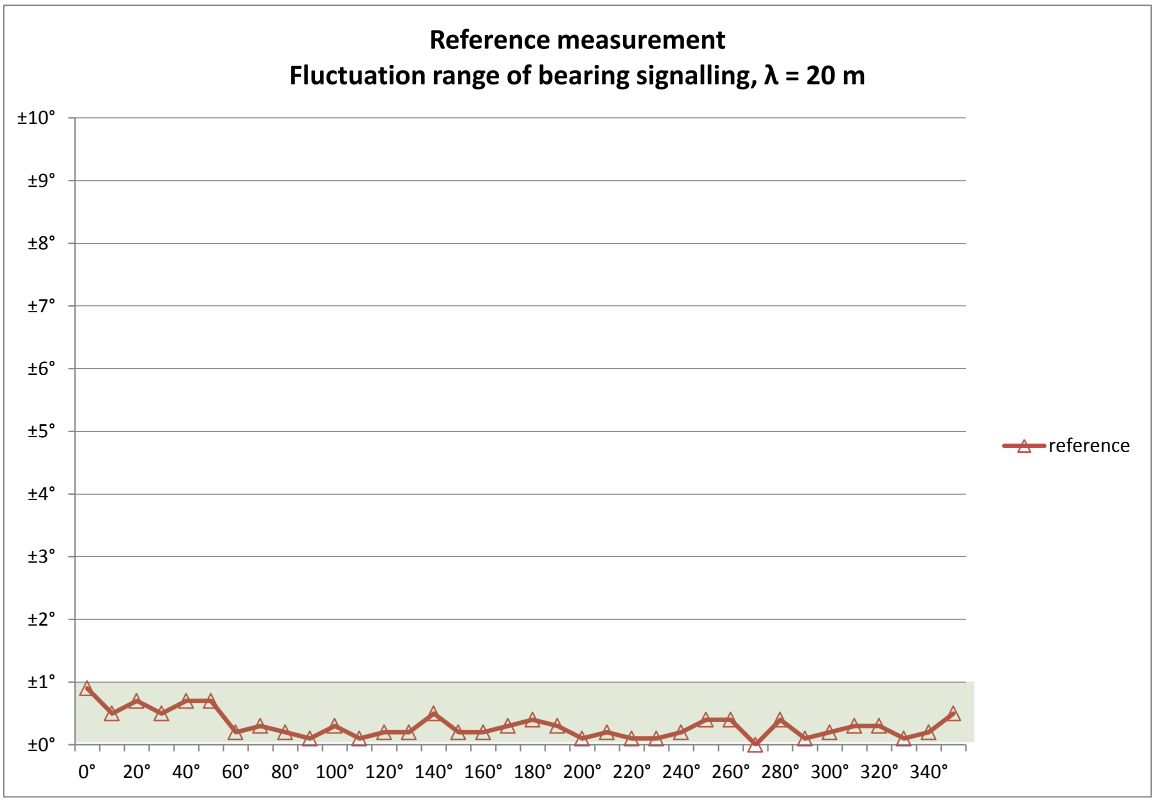
The contracting entity also requested that information be collected for the HF range, which covers a frequency range of 3 … 30 MHz and thus a wavelength range of 80 m … 10 m. As the size of antennas is heavily dependent on the intended operating wavelength, large antennas are required for physical reasons in the HF range and these are not compatible with a portable/mobile measurement approach. Technical tricks can be used to reduce the antenna size. However, this leads to a reduction in radiation efficiency and potentially to a distorted radiation pattern. Further influences may result from the emission of radiation from the measurement set-up (cables, etc.), which leads to horizontal radiation components, which could affect the functioning of the direction finder.

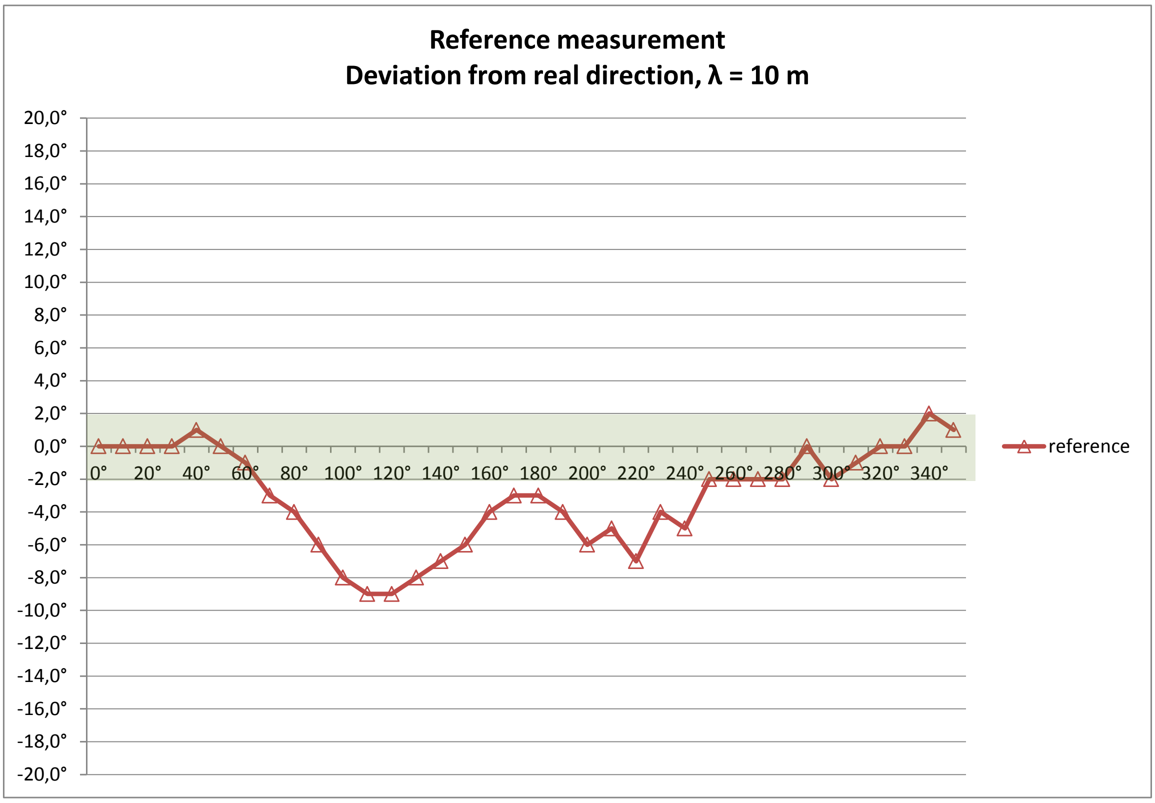
Reference measurements for the HF range were therefore also taken for the measurement set-up pursuant to § 5. The results are presented below:

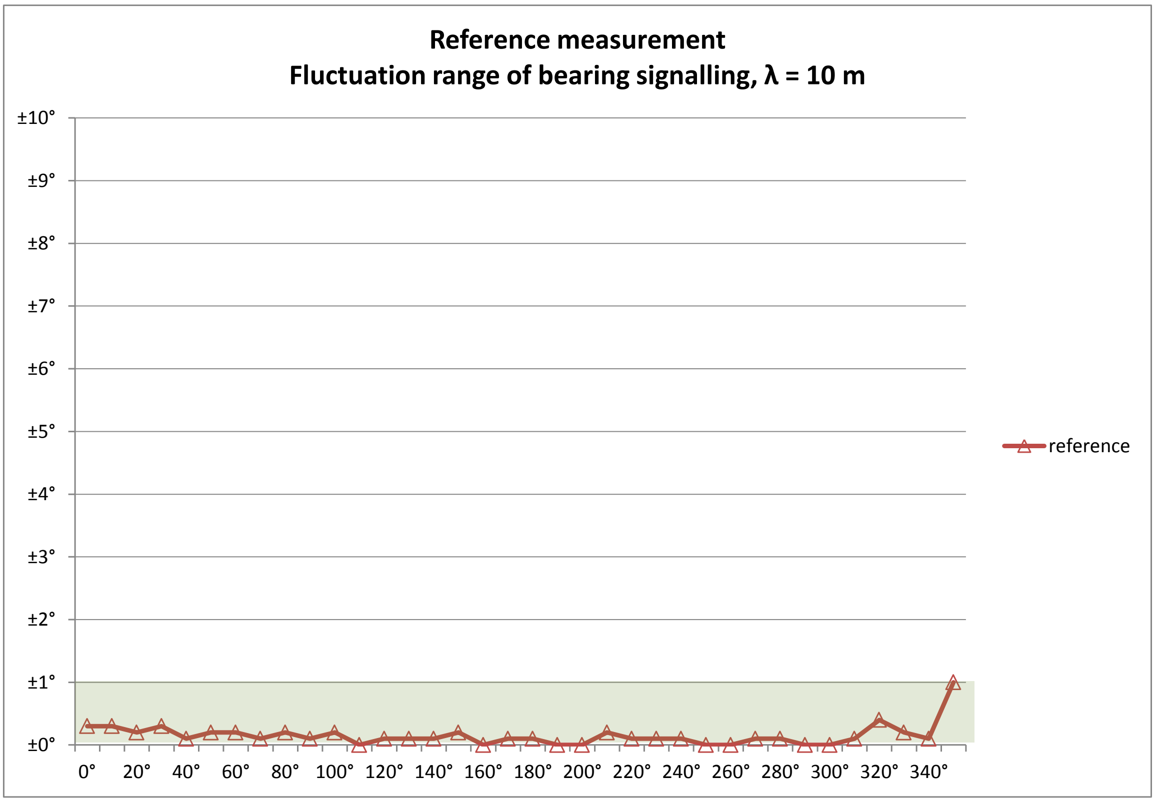



Reference measurement
Fluctuation range of bearing signalling, λ = 60 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference


Reference measurement
Deviation from real direction, λ = 20 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference


Reference measurement
Fluctuation range of bearing signalling, λ = 20 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference


Reference measurement
Deviation from real direction, λ = 10 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
reference



For the 60 m band, the deviations in DF values were largely within the tolerated range, with values exceeding just 1°. In the 20 m band, however, the tolerance range was exceeded by up to 10° and in the 10 m band by up to 7°.

Due to these significant deviations, the measurement set-up was subjected to further tests. These showed that, particularly in the 10 m band, the radiation pattern differed substantially from the desired omnidirectional radiation pattern, with a clear preferred direction above the front of the vehicle and a minimum to the rear of the vehicle.

A non-resonant vertical earth (ground)-symmetrical transmitting antenna must be used in connection with the mobile measurement set-up. The radiation efficiency of such an antenna is poor and heavily dependent on the counterpoise (earth or conductive vehicle body). As described in § 5.2, when mounting the antenna on the rear of the vehicle, a highly conductive counterpoise (ground plane) is required to the front of the vehicle (in front of the antenna), with no counterpoise behind the antenna (in the direction away from the direction of travel) or to the sides. In the 10 m band, the size of the counterpoise to the front of the vehicle extends half a wavelength and, in the 20 m band, it extends one quarter of a wavelength, thus increasing the radiation efficiency and therefore the antenna gain to the front of the vehicle.

In the upper HF range, the omnidirectional radiation pattern is therefore no longer present; consequently, the direction finder can no longer function properly in a severely distorted radiation field. It is likely that the occurrence of reflections caused by objects which are further away have a particularly marked effect due to the dampened direct wave radiated transversely to the vehicle.

In the 60 m band, the counterpoise of the vehicle roof only extends approximately 8% of the wavelength and is therefore only marginally effective. The resulting radiation efficiency is therefore more or less equally poor in all directions, with an omnidirectional radiation pattern influenced only by the surrounding earth. For the purposes of this investigation, the poor radiation efficiency can be compensated for without any detrimental effect by higher transmitter power. It can be assumed that the characteristics of the earth are largely consistent, both at the reference measurement location and in the Rütenbrooker Moor area.

The authors would also like to underline that fixed short-wave direction finders work with sky waves (hence the safety cone described in § 1), whereas a mobile measurement set-up works with ground waves. Therefore, the results are not directly transferable to a fixed short-wave direction finder. Because the measurements for the 60 m band nonetheless provide an insight into whether a safety distance is required at all, only the results for the 60 m band are presented below.

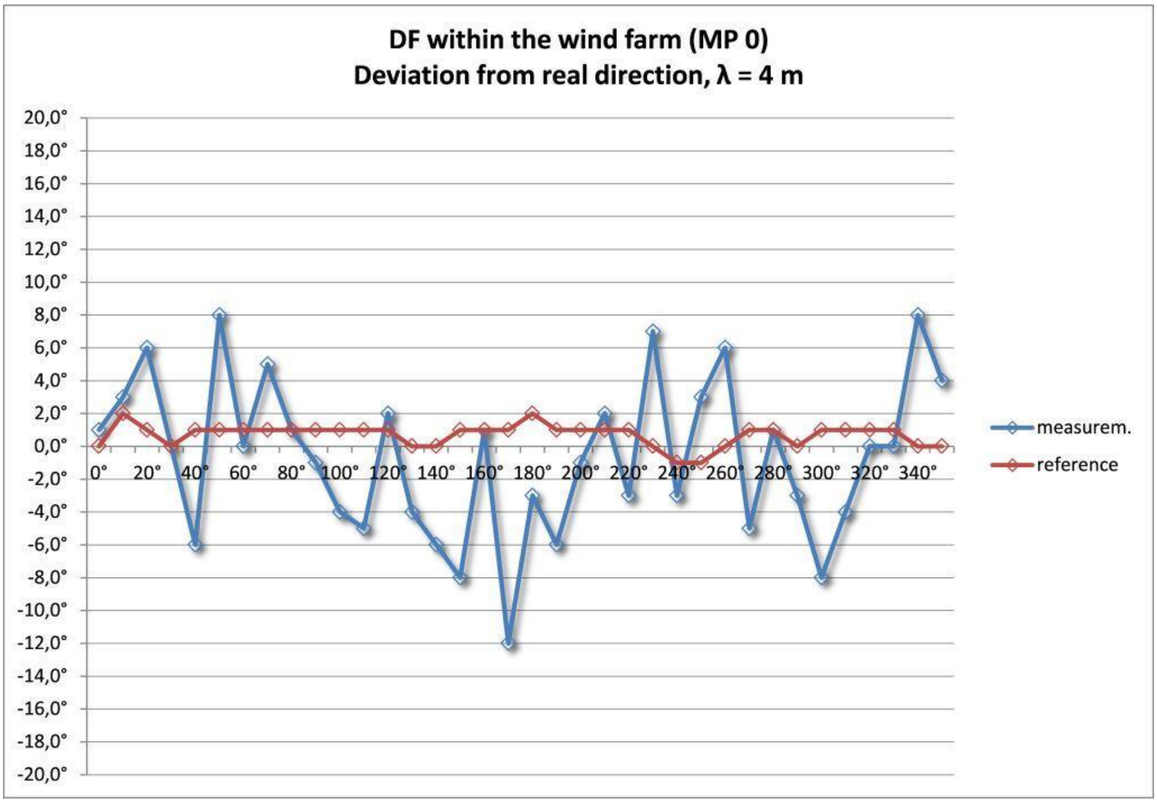
9.2 Measurement series

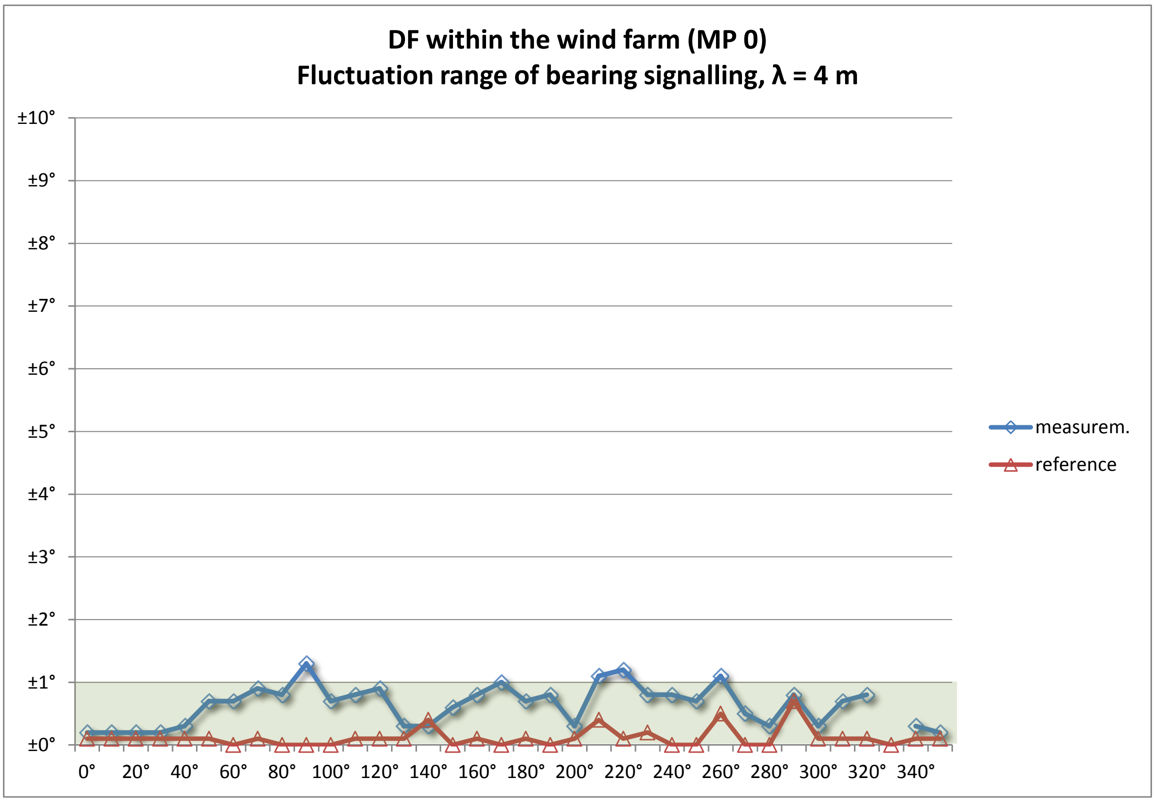
The first set of measurements addressed the question of which influences a radio direction finder is exposed to when situated in the centre of a wind farm in proximity to wind turbines in all four DF quadrants. To this end, the direction finder was set up in accordance with § 7.1. Further measurement series looked at the influences affecting a radio direction finder situated at the edge of a wind farm (wind turbines in two quadrants, see § 7.2), and a direction finder situated 2.5 km (see § 7.3, one quadrant) and 4.6 km from the wind farm (see § 7.4).

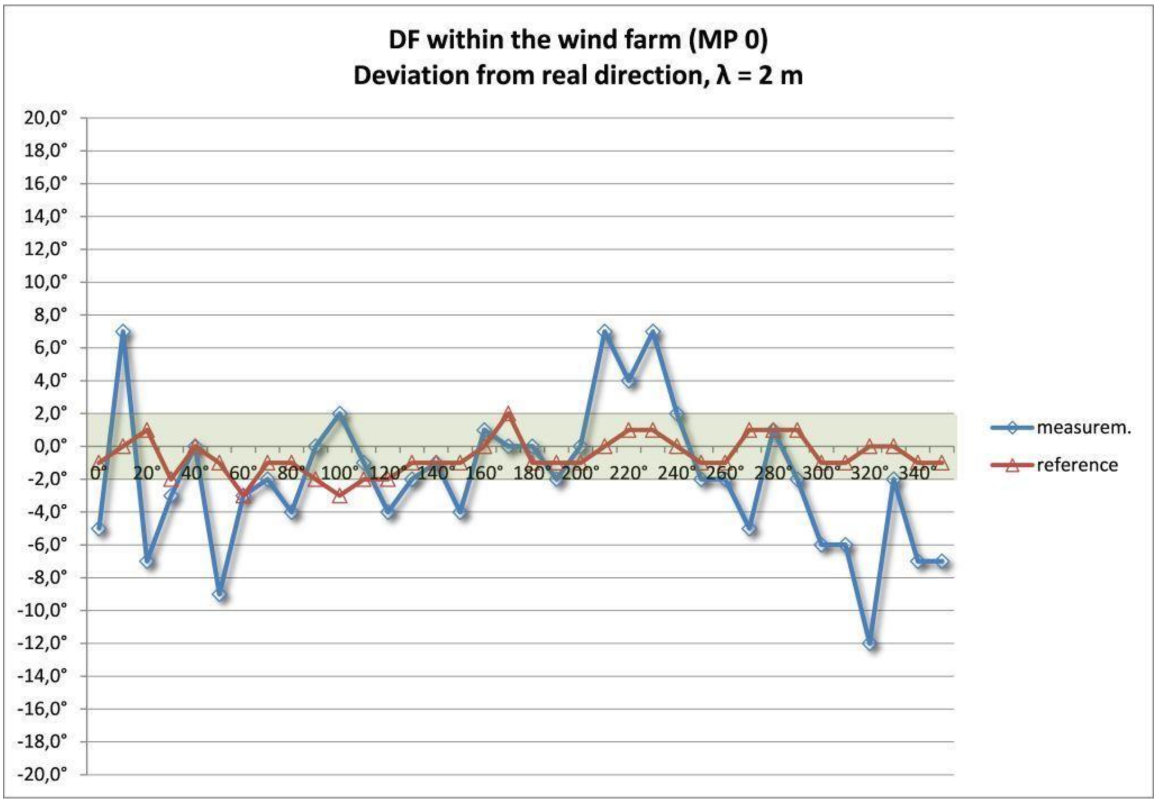
For better comparability, the diagrams below show the results of the measurement series as well as the results of the relevant reference measurements and the tolerance range.

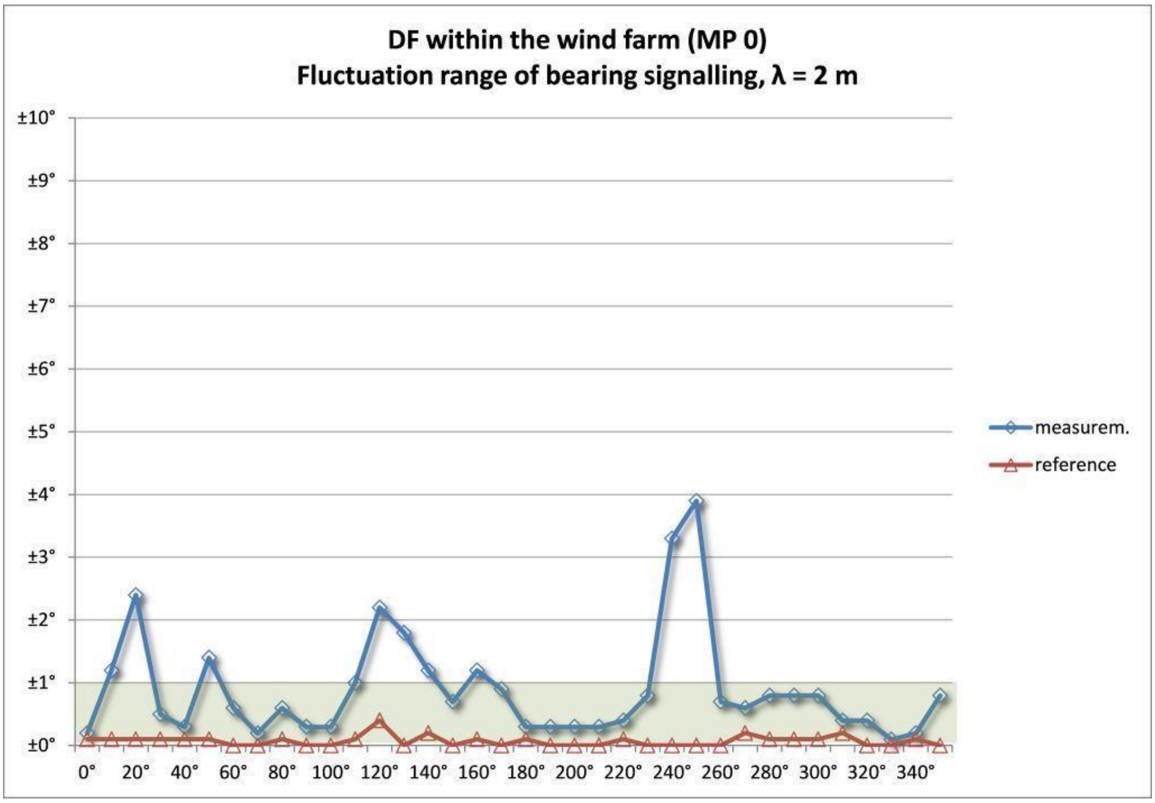
The same scale is used throughout the report to enable direct comparability of all diagrams of measured variables. This means that, where the effect exerted on the direction finder is particularly strong, the absolute size of the bearing deviation may be no longer visible. For the sake of comparability and diagram resolution in the relevant value range, this has been deemed acceptable. In any case, a DF result which lies outside the value area shown in the diagrams would certainly not be used for any application, which means that the exact size of the deviation is, in fact, irrelevant. Deviations in the bearing indication of >20° from the true value are therefore known as rotary bearings, especially when these are also accompanied by marked fluctuations in the bearing indication.

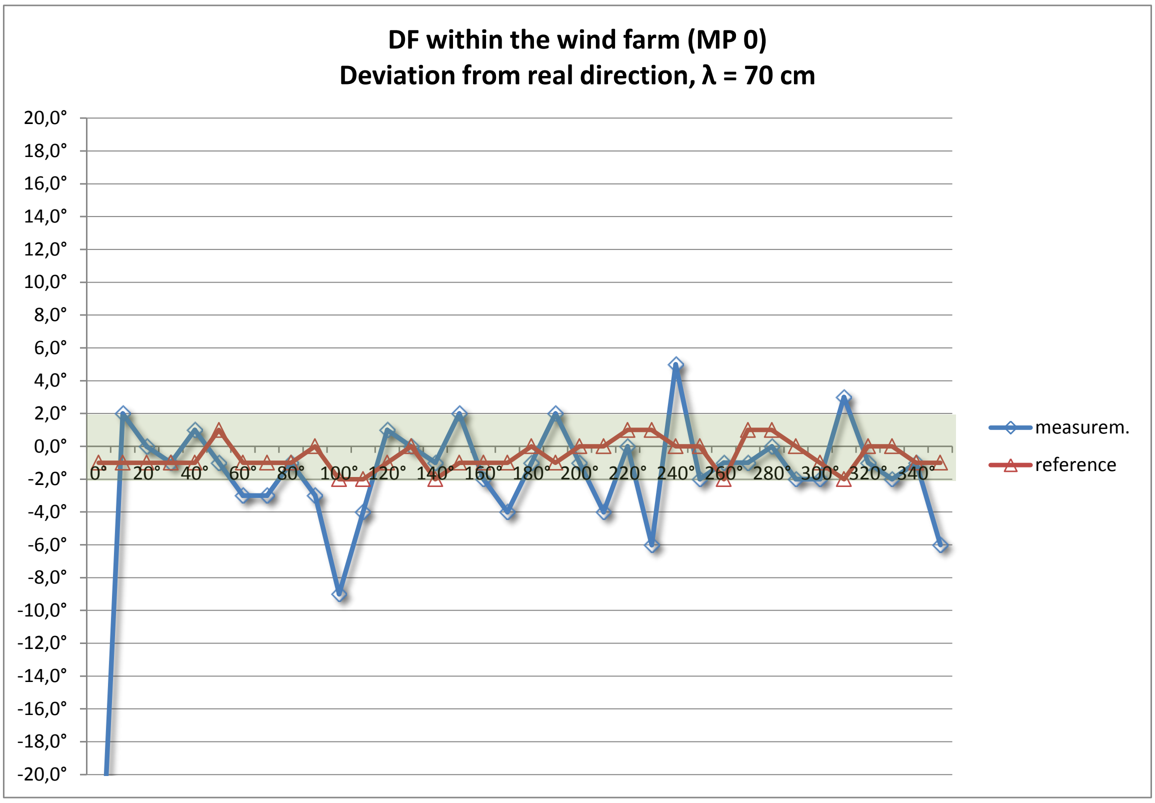
9.2.1 Radio direction finder situated within the wind farm

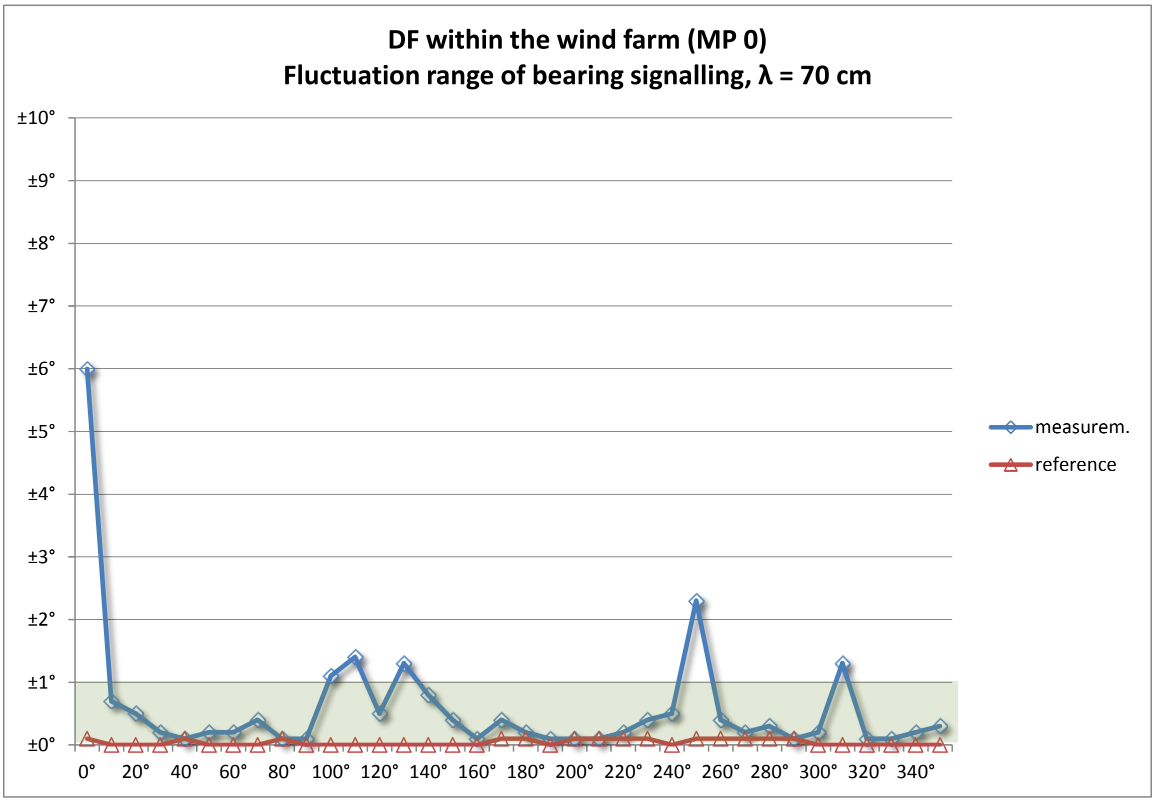


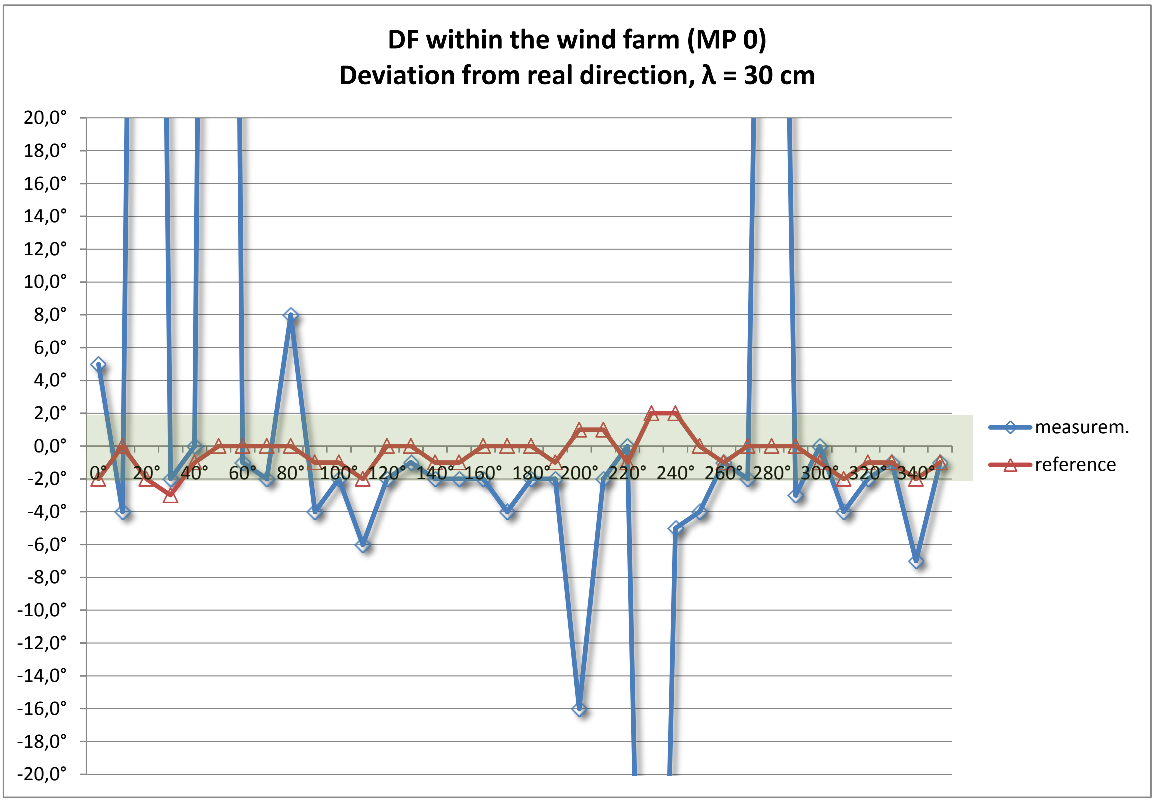

DF within the wind farm (MP 0)
Fluctuation range of bearing signalling, λ = 4 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
220°
240°
260°
280°
300°
320°
340°
measurem.
reference

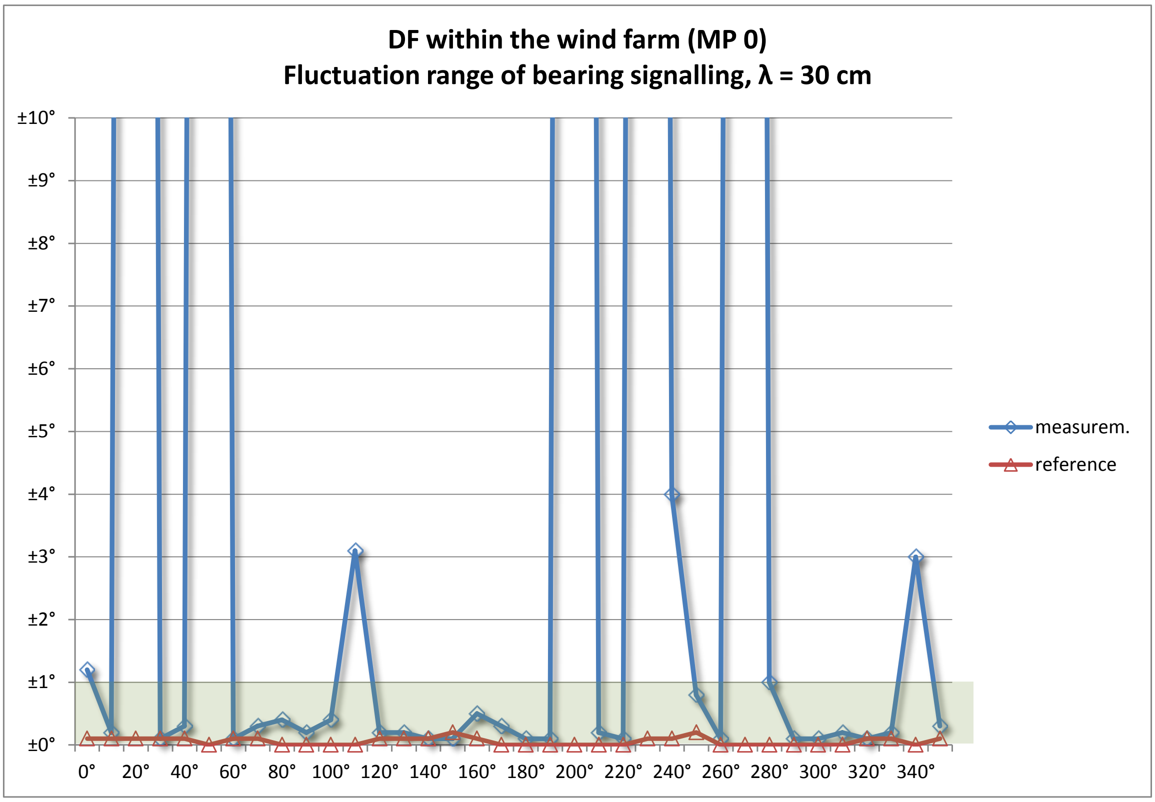

DF within the wind farm (MP 0)
Deviation from real direction, λ = 2 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
220°
240°
260°
280°
300°
320°
340°
measurem.
reference

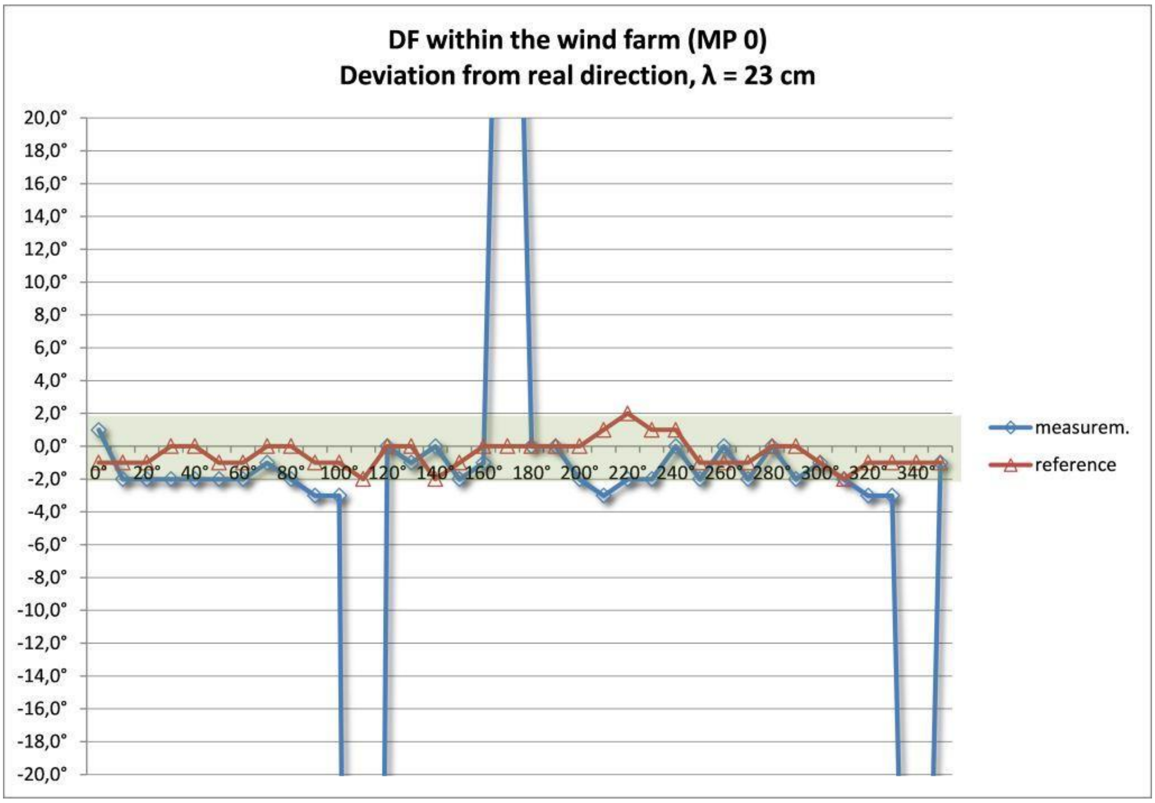

DF within the wind farm (MP 0)
Fluctuation range of bearing signalling, λ = 2 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

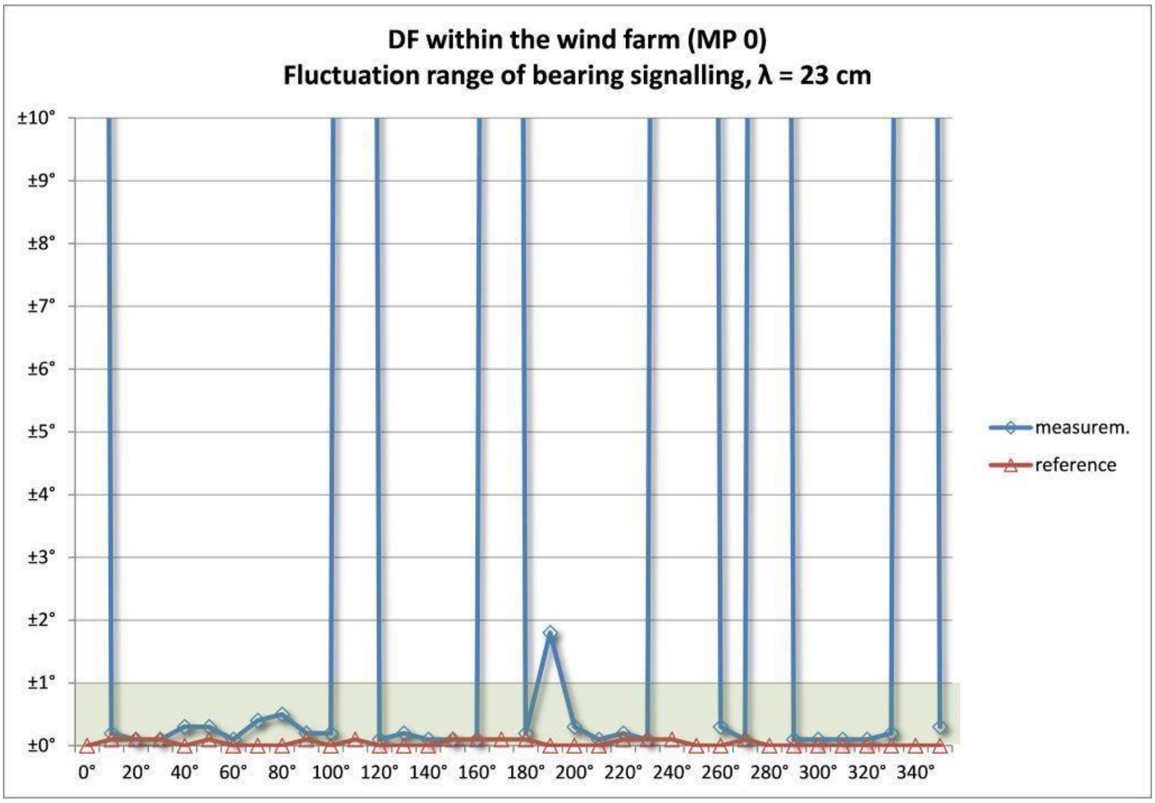

DF within the wind farm (MP 0)
Deviation from real direction, λ = 70 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

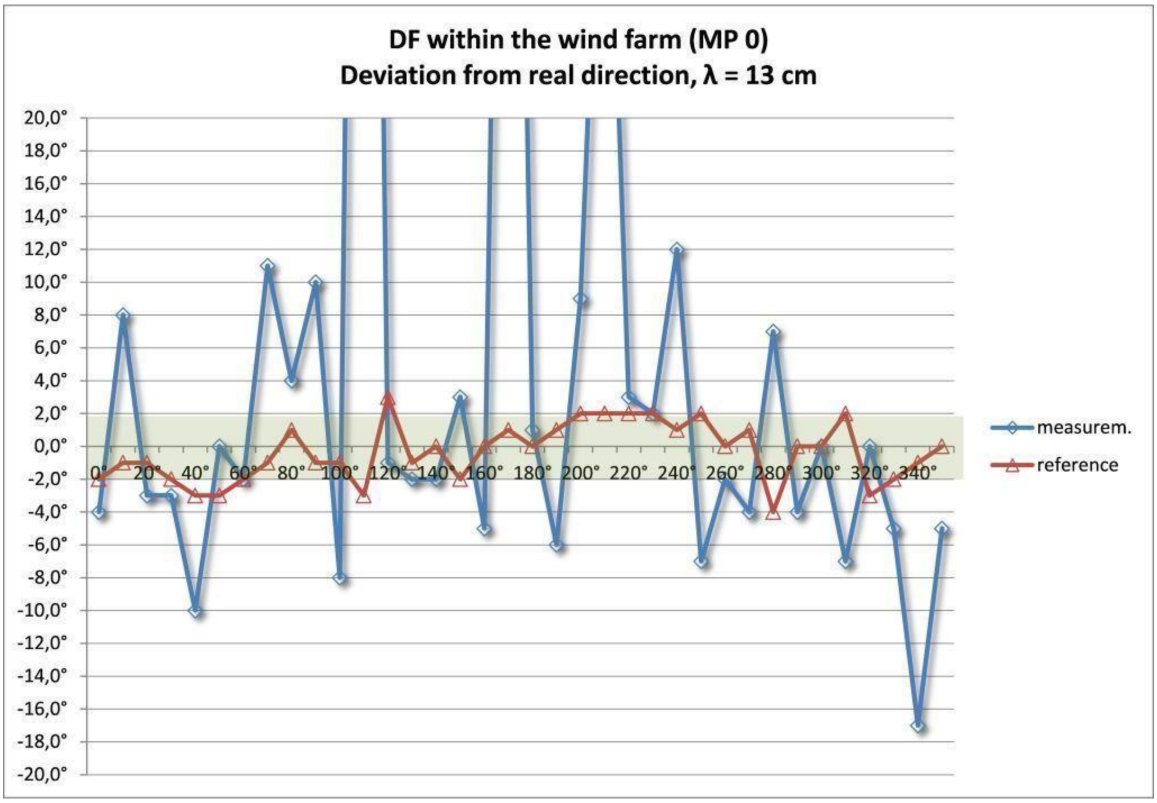

DF within the wind farm (MP 0)
Fluctuation range of bearing signalling, λ = 70 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

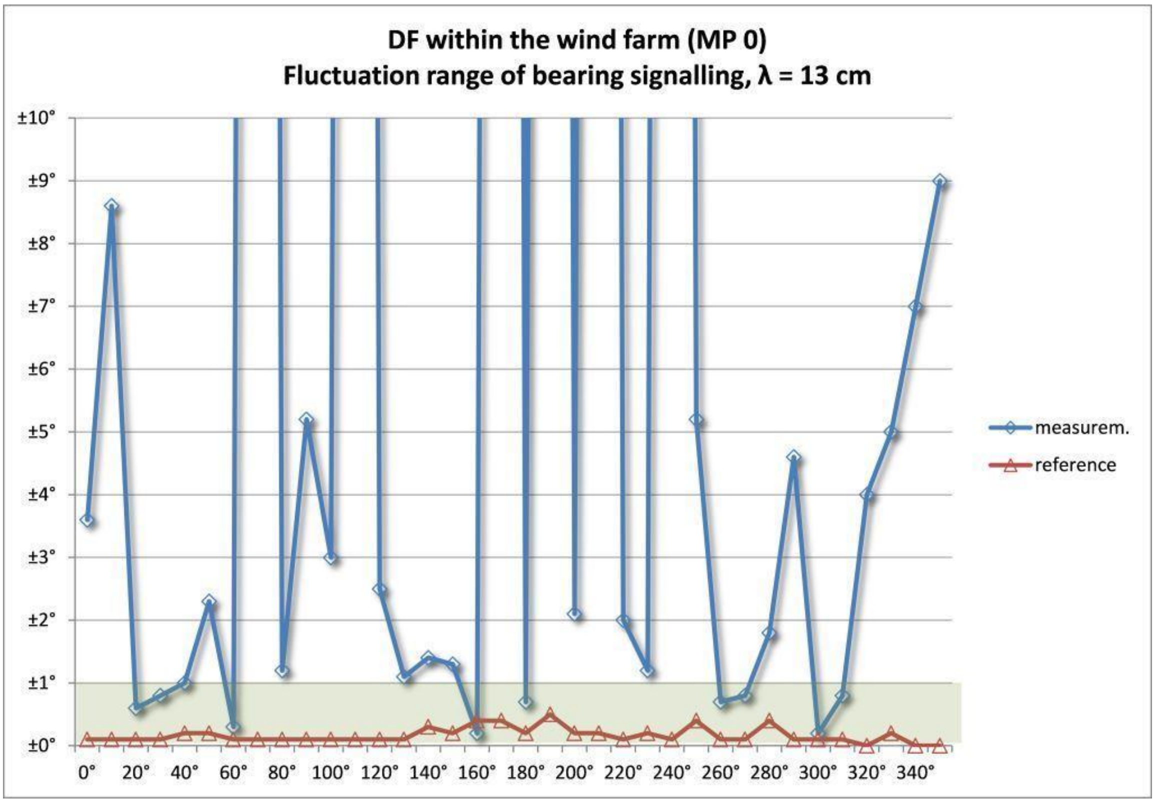

DF within the wind farm (MP 0)
Deviation from real direction, λ = 30 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

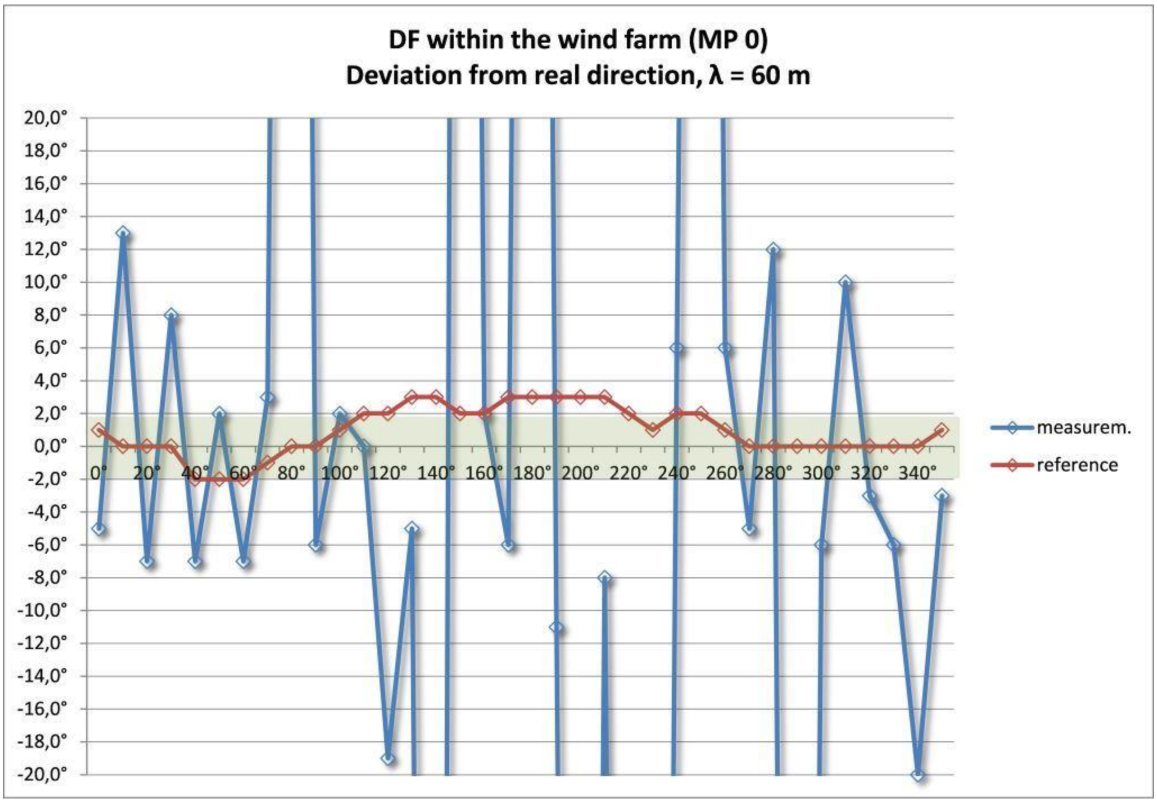

DF within the wind farm (MP 0)
Fluctuation range of bearing signalling, λ = 30 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

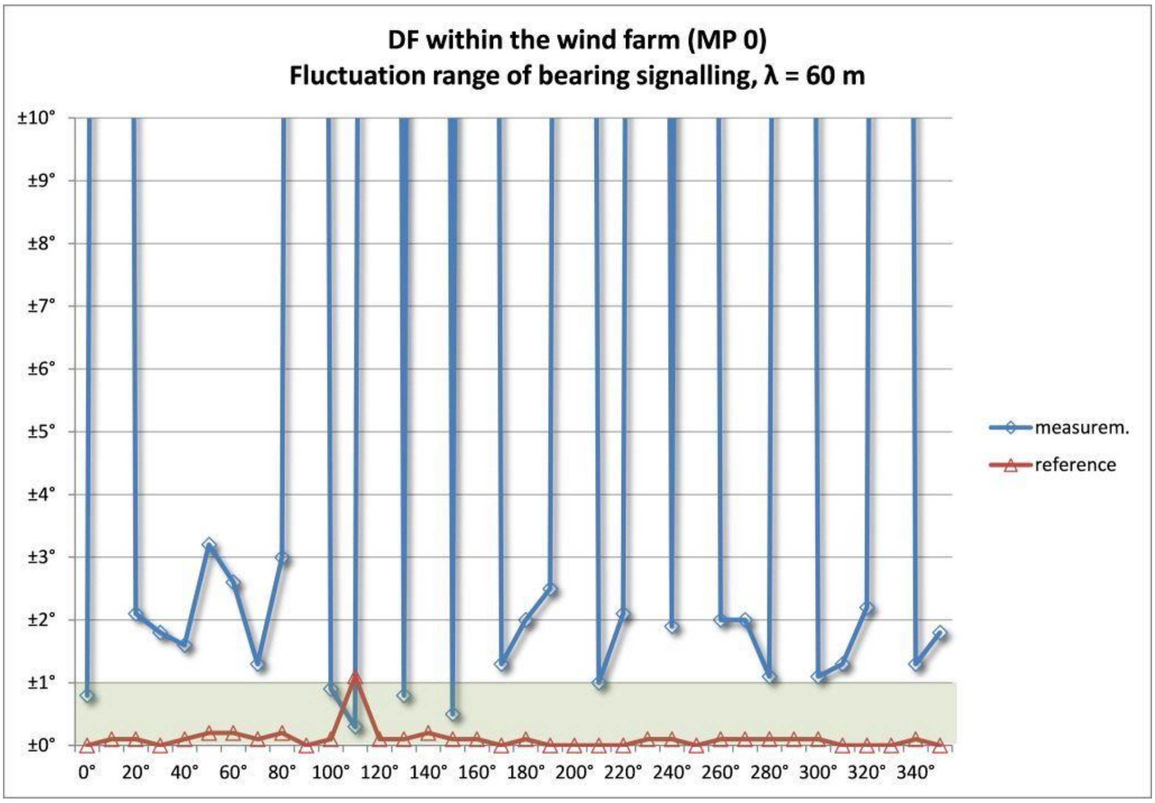

DF within the wind farm (MP 0)
Deviation from real direction, λ = 23 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF within the wind farm (MP 0)
Fluctuation range of bearing signalling, λ = 23 cm
±10° ±9° ±8° ±7° ±6° ±5° ±4° ±3° ±2° ±1° ±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF within the wind farm (MP 0)
Deviation from real direction, λ = 13 cm
20,0° 18,0° 16,0° 14,0° 12,0° 10,0° 8,0° 6,0° 4,0° 2,0° 0,0° -2,0° -4,0° -6,0° -8,0° -10,0° -12,0° -14,0° -16,0° -18,0° -20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF within the wind farm (MP 0)
Fluctuation range of bearing signalling, λ = 13 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF within the wind farm (MP 0)
Deviation from real direction, λ = 60 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference



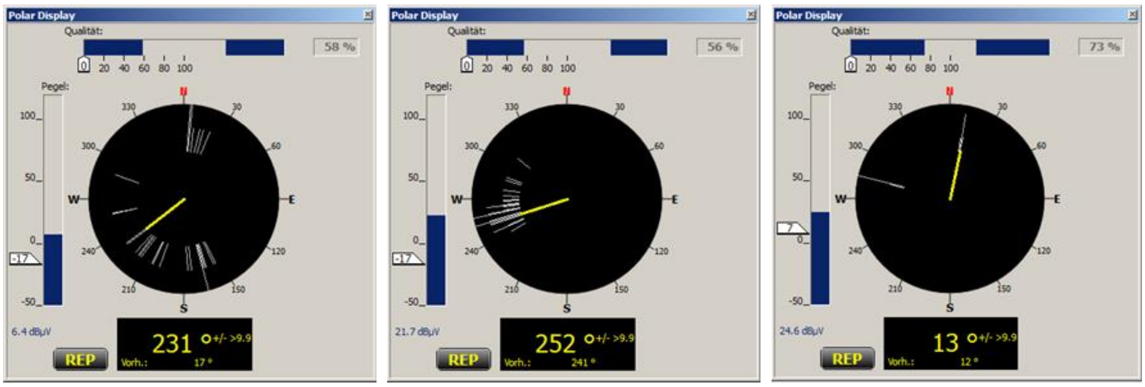
When operating the radio direction finder in a wind farm, significant DF errors were recorded in all VHF/UHF frequency bands examined. A sharp increase in the margin of fluctuation of bearing indications was also observed for wavelengths measuring less than 70 cm, which translates roughly into a frequency band of 800 MHz – 3 GHz.

In line with the physical characteristics of the different frequency bands, errors can, in the case of long wavelengths, be observed across all radials, irrespective of the actual direction to individual masts. By contrast, in the case of shorter wavelengths, interference was recorded in ever sharper angle ranges with an even more pronounced effect. In the case of very short wavelengths (13 cm band), there are so many highly distorted ranges that the radio direction finder is effectively rendered unusable in all directions.

The diagrams for the 23 cm band are particularly noteworthy in this regard. Looking at the deviation from the true bearing, there are only three relatively narrow angle ranges in which the bearing indication appears to be highly distorted. Upon closer inspection of the range of fluctuation, however, extremely marked fluctuations (rotary bearings) are evident in six directions in a 360 radius. In those directions in which a bearing indication presumed to be correct (little deviation) coincides with a pronounced range of fluctuation, these are actually random correct DF results which cannot be reproduced in the same way again.

It is therefore important to always consider both diagrams. Only when the deviation from the true bearing angle and the fluctuation range both lie within the tolerance range is the bearing deemed to be valid.

The following examples of screenshots of bearing indications, which were taken at this measurement point, illustrate the practical effects on the operation of the direction finder:

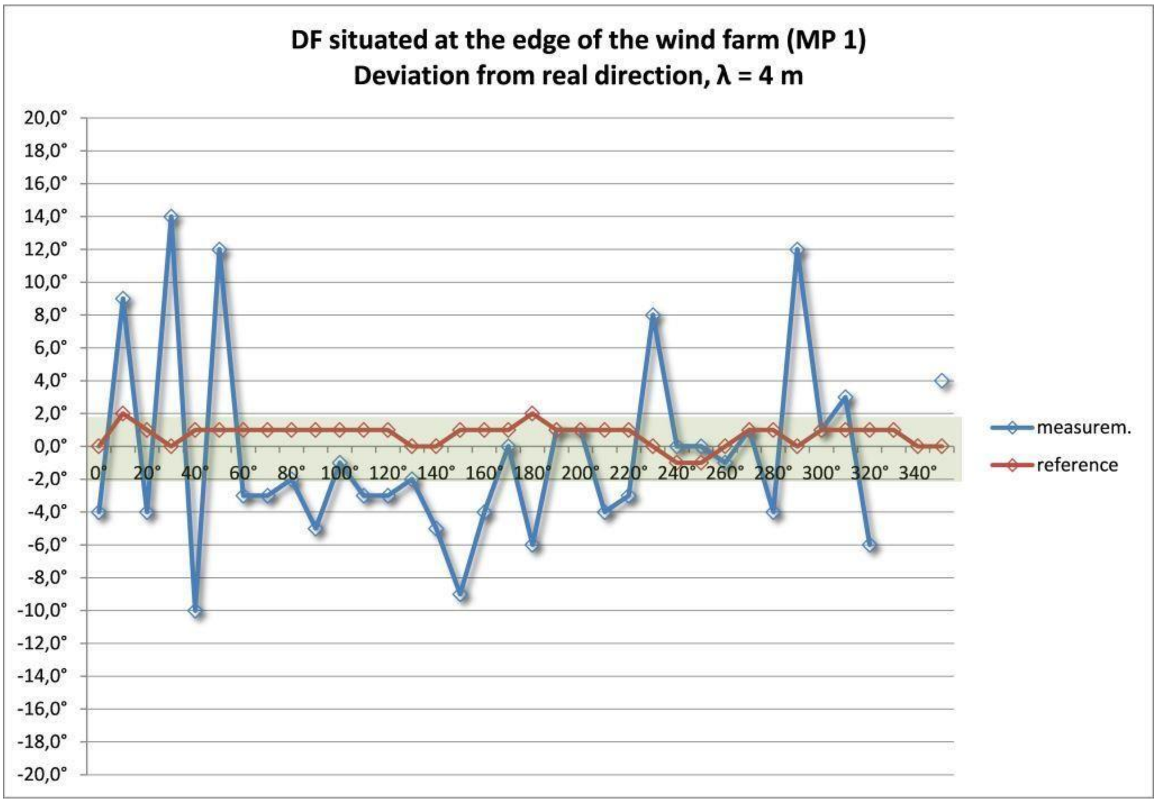


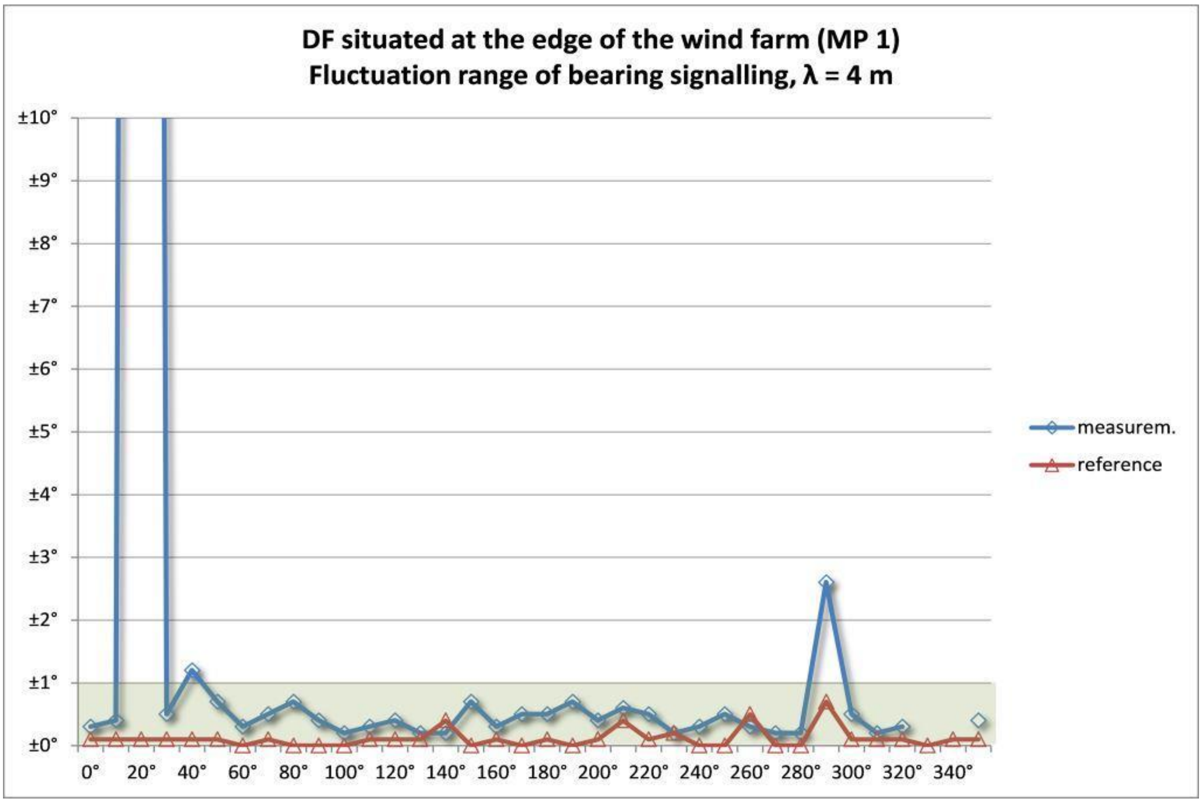
The white lines show the bearing history for the previous 30 seconds, while the yellow line shows the bearing at the time the screenshot was taken. In the first example (23 cm band), the bearing fluctuates chaotically in almost all directions; in the second example (13 cm band), the DF result appears to fluctuate around an average value. In the third example (30 cm band), there are two extreme DF results, although neither is correct!

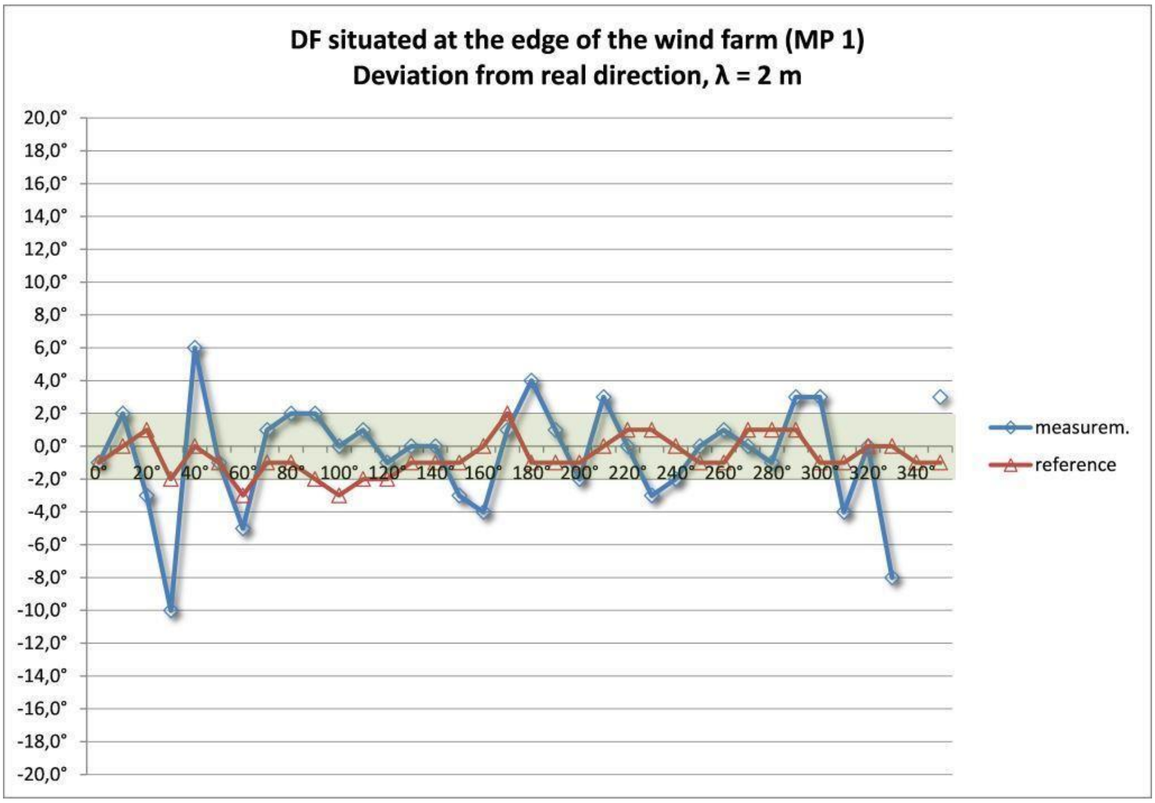
In the HF range, the radio direction finder behaves chaotically and is therefore unusable.

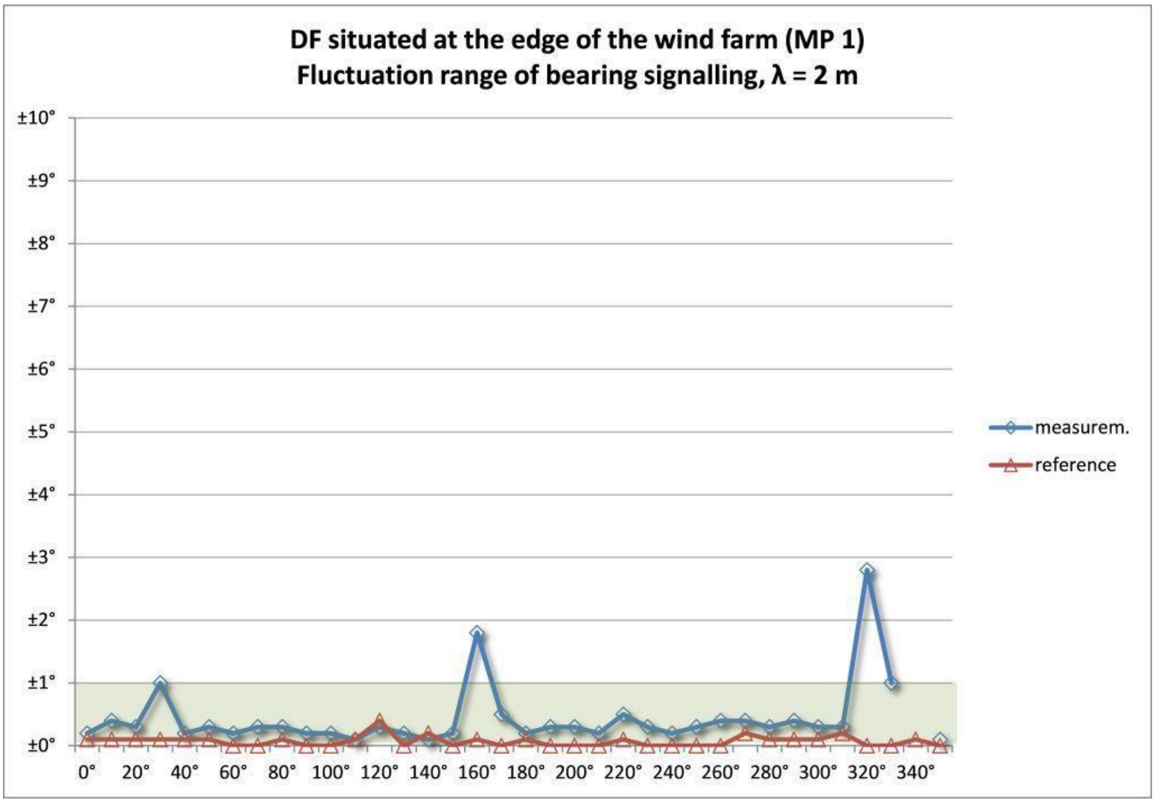
Conclusion: A radio direction finder cannot be used in a wind farm.

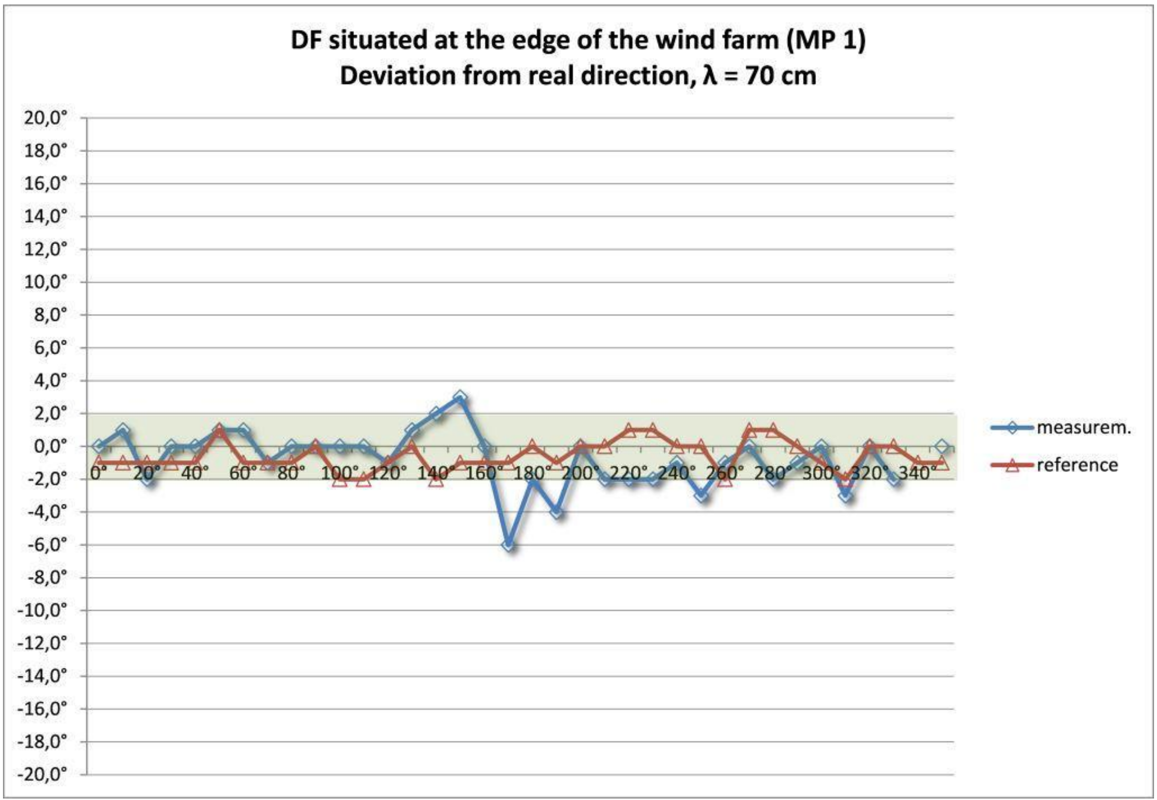
9.2.2 Radio direction finder situated at the edge of the wind farm

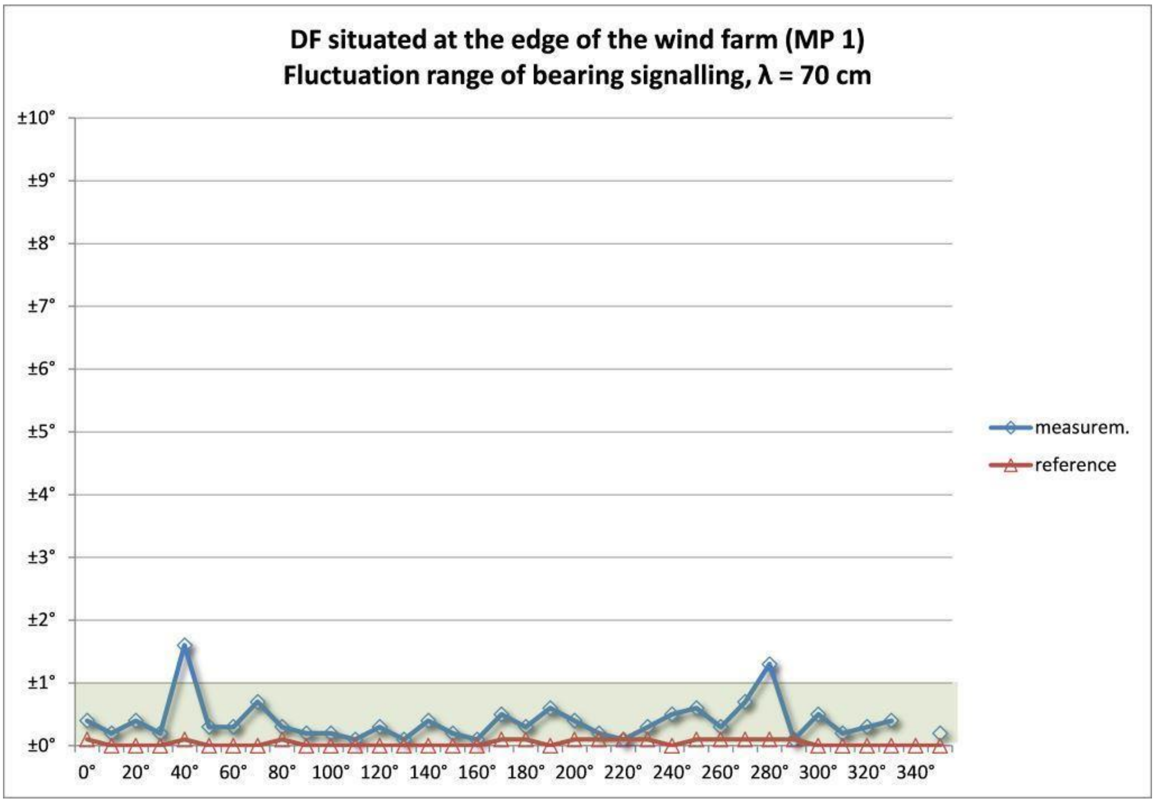


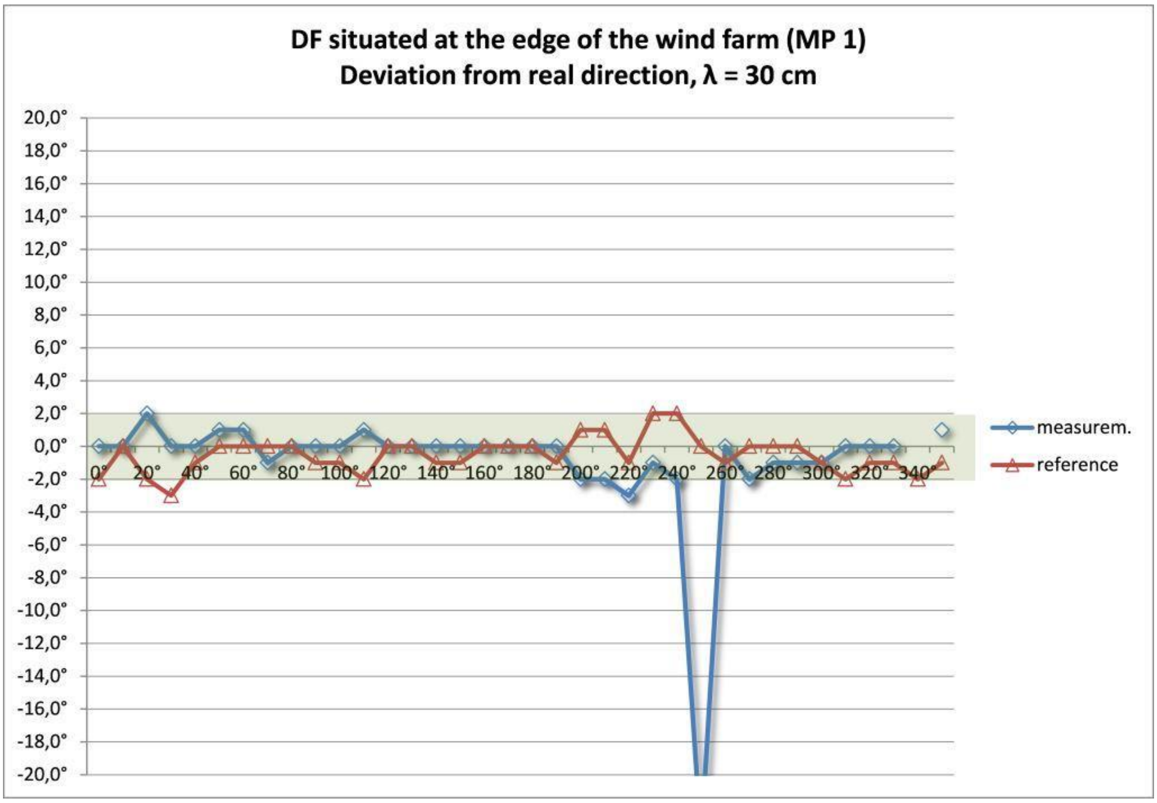

DF situated at the edge of the wind farm (MP 1)
Fluctuation range of bearing signalling, λ = 4 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

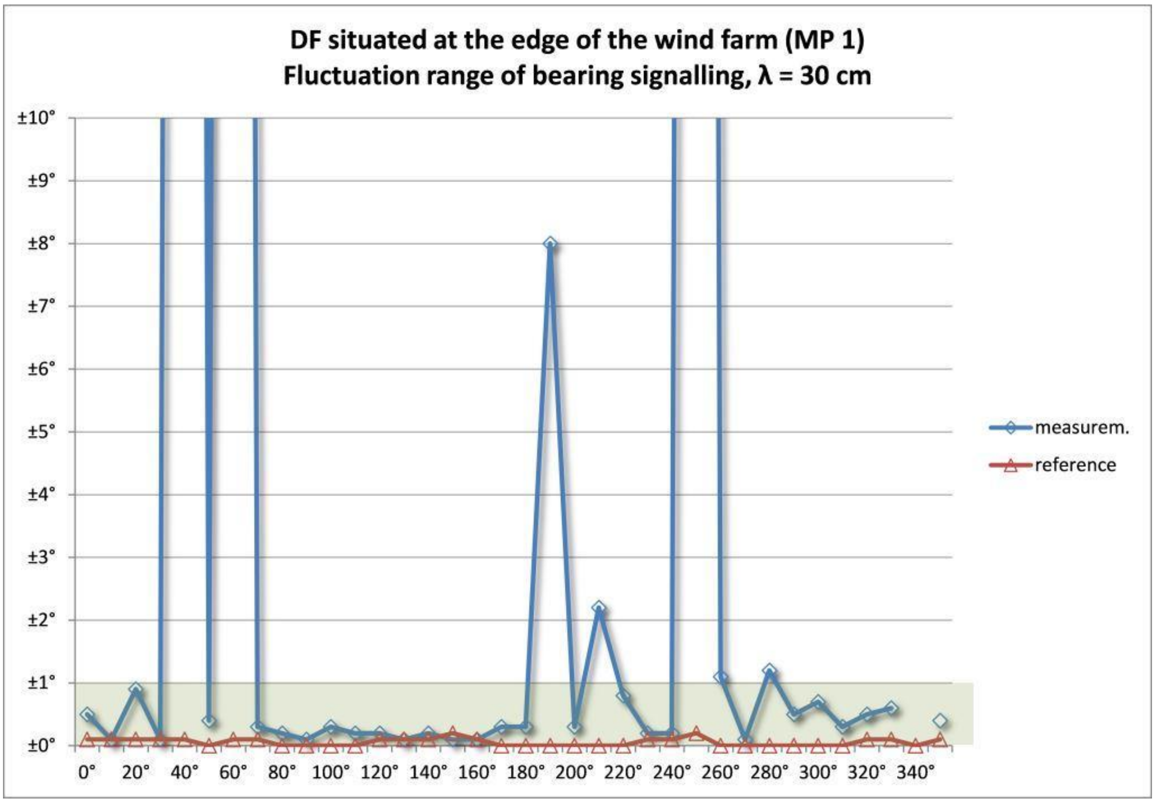

DF situated at the edge of the wind farm (MP 1)
Deviation from real direction, λ = 2 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

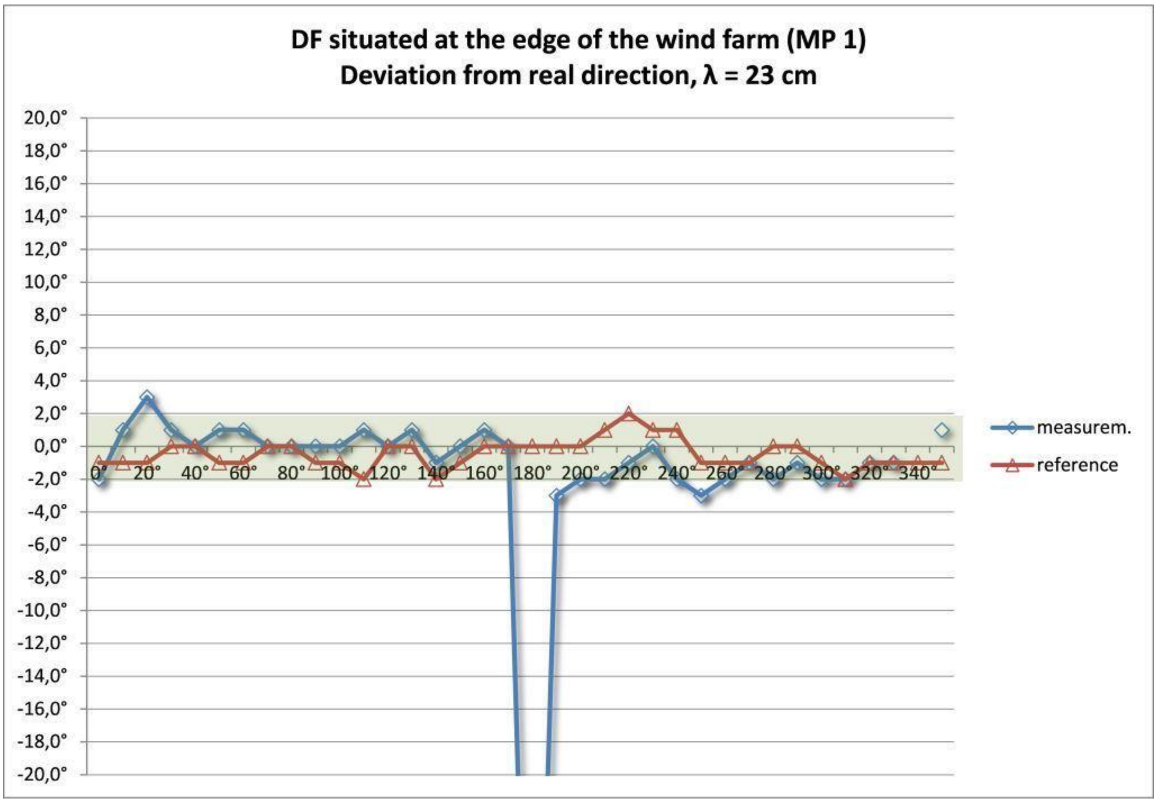

DF situated at the edge of the wind farm (MP 1)
Fluctuation range of bearing signalling, λ = 2 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

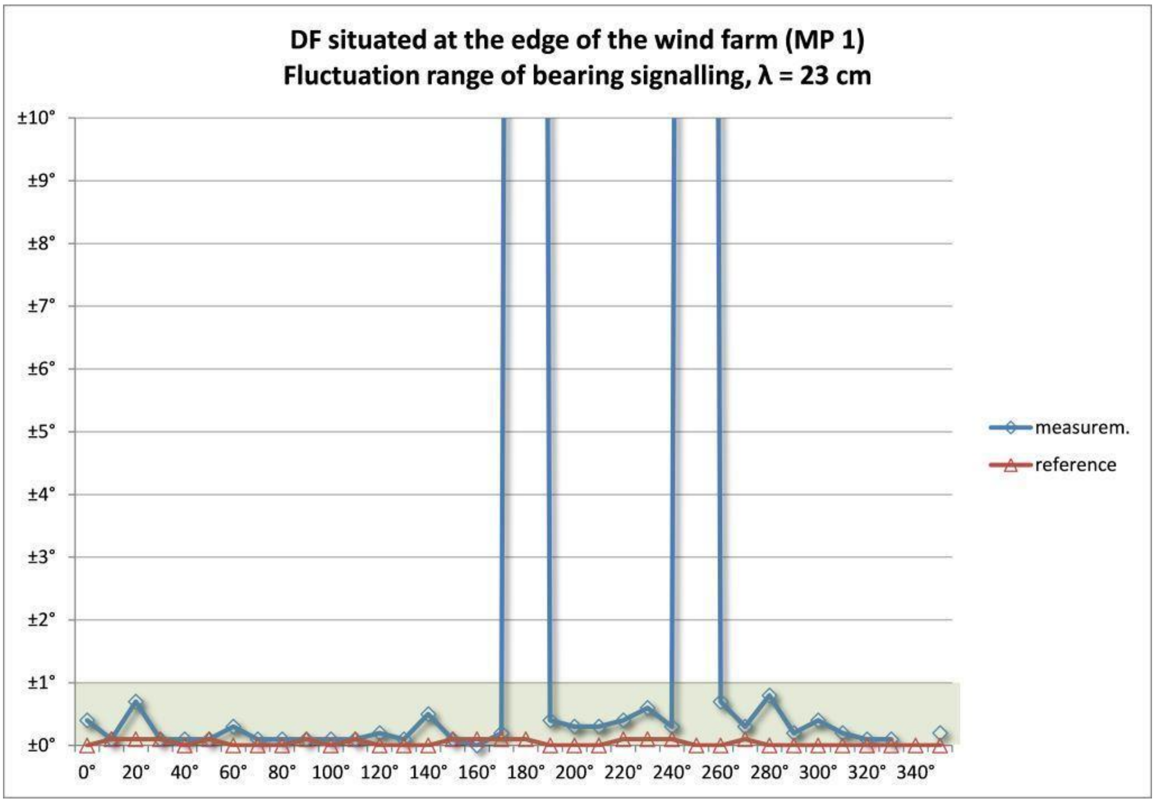

DF situated at the edge of the wind farm (MP 1)
Deviation from real direction, λ = 70 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

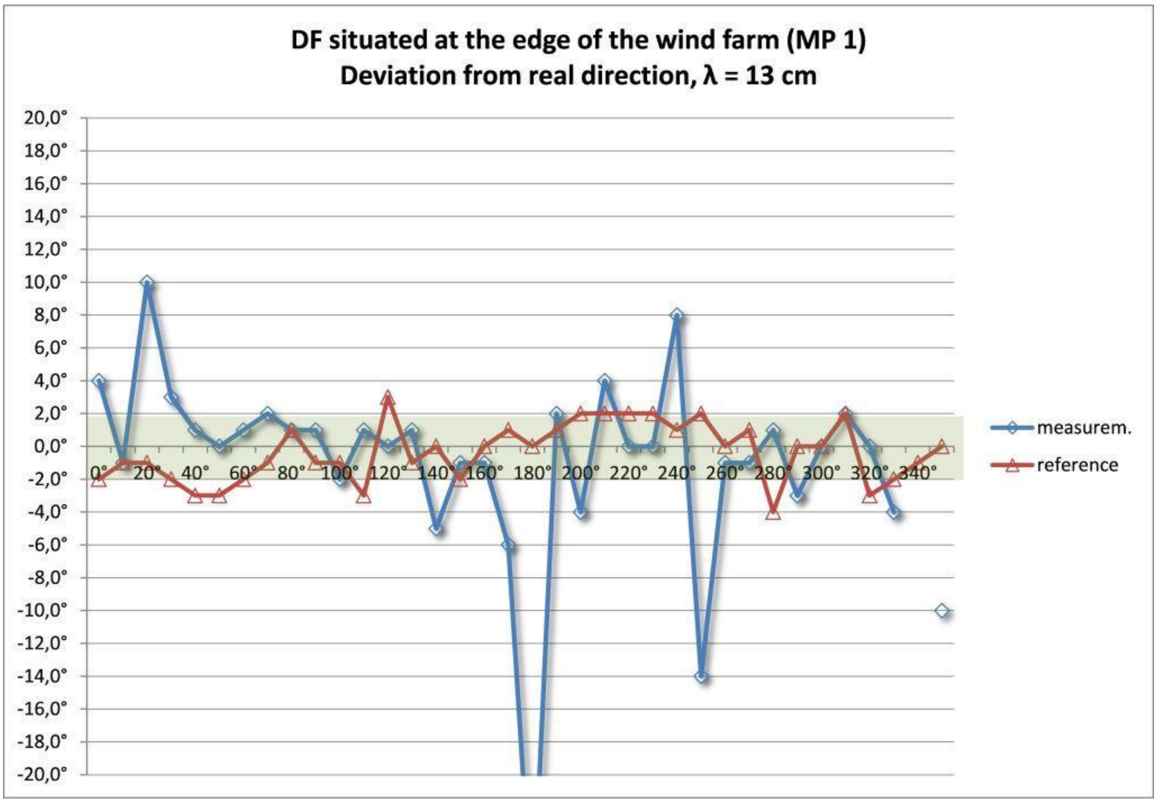

DF situated at the edge of the wind farm (MP 1)
Fluctuation range of bearing signalling, λ = 70 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

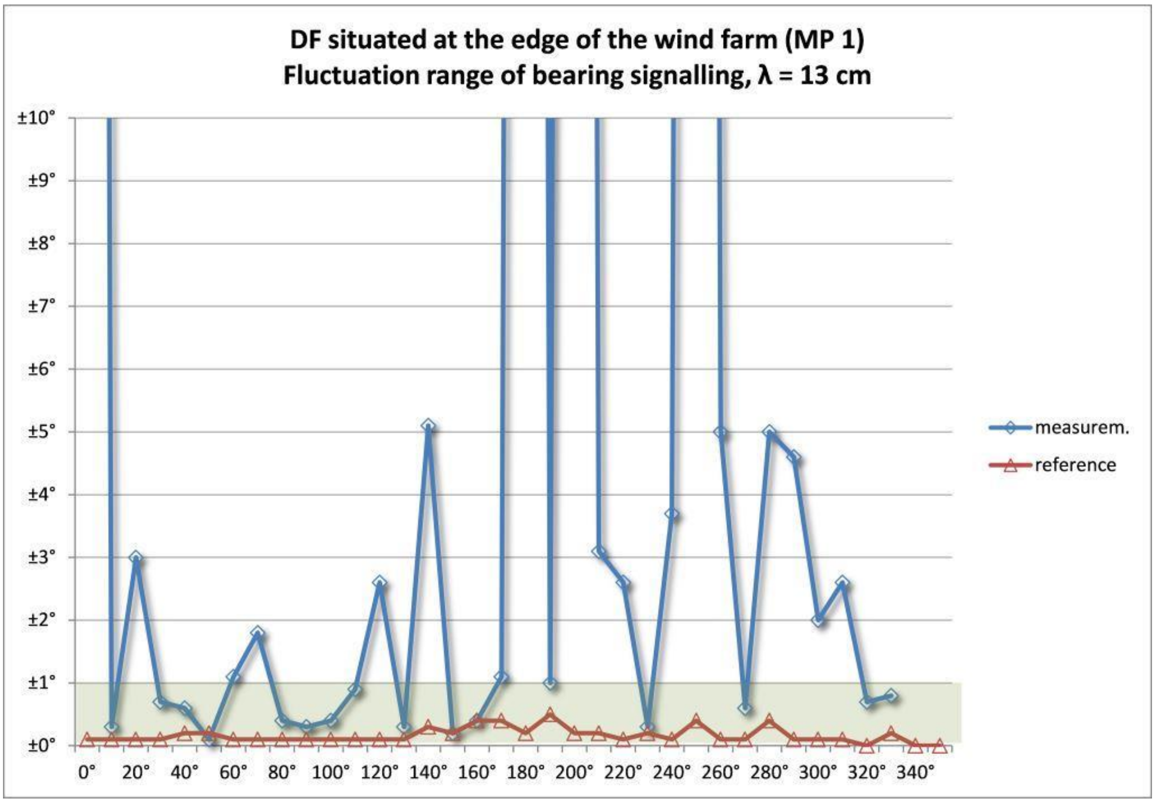

DF situated at the edge of the wind farm (MP 1)
Deviation from real direction, λ = 30 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated at the edge of the wind farm (MP 1)
Fluctuation range of bearing signalling, λ = 30 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated at the edge of the wind farm (MP 1)
Deviation from real direction, λ = 23 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated at the edge of the wind farm (MP 1)
Fluctuation range of bearing signalling, λ = 23 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated at the edge of the wind farm (MP 1)
Deviation from real direction, λ = 13 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference



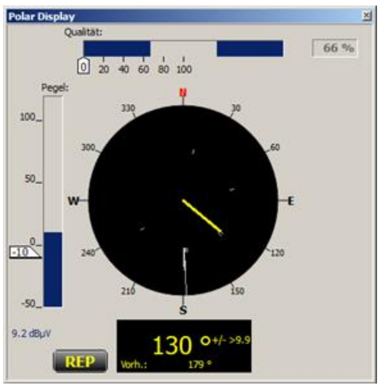
Interference – in some cases, considerable interference – was recorded in all frequency bands tested. It is particularly pronounced in the 4 m band, where significant DF errors were observed in all directions, whereby the errors were strongest in the case of bearings through the wind farm and, interestingly, in the opposite direction.

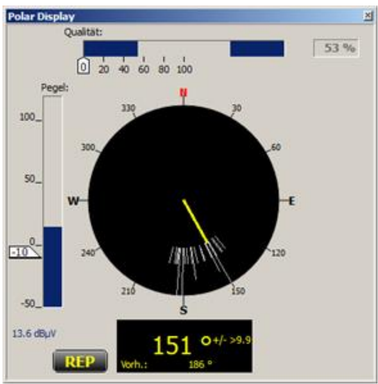
In the 2 m band, the most pronounced DF errors were recorded in the case of bearings through the wind farm and in the opposite direction. Here, marked fluctuations in the bearing indication were once again observed, with a random "correct" bearing at 320°.

The 70 cm band behaves relatively well in this constellation, with relevant DF errors in directions pointing away from the wind farm (to the south)!

The three highest frequency bands (800 MHz – 3 GHz) are once again remarkable due to the, in some cases, marked fluctuations in the bearing indication within limited angle ranges. At 30 cm and 23 cm, reliable bearings are possible within larger angle ranges. However, due to the marked fluctuations in bearing indication in certain directions, this can, in some cases, only be achieved over a long observation period, which is not possible for most digital radio systems.

In the 13 cm band, bearings are chaotic and subject to marked fluctuations, above all in the direction of the wind farm and in the direction away from the wind farm.

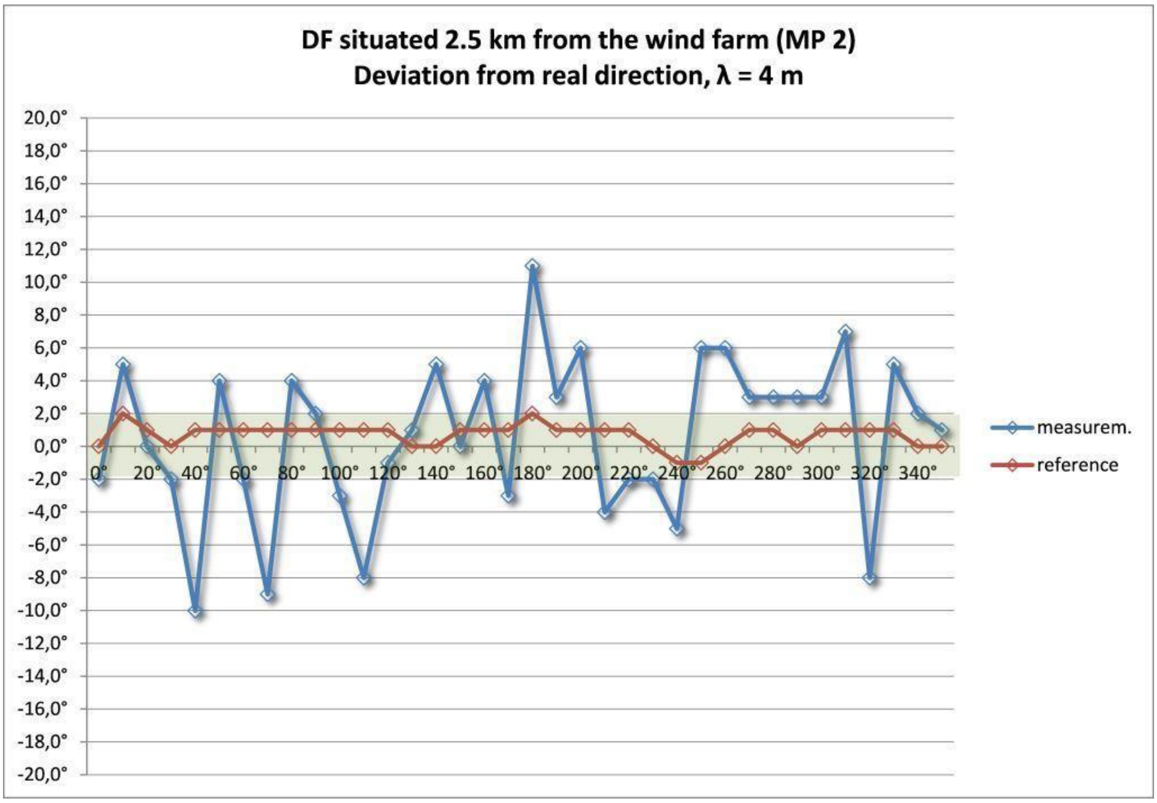


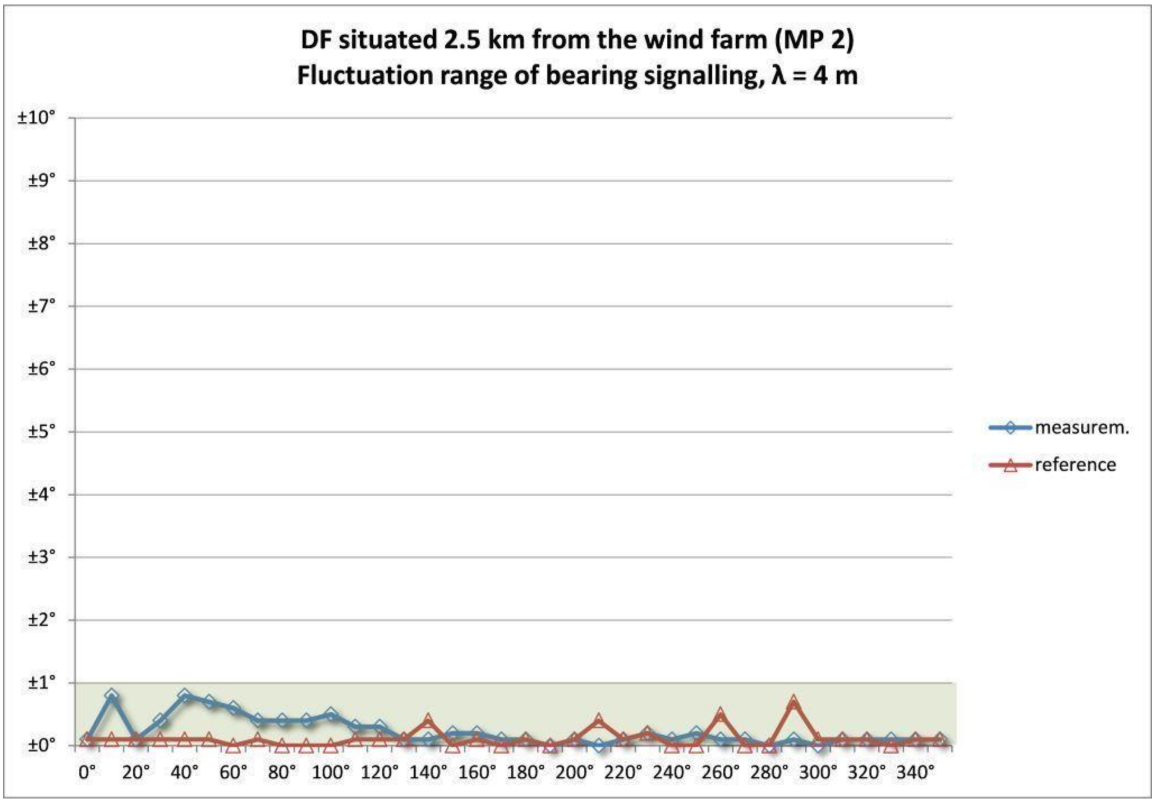


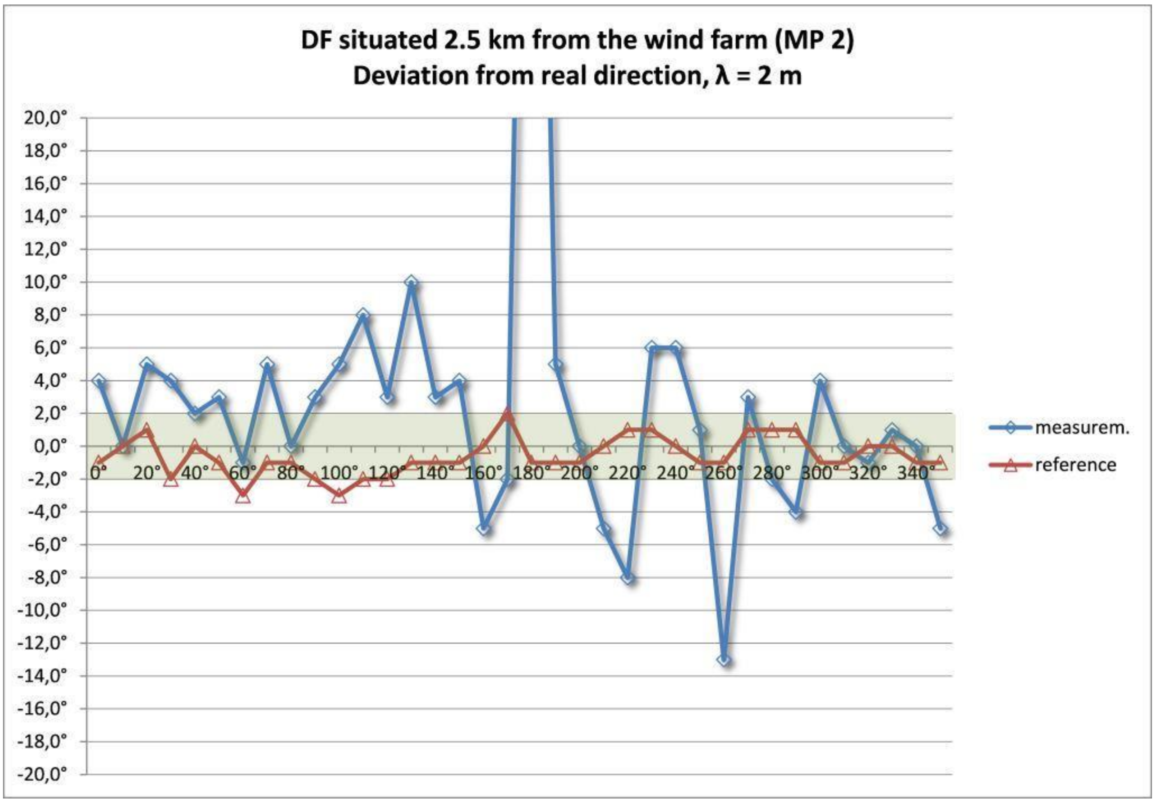
The screenshots show two examples of typical bearing indications in this measurement series. The first shows a bearing indication in the 23 cm band with several discrete bearing directions. The short white lines of the bearing history indicate that the direction finder is jumping slowly between individual bearing directions. The second example shows a bearing in the 13 cm band with a bearing indication which appears to fluctuate around an average value.

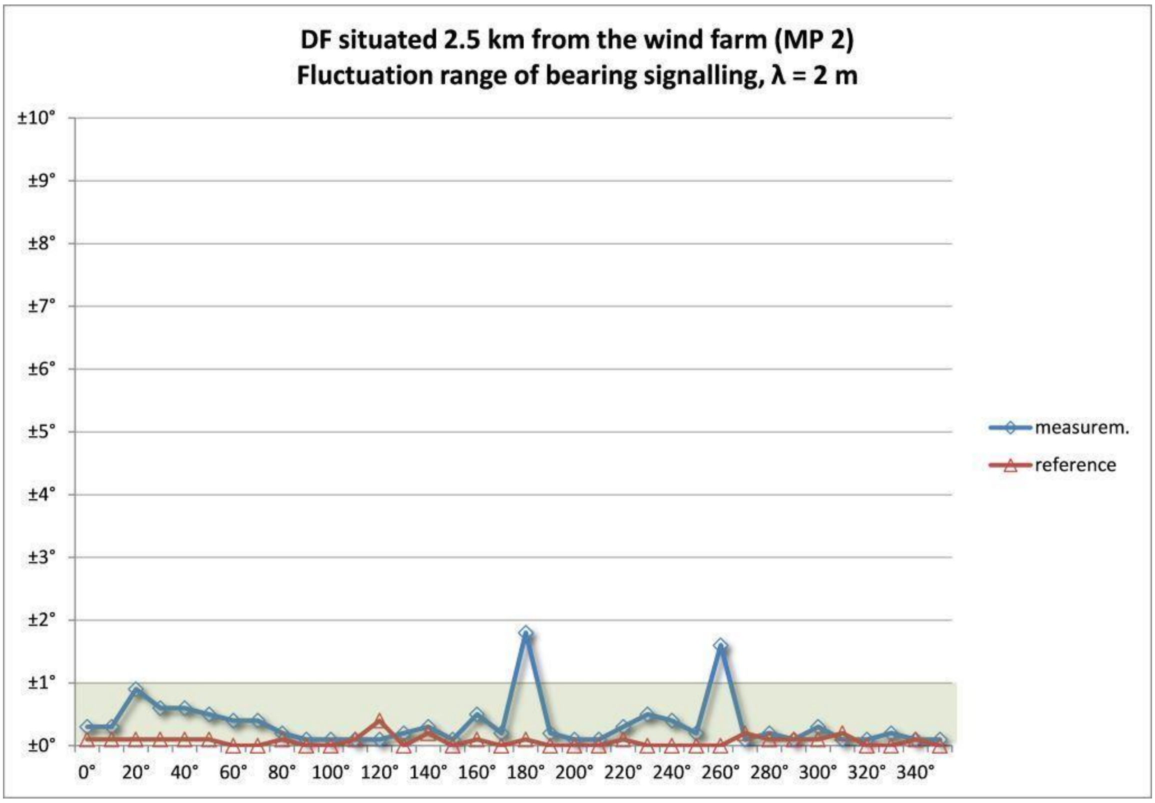
Conclusion: When situated at the edge of the wind farm, the radio direction finder can only be used in the 70 cm and, even then, only to a limited extent.

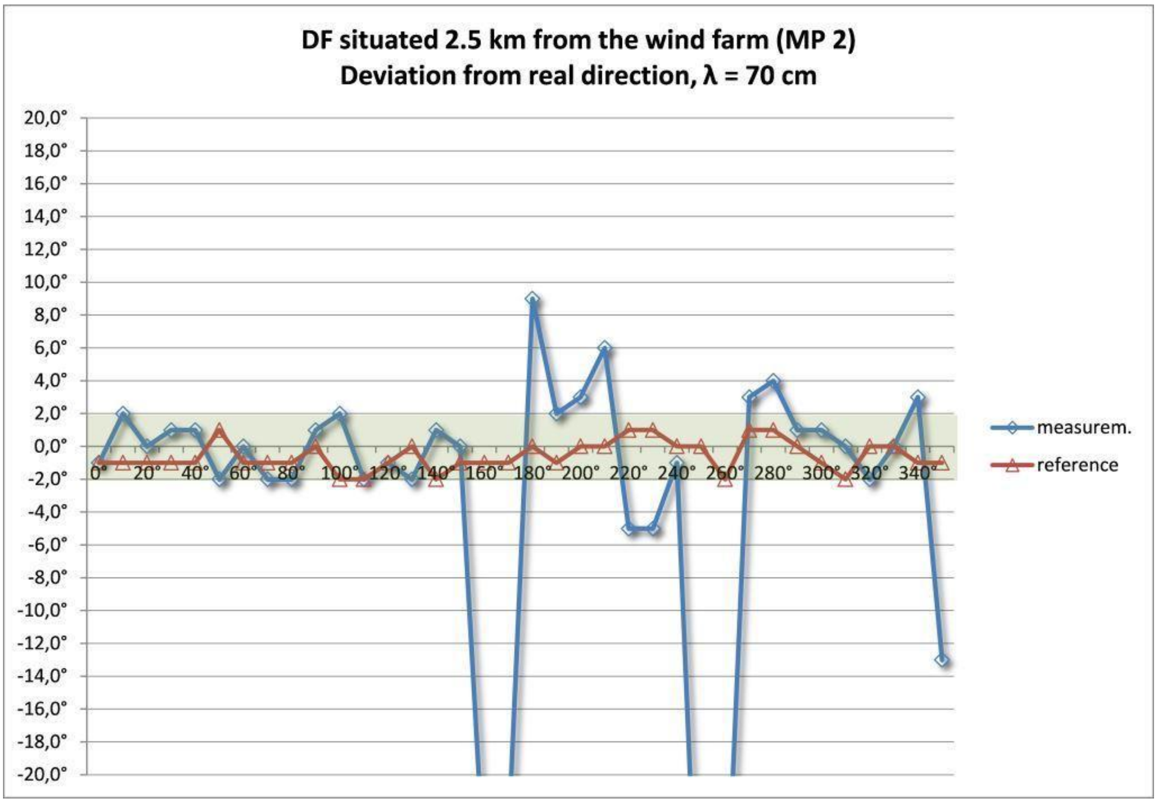
9.2.3 Radio direction finder located 2.5 km from the wind farm

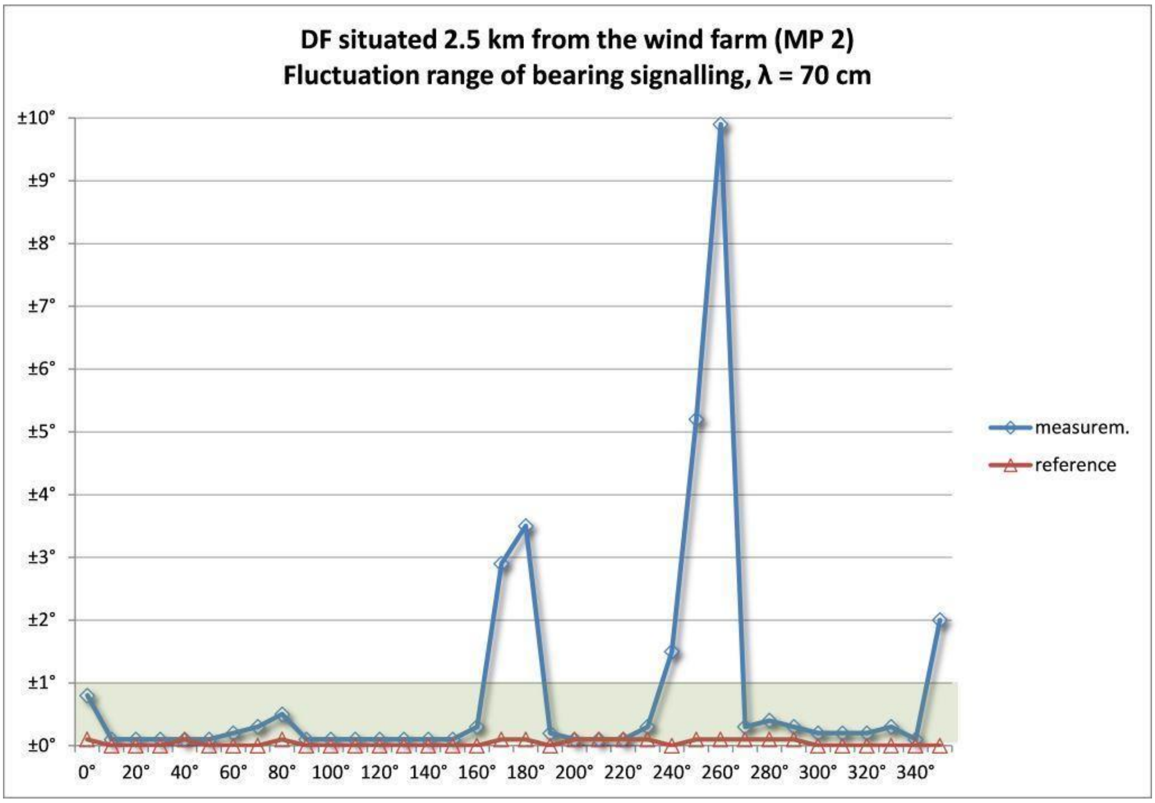


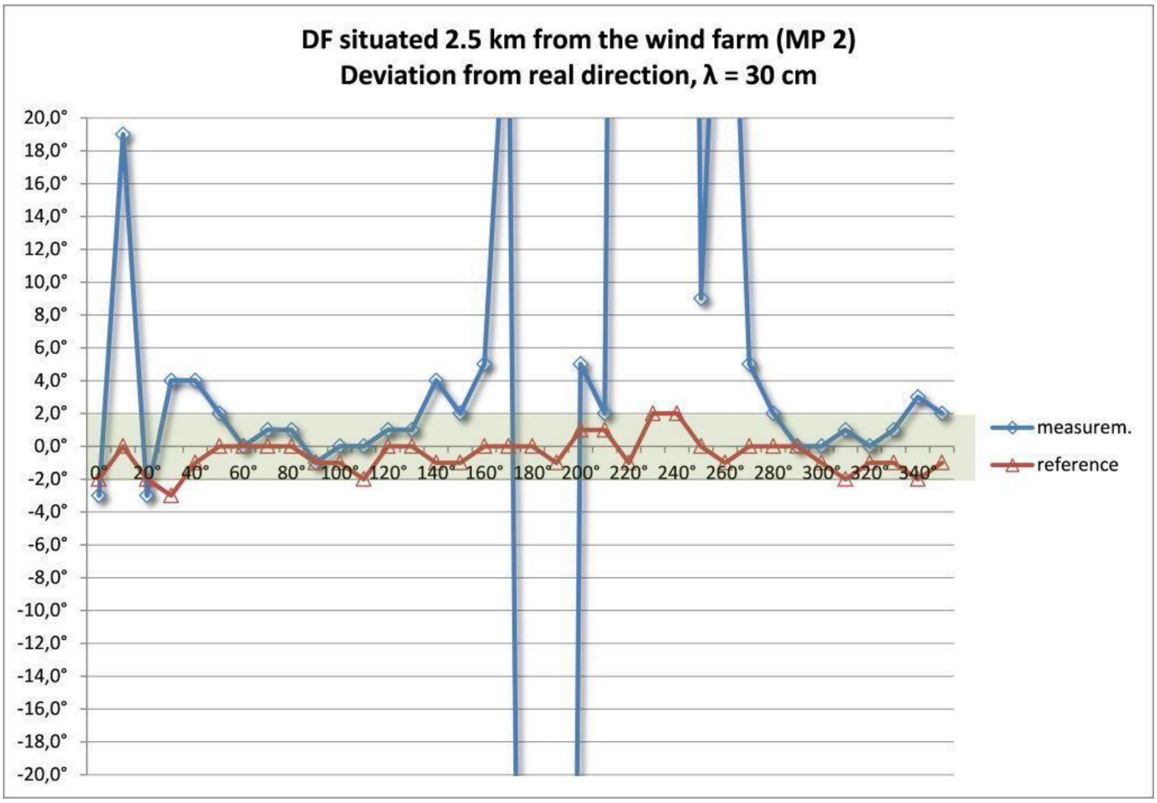

DF situated 2.5 km from the wind farm (MP 2)
Fluctuation range of bearing signalling, λ = 4 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

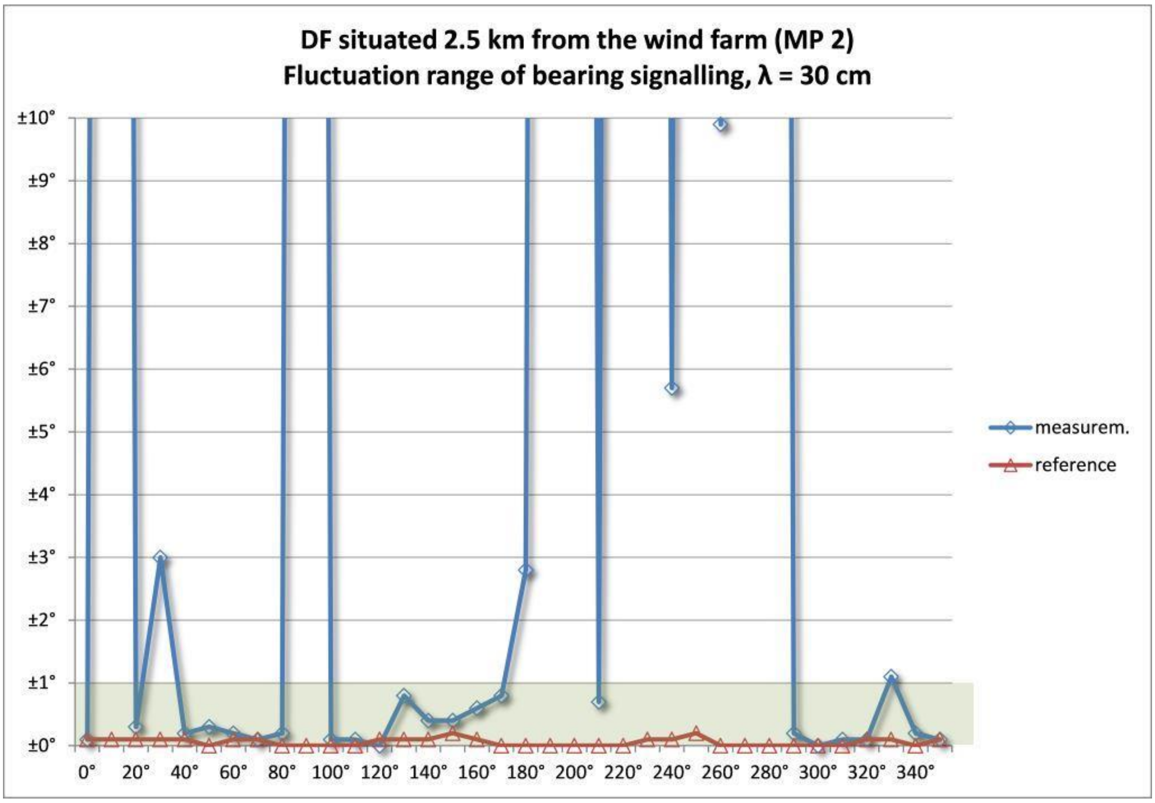

DF situated 2.5 km from the wind farm (MP 2)
Deviation from real direction, λ = 2 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

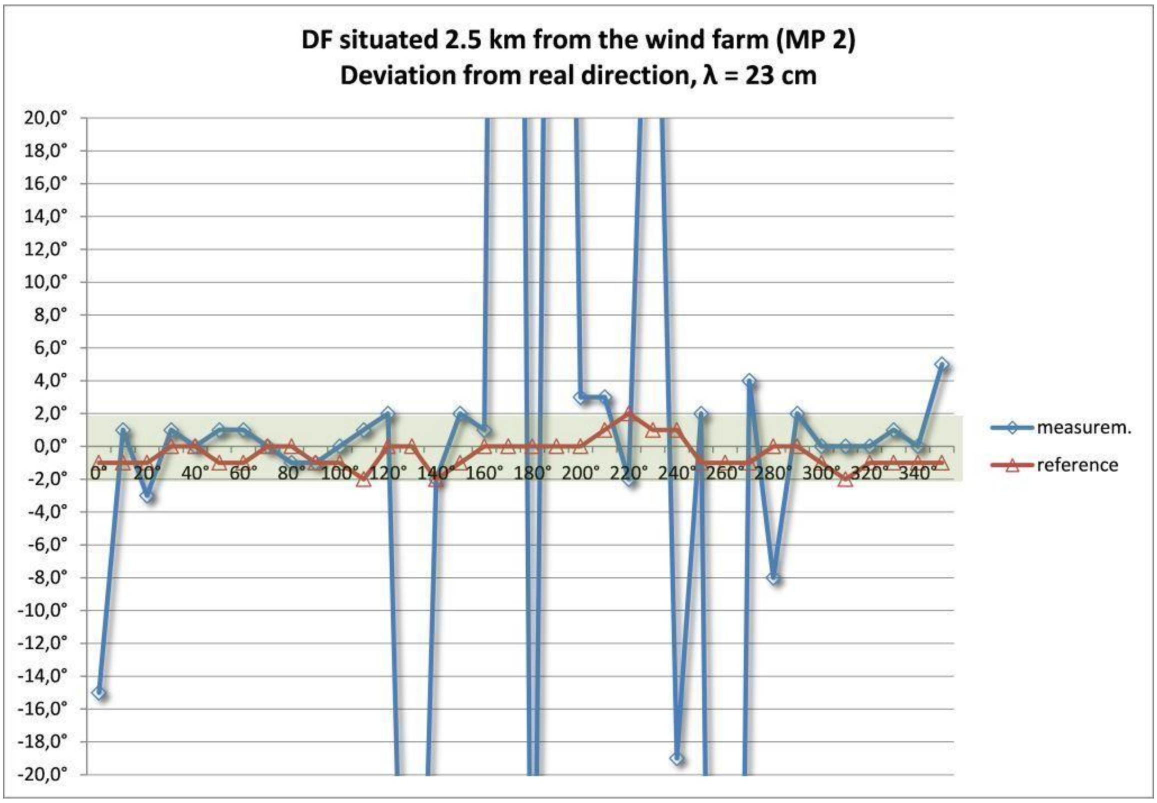

DF situated 2.5 km from the wind farm (MP 2)
Fluctuation range of bearing signalling, λ = 2 m
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

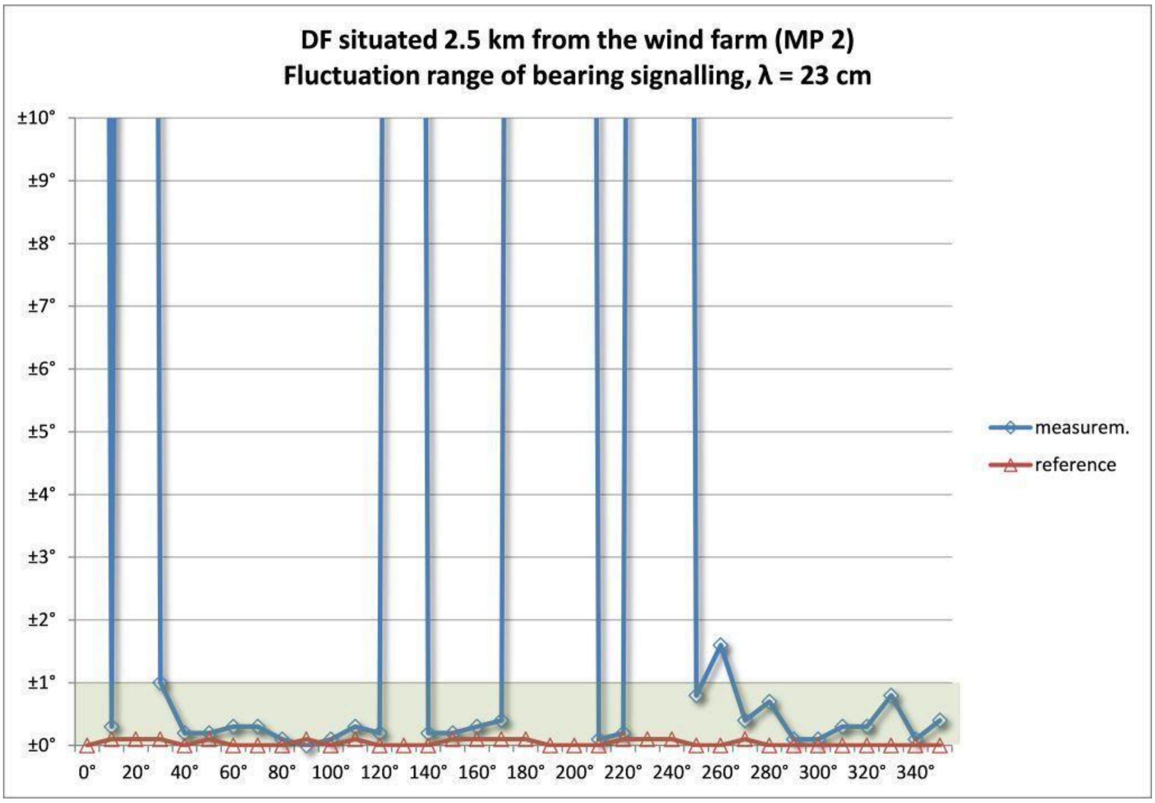

DF situated 2.5 km from the wind farm (MP 2)
Deviation from real direction, λ = 70 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

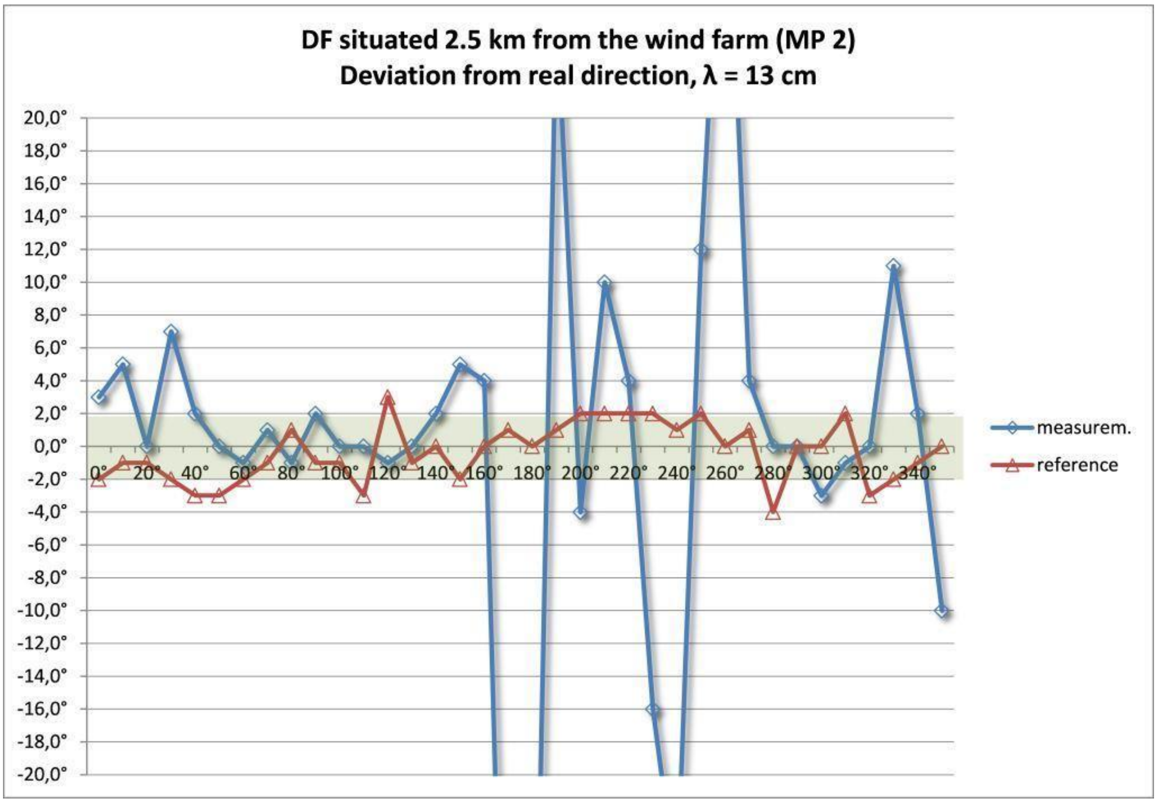

DF situated 2.5 km from the wind farm (MP 2)
Fluctuation range of bearing signalling, λ = 70 cm
±10° ±9° ±8° ±7° ±6° ±5° ±4° ±3° ±2° ±1° ±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

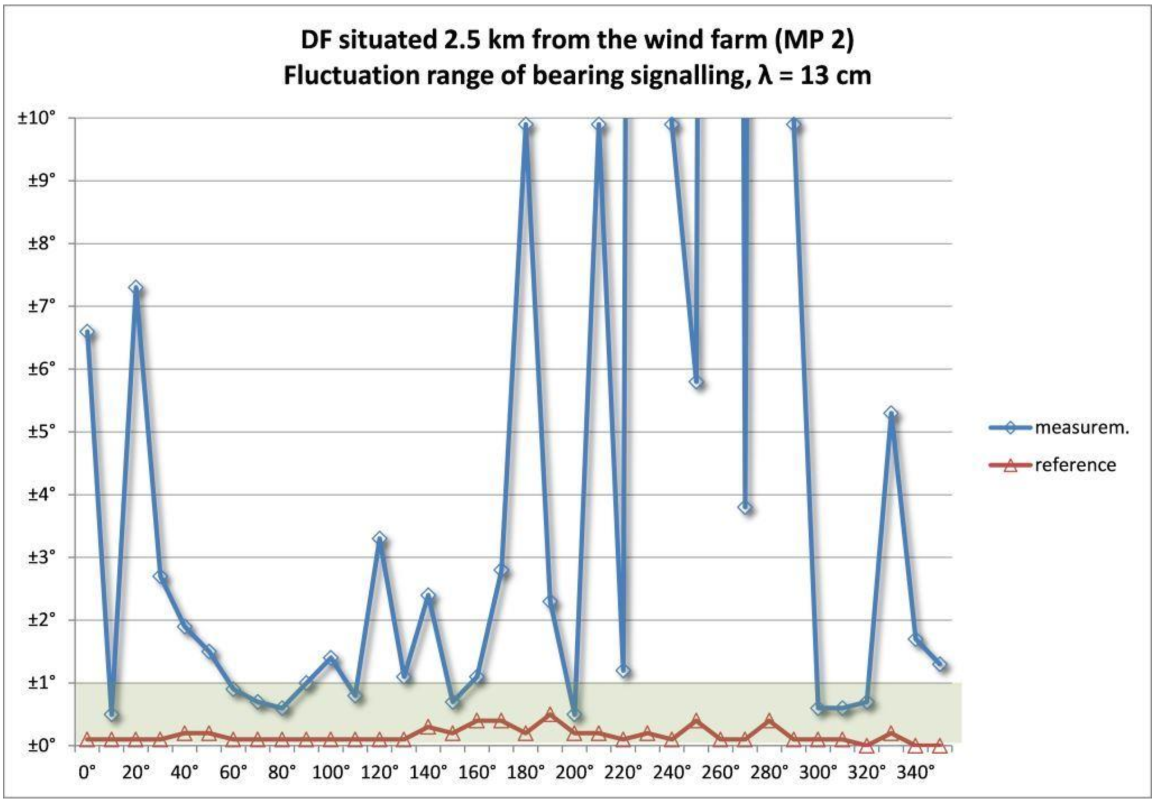

DF situated 2.5 km from the wind farm (MP 2)
Deviation from real direction, λ = 30 cm
20,0° 18,0° 16,0° 14,0° 12,0° 10,0° 8,0° 6,0° 4,0° 2,0° 0,0° -2,0° -4,0° -6,0° -8,0° -10,0° -12,0° -14,0° -16,0° -18,0° -20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

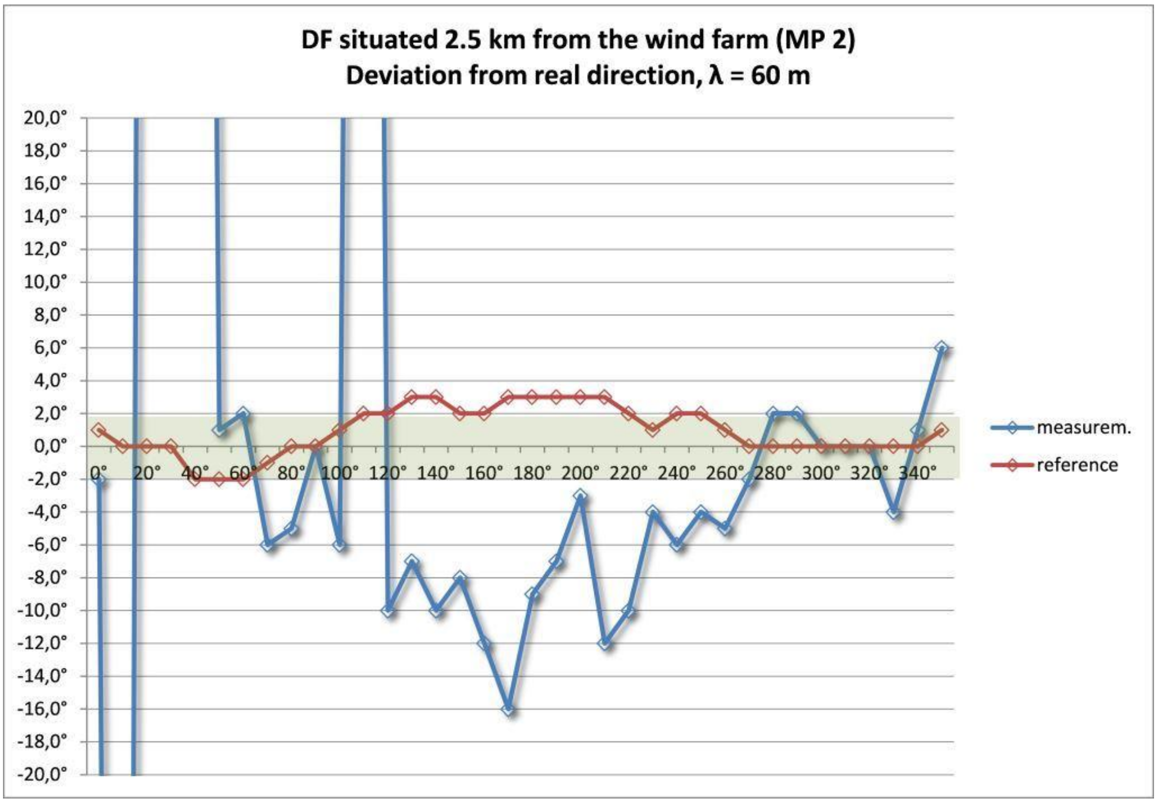

DF situated 2.5 km from the wind farm (MP 2)
Fluctuation range of bearing signalling, λ = 30 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

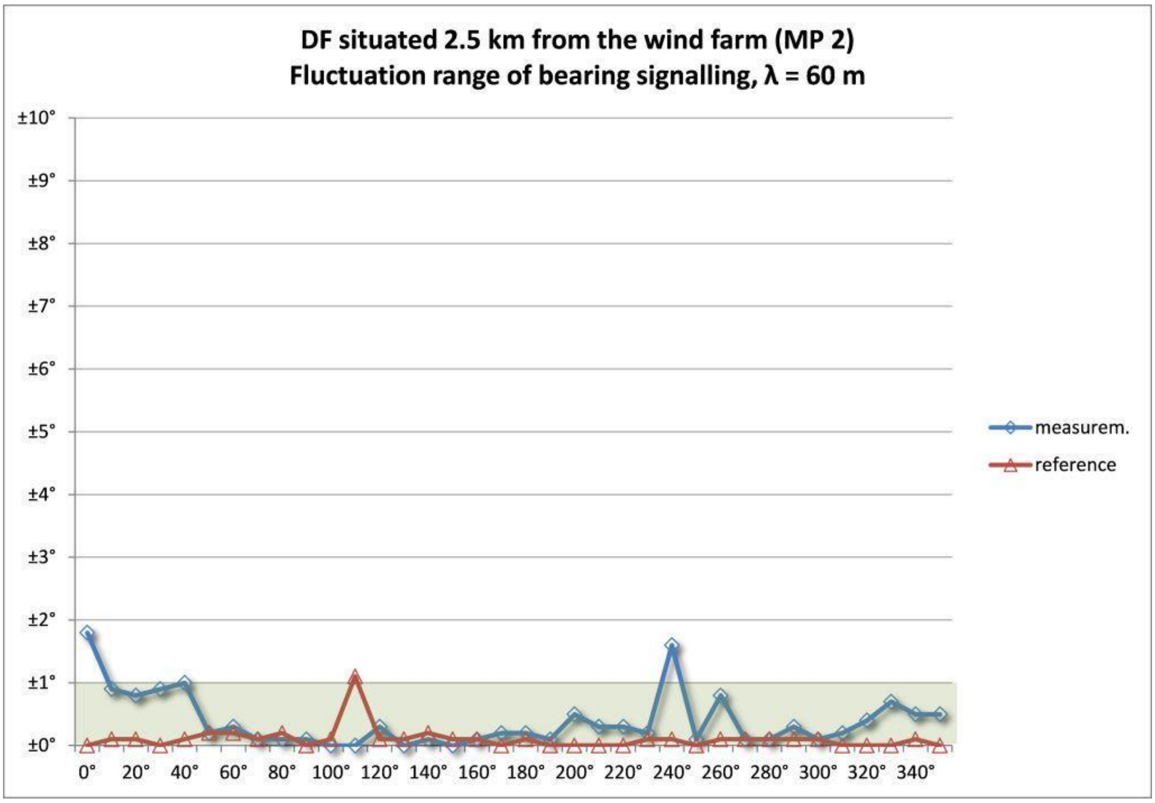

DF situated 2.5 km from the wind farm (MP 2)
Deviation from real direction, λ = 23 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated 2.5 km from the wind farm (MP 2)
Fluctuation range of bearing signalling, λ = 23 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated 2.5 km from the wind farm (MP 2)
Deviation from real direction, λ = 13 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated 2.5 km from the wind farm (MP 2)
Fluctuation range of bearing signalling, λ = 13 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated 2.5 km from the wind farm (MP 2)
Deviation from real direction, λ = 60 m
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference



When situated 2.5 km from the wind farm, significant DF errors were recorded in all VHF/UHF bands.

In the 4 m and 2 m bands, marked DF errors were observed across all four quadrants.

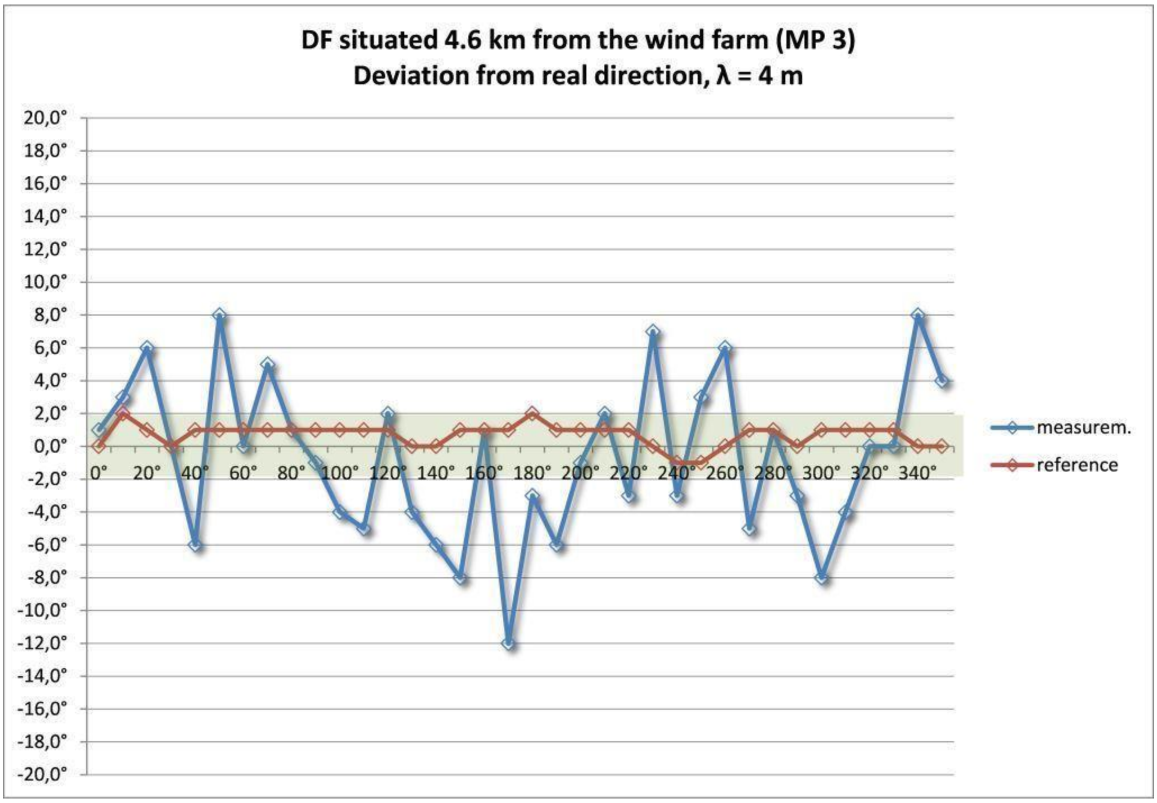
In the other bands (70 cm … 13 cm), only minor DF errors were recorded in the angle range from north-east to the south-east (i.e. roughly in the direction of the wind farm). However, significant DF errors were observed in the opposite direction. The angle range in which particularly strong interference was observed forms an arc, the length of which clearly correlates with the length of the arc formed on the horizon by the wind farm from the perspective of the direction finder. However, the angle range in which interference is experienced is always bigger than the arc formed by the wind farm.

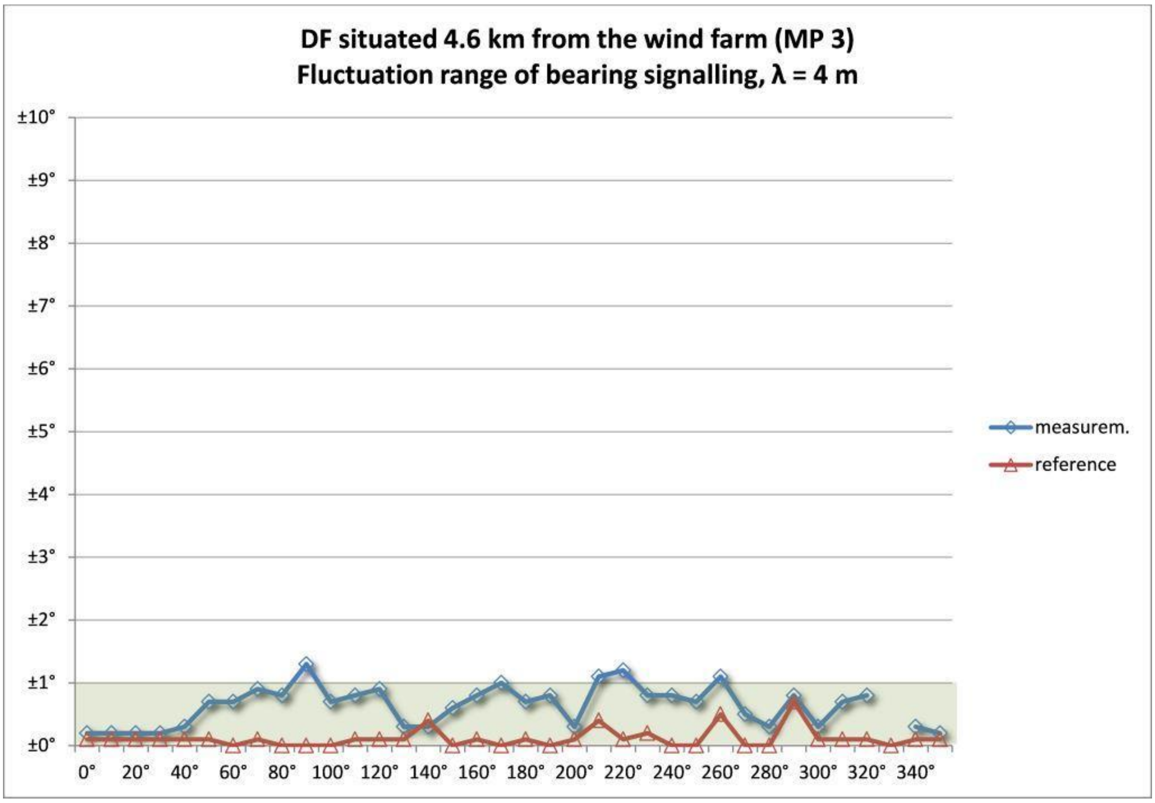
In the 70 cm band, marked fluctuations in bearing indications were also observed in individual angle ranges in addition to those DF errors described above. This effect is even more pronounced in the even shorter wavelength bands (30 cm, 23 cm and 13 cm) and extends to ever larger angle ranges as the wavelengths get shorter.

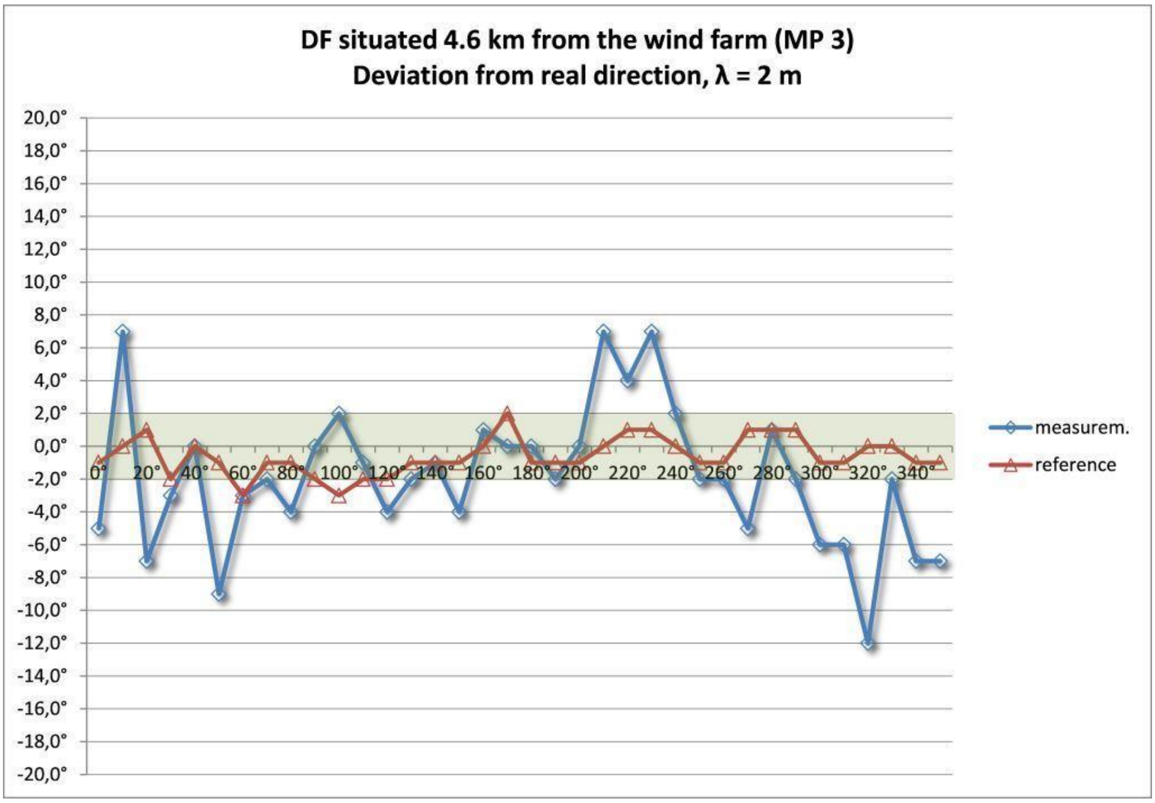
In the HF range, significant DF errors were recorded in all four quadrants, with the exception of a narrow sector transverse to the wind farm. In the direction of the wind farm, the DF errors are so pronounced that it is no longer possible to identify even the correct quadrant.

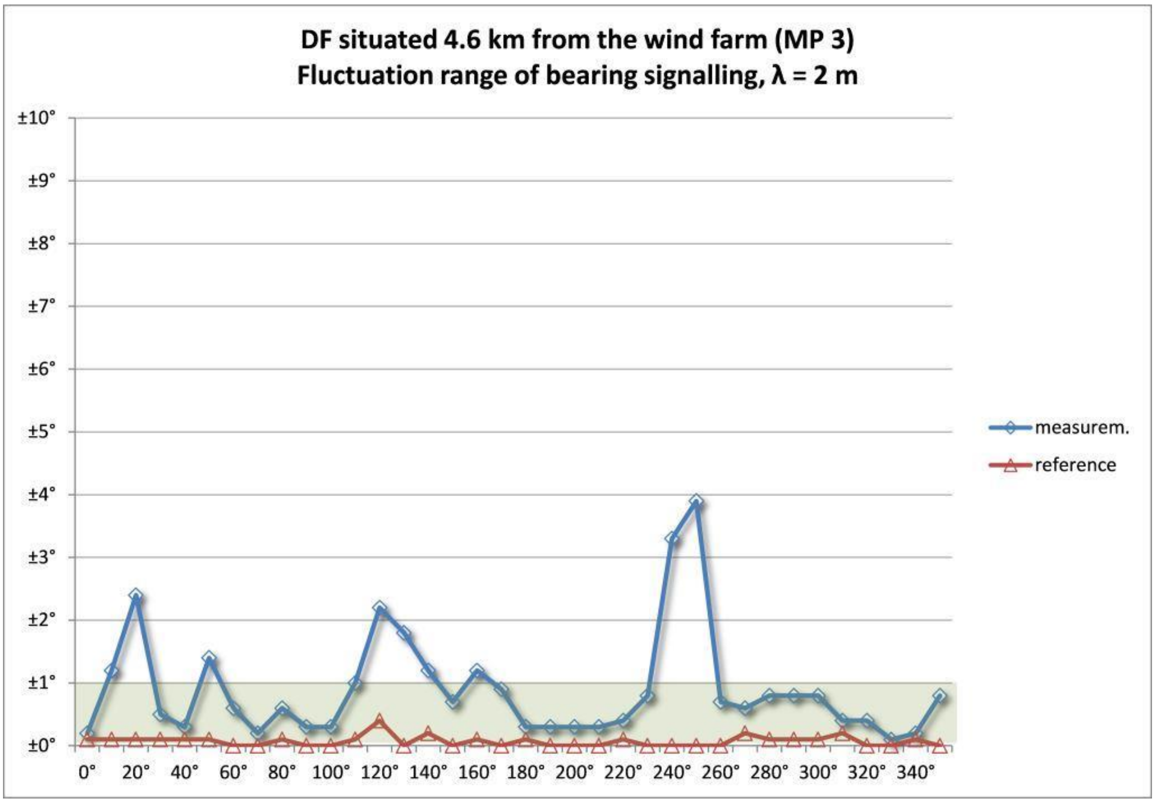
Conclusion: A fixed radio direction finder situated 2.5 km from the wind farm can only be used in the 70 cm band and, even then, only within a limited angle range.

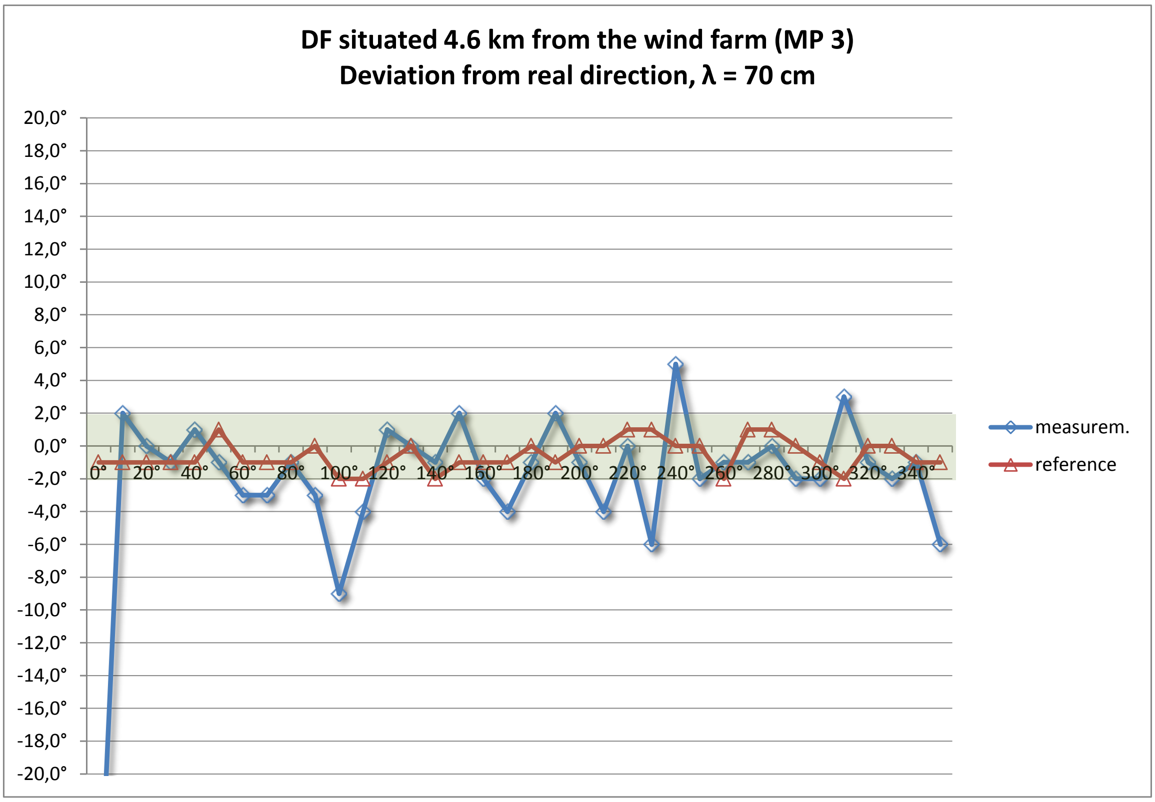
9.2.4 Radio direction finder located 4.6 km from the wind farm

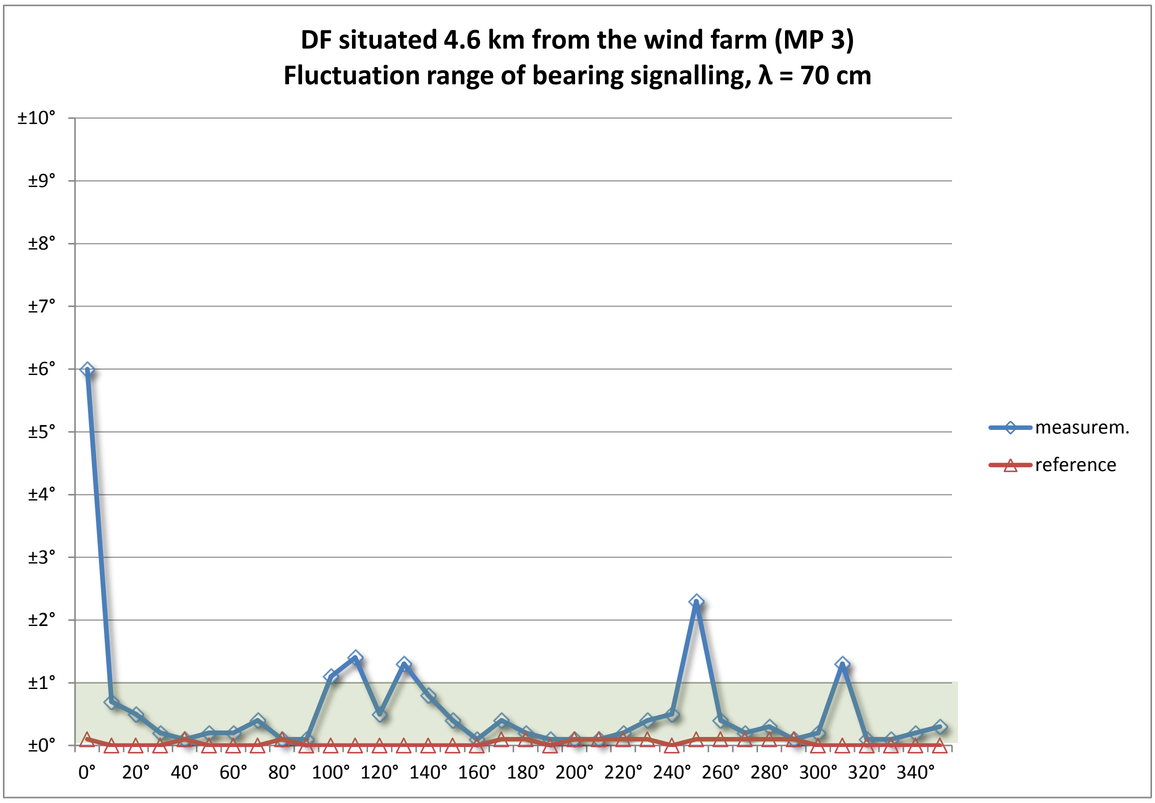


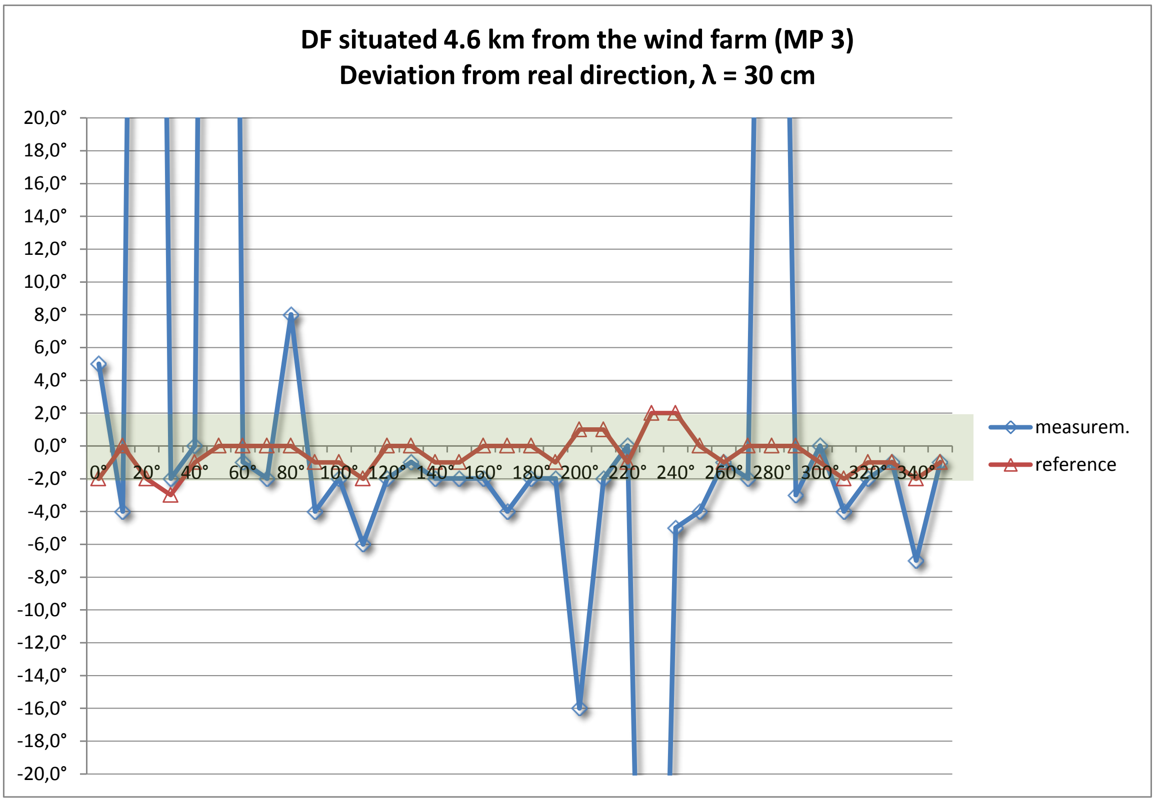


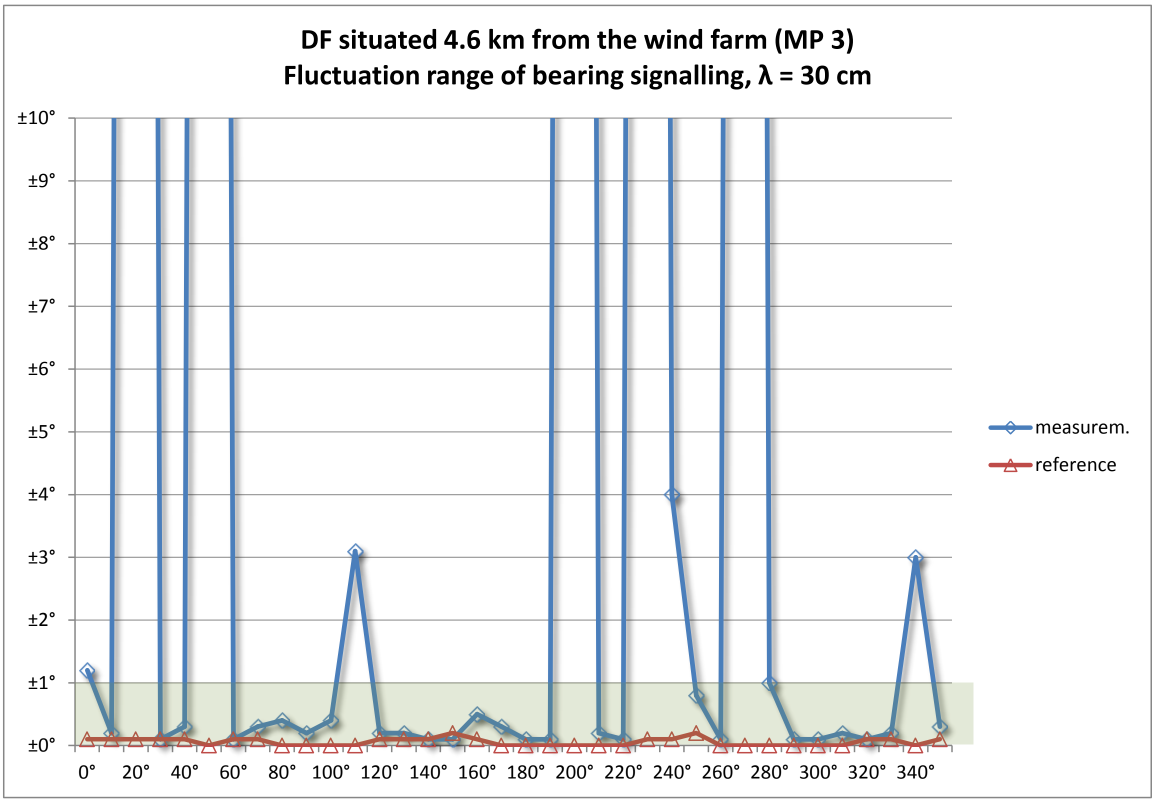

DF situated 4.6 km from the wind farm (MP 3)
Deviation from real direction, λ = 2 m
20,0° 18,0° 16,0° 14,0° 12,0° 10,0° 8,0° 6,0° 4,0° 2,0° 0,0° -2,0° -4,0° -6,0° -8,0° -10,0° -12,0° -14,0° -16,0° -18,0° -20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

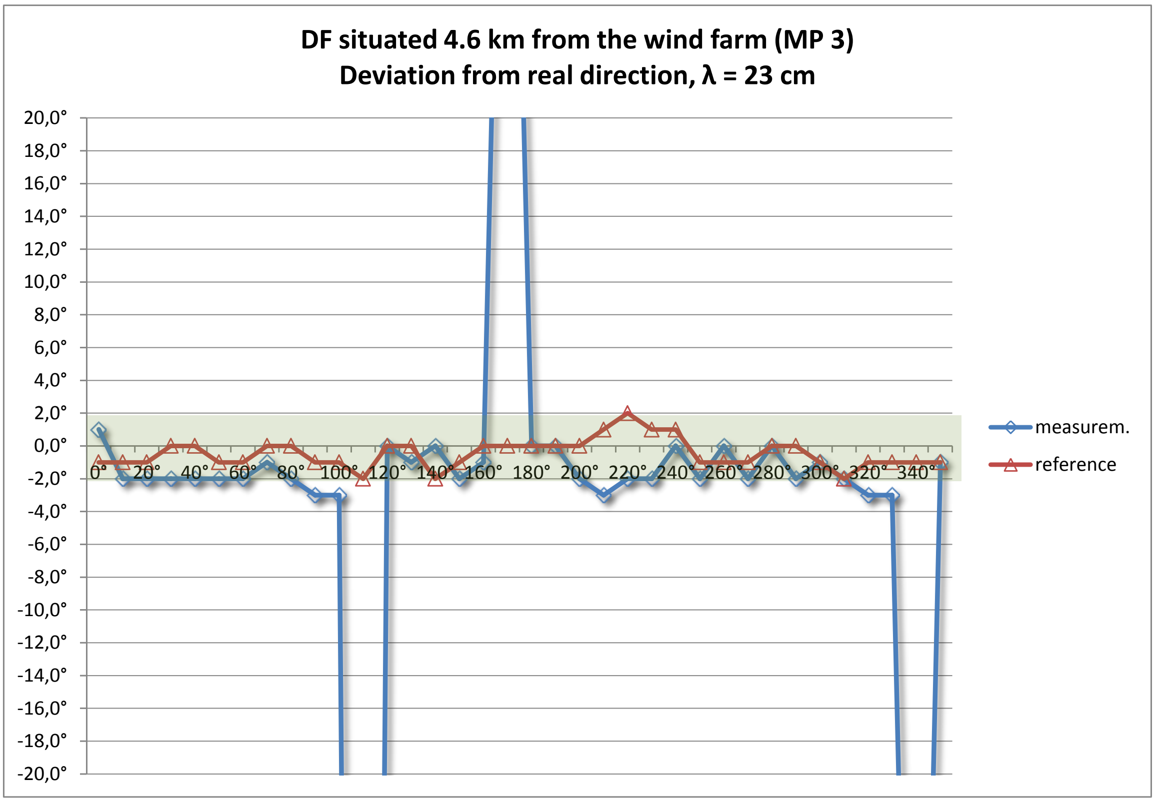

DF situated 4.6 km from the wind farm (MP 3)
Fluctuation range of bearing signalling, λ = 2 m
±10° ±9° ±8° ±7° ±6° ±5° ±4° ±3° ±2° ±1° ±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

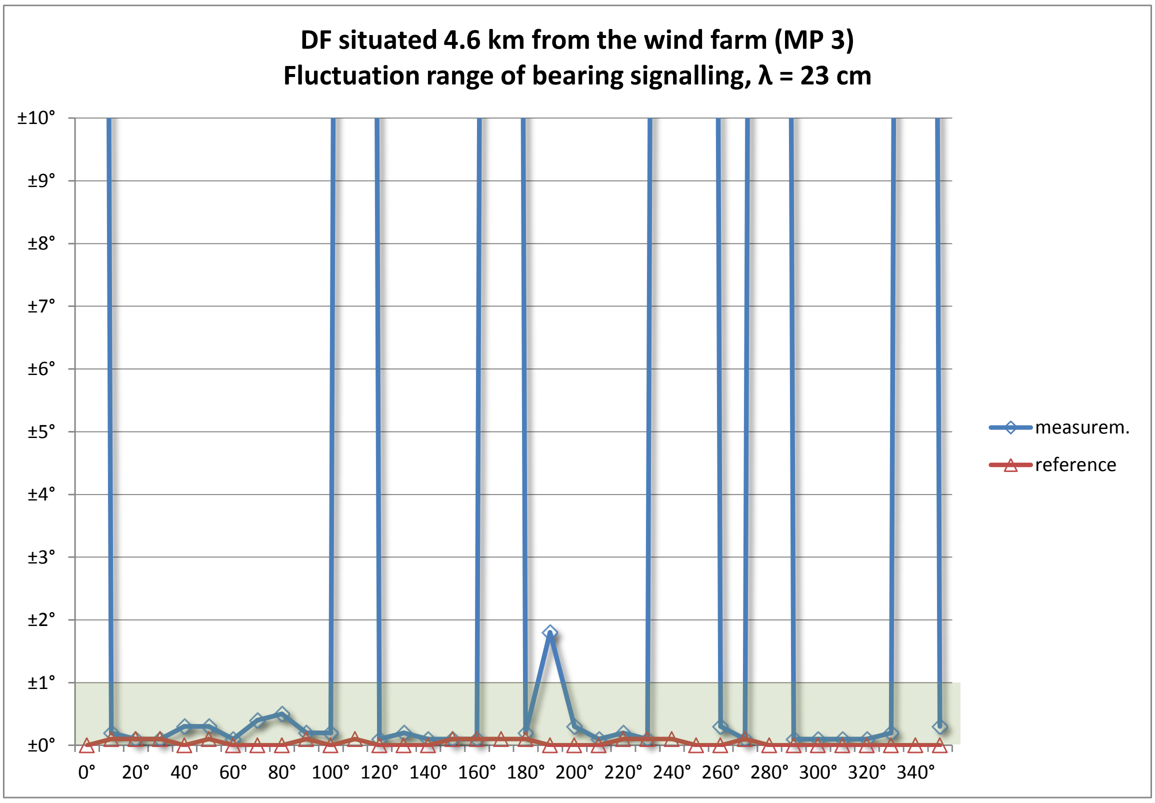

DF situated 4.6 km from the wind farm (MP 3)
Deviation from real direction, λ = 70 cm
20,0° 18,0° 16,0° 14,0° 12,0° 10,0° 8,0° 6,0° 4,0° 2,0° 0,0° -2,0° -4,0° -6,0° -8,0° -10,0° -12,0° -14,0° -16,0° -18,0° -20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

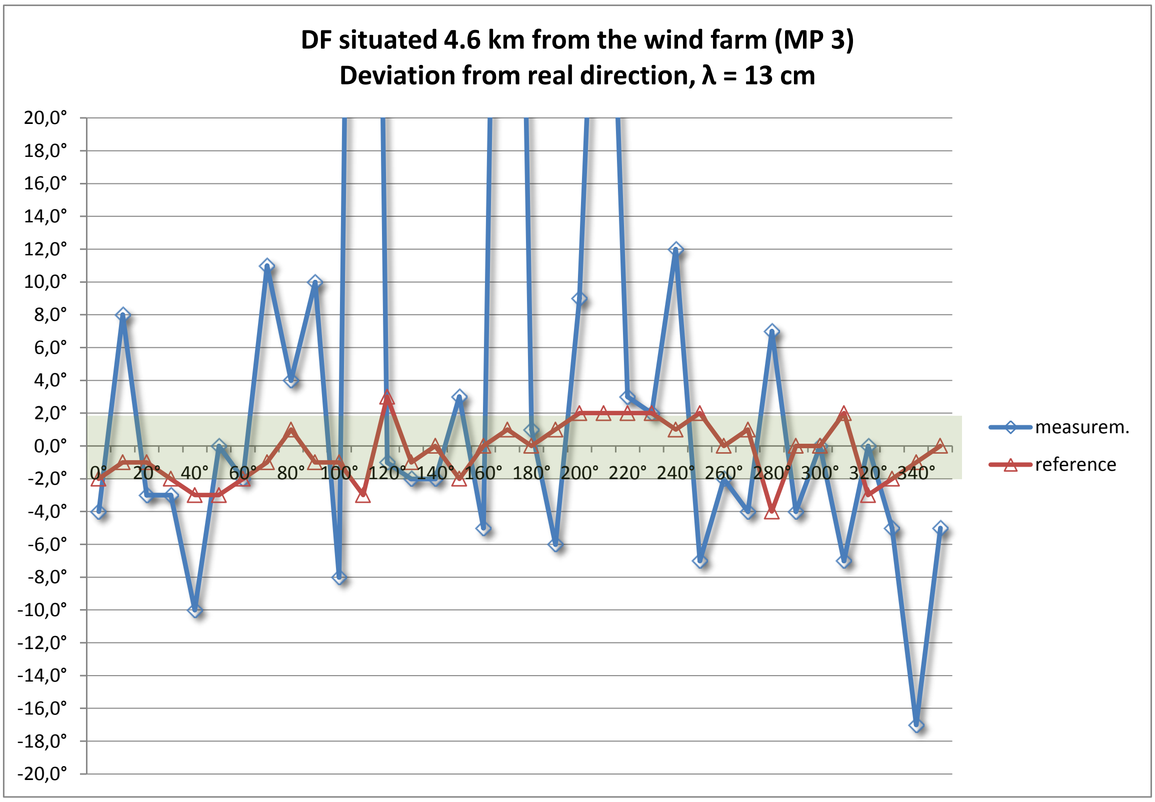

DF situated 4.6 km from the wind farm (MP 3)
Fluctuation range of bearing signalling, λ = 70 cm
±10° ±9° ±8° ±7° ±6° ±5° ±4° ±3° ±2° ±1° ±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

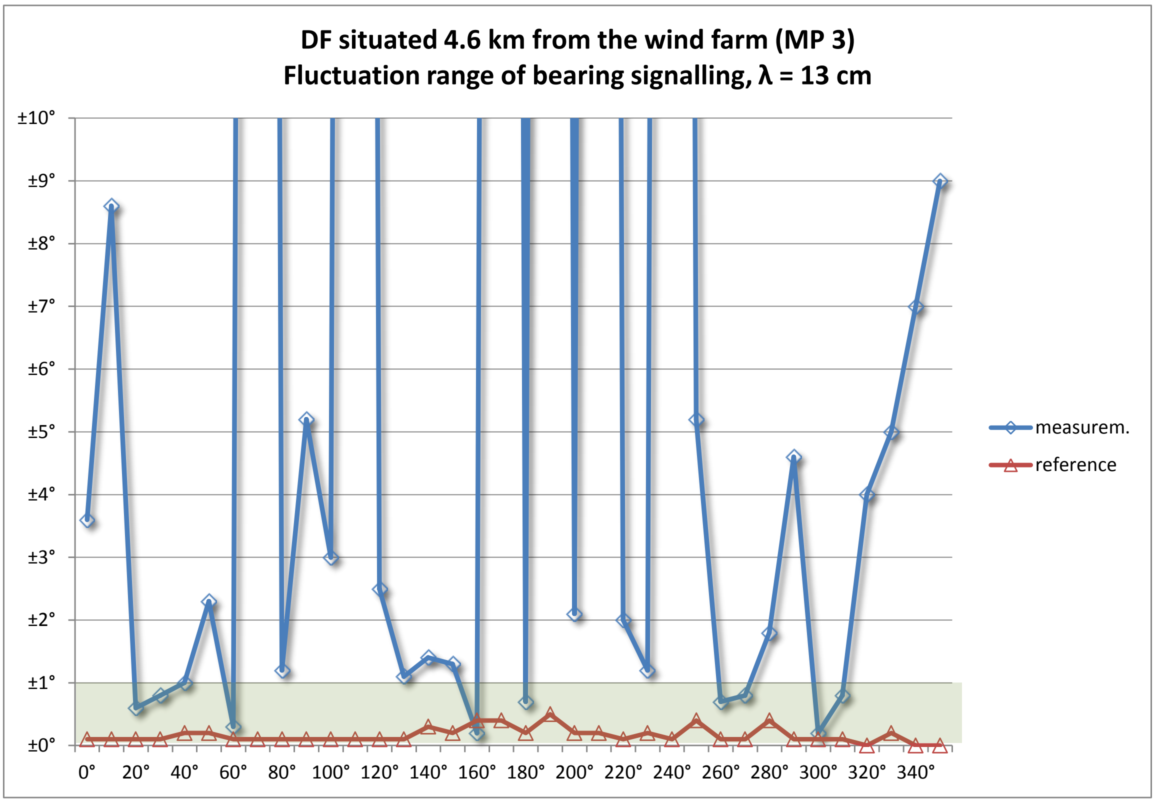

DF situated 4.6 km from the wind farm (MP 3)
Deviation from real direction, λ = 30 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

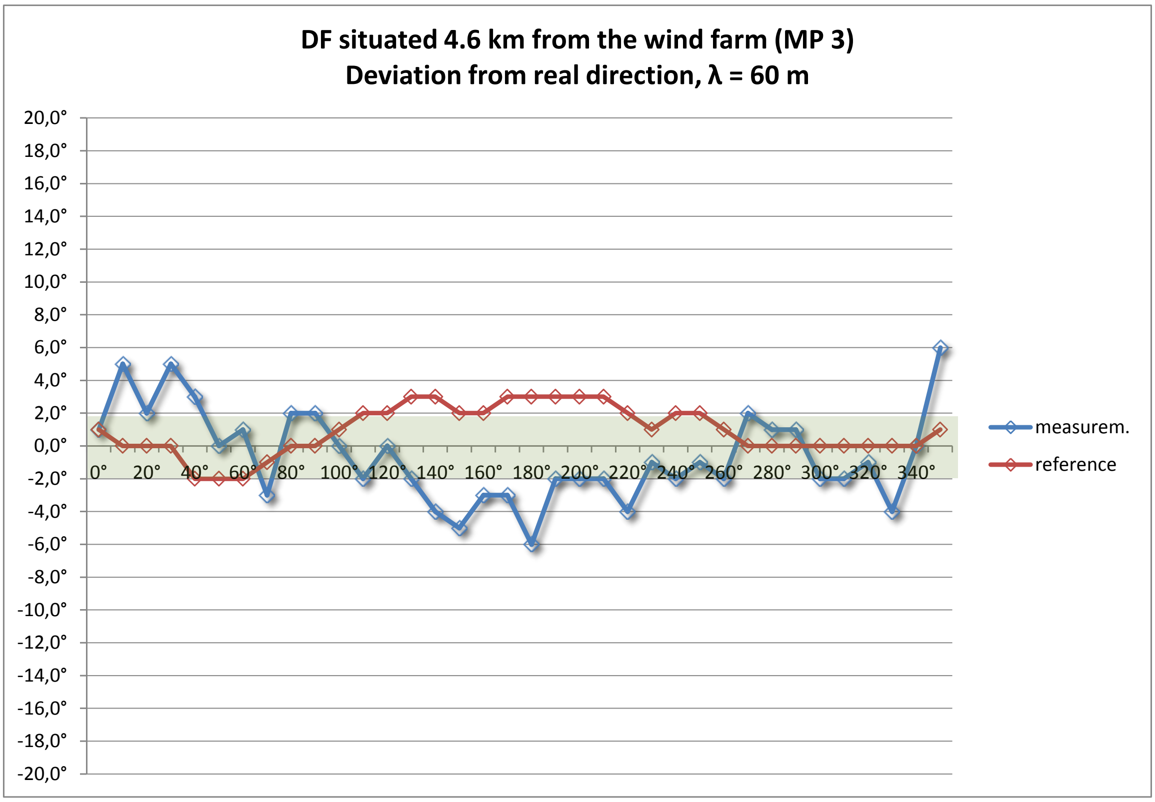

DF situated 4.6 km from the wind farm (MP 3)
Fluctuation range of bearing signalling, λ = 30 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference

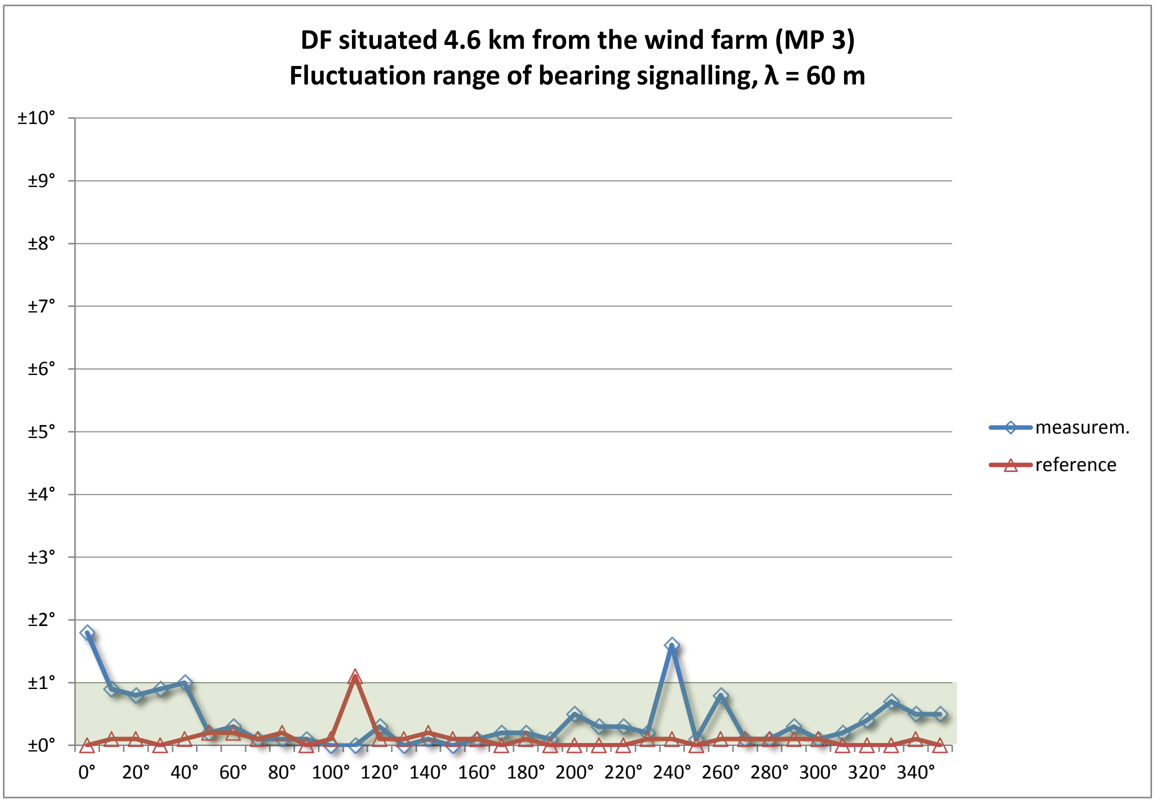

DF situated 4.6 km from the wind farm (MP 3)
Deviation from real direction, λ = 23 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated 4.6 km from the wind farm (MP 3)
Fluctuation range of bearing signalling, λ = 23 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated 4.6 km from the wind farm (MP 3)
Deviation from real direction, λ = 13 cm
20,0°
18,0°
16,0°
14,0°
12,0°
10,0°
8,0°
6,0°
4,0°
2,0°
0,0°
-2,0°
-4,0°
-6,0°
-8,0°
-10,0°
-12,0°
-14,0°
-16,0°
-18,0°
-20,0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference


DF situated 4.6 km from the wind farm (MP 3)
Fluctuation range of bearing signalling, λ = 13 cm
±10°
±9°
±8°
±7°
±6°
±5°
±4°
±3°
±2°
±1°
±0°
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
measurem.
reference





When situated 4.6 km from the wind farm, significant DF errors were recorded in all VHF/UHF bands.

In the 4 m and 2 m bands, marked DF errors were observed across all four quadrants. All in all, they are somewhat less pronounced than the measurements taken at a distance of 2.5 km (see § 9.2.3), although, in the 4 m band, even more pronounced DF errors were, in some cases, recorded in the direction away from the wind farm.

In the 70 cm band, the particularly marked DF errors recorded at a distance of 2.5 km in the direction away from the wind farm were no longer observed. By contrast, however, all four quadrants were affected by considerable DF errors, with the exception of a small angle range in the direction of the wind farm. This corresponds to the previous observations that, as a result of the greater distance, the arc formed by the wind farm is much shorter from the perspective of the direction finder.

In the 30 cm band, very marked DF errors in the direction away from the wind farm were once again evident. In a new development, however, very pronounced DF errors were recorded in the direction of the wind farm. Only narrow angle ranges transverse to the wind farm remain, with smaller but nonetheless marked DF errors.

In the 23 cm band, there are two larger angle ranges transverse to the wind farm with only small DF errors. In the 230° … 330° angle range, however, very pronounced fluctuations in DF values were observed, thus leaving only one usable sector in the direction of the wind farm.

In the 13 cm band, strong interference and chaotic DF errors were observed in all four quadrants.

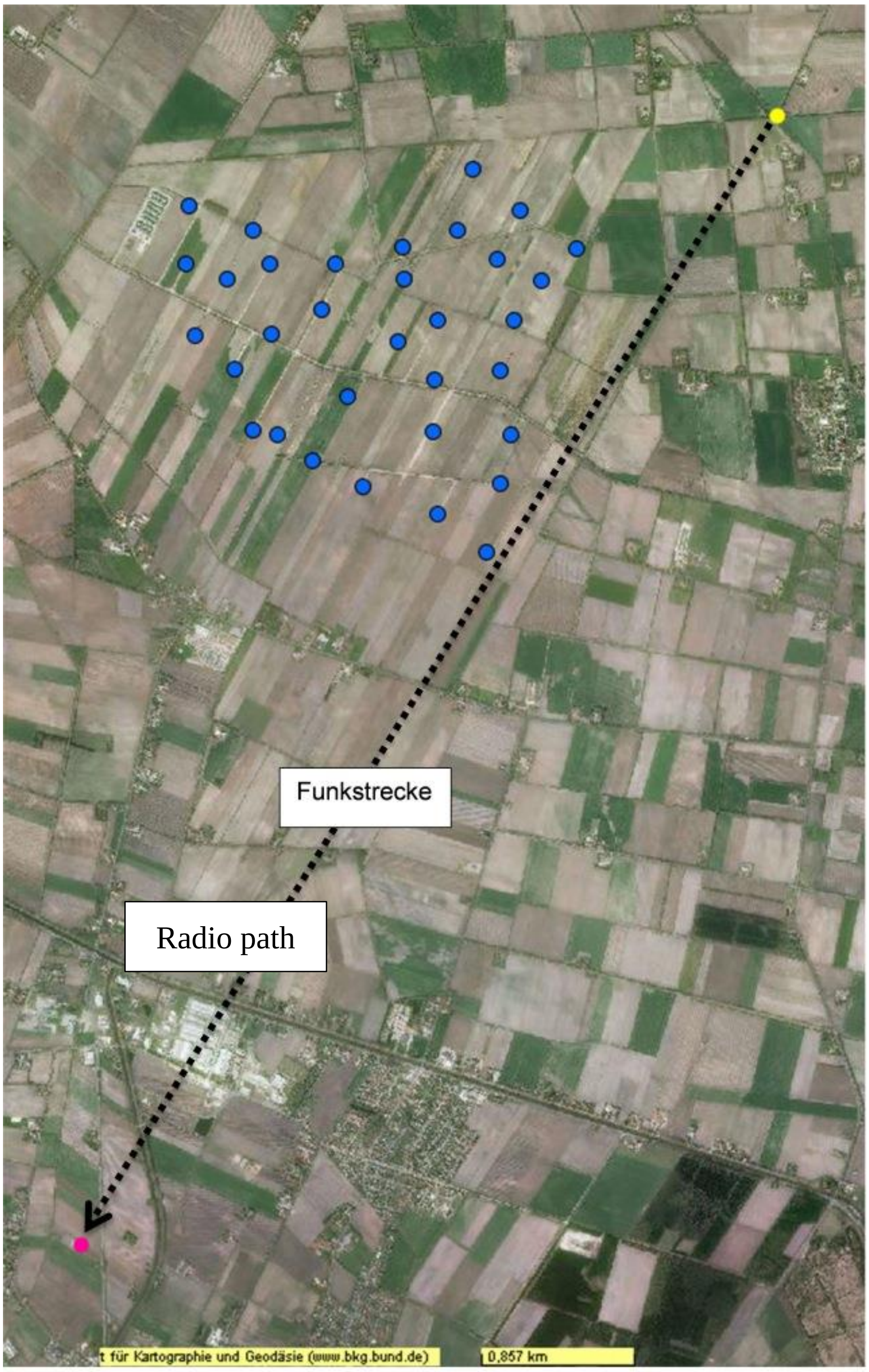
In the HF range, too, intolerable DF errors were recorded at this distance, both in the direction of and the direction away from the wind farm. However, these are much less pronounced than those recorded at a distance of 2.5 km. At this point, it is worth drawing attention to the explanations in § 9.1.2, which raise the question of the transferability of these measurements to a fixed HF direction finder for sky waves.

Conclusion: A fixed radio direction finder situated 4.6 km from the wind farm cannot be used in any of the specified VHF/UHF bands.

10 Level measurements

To examine the effect of wind turbines on reception levels, a radio monitoring path measuring approximately 7.5 km in length and skimming the south-east periphery of the wind farm in Haren was established. The purpose of the examination is to identify any level fluctuations at the location of the direction finder and to pinpoint the direct causality to the surrounding wind turbines.

Radio monitoring path showing the location of the direction finder (red dot) and transmitter (yellow dot)



Location of the transmitter for level measurements

A wind turbine functions best when the rotor speed is calibrated to the wind speed. In partial load working conditions (torque regulation), the blade angle and tip speed ratio are optimised in such a way that the rotor speed is roughly proportional to the wind speed. Modern three-blade turbines function in an effective range of 5 to 32 revolutions/minute. Measurements of the rotor speed carried out during the level measurements at the wind farm in Haren showed a variable rotation speed of between 5.1 and 6.5 seconds.

10.1 System sensitivity

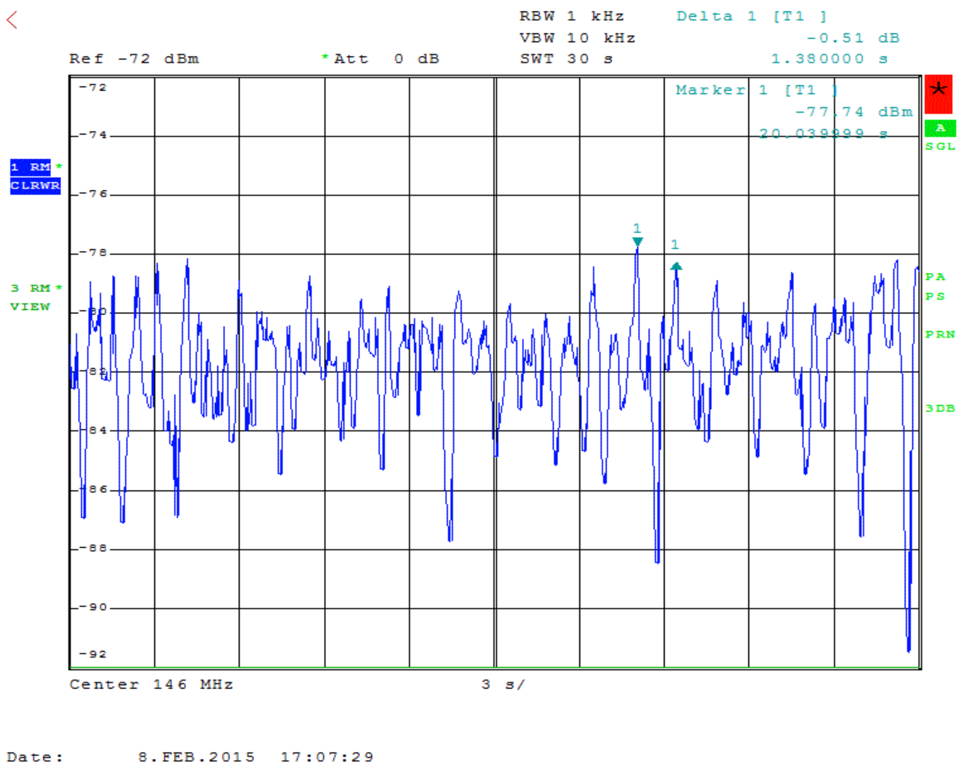
The system sensitivity of the receiving system used, which consisted of the spectrum analyser and a ground-plane antenna tuned to the relevant frequency range, is better than −134 dBm for all frequencies examined.

10.2 Registration within the time domain

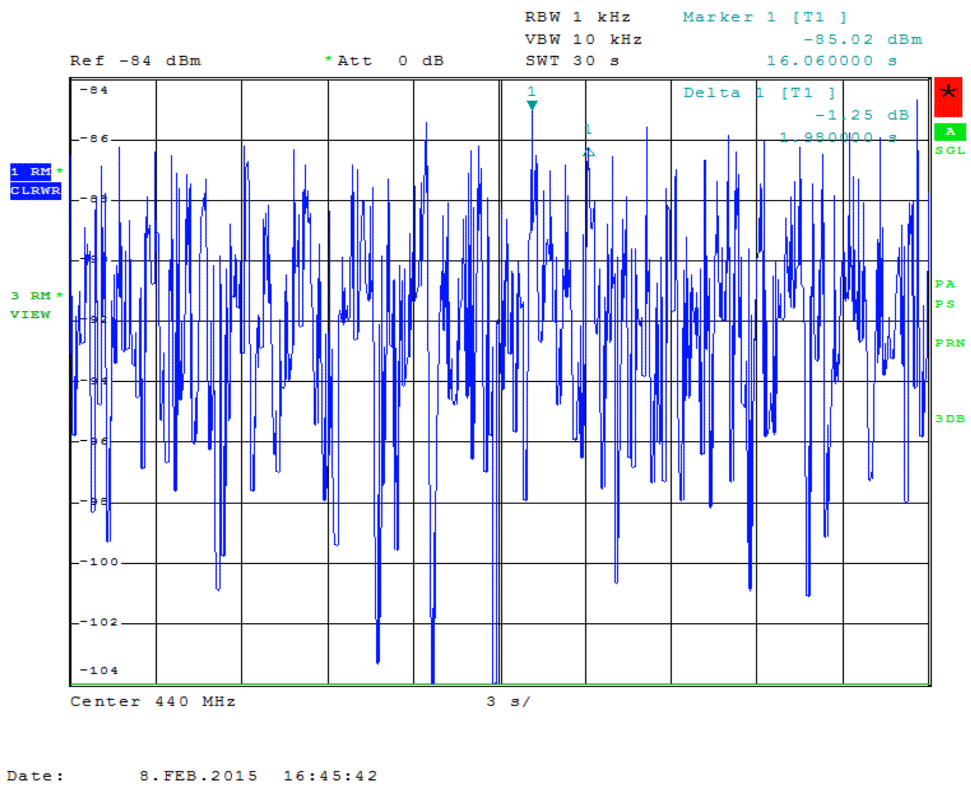
To gain an initial overview of the level fluctuations, levels were initially recorded across all frequency ranges over a period of three seconds within the time domain (zero span). An N0N signal was used as the test signal (unmodulated continuous carrier, continuous transmitter power/CW).

In all subsequent measurement recordings, the blue curve represents the level of signal received, while the green curve represents system sensitivity. In some cases, the received signal is so far above the noise that the green curve showing the noise floor is no longer visible.

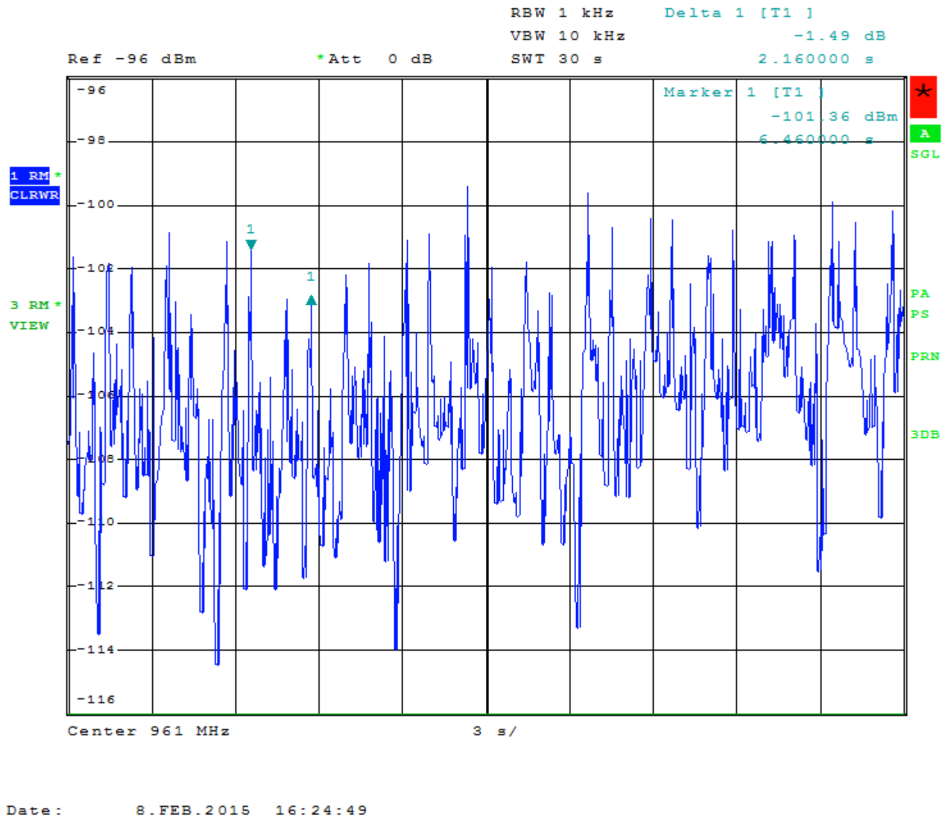
2 m band



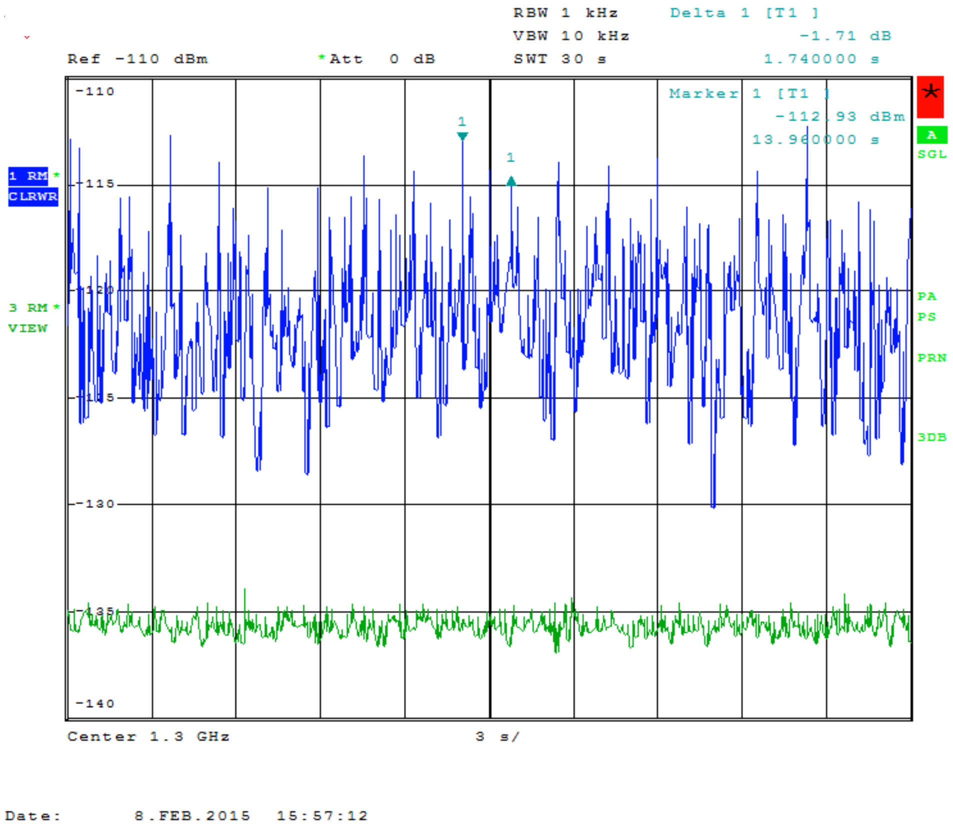
70 cm band



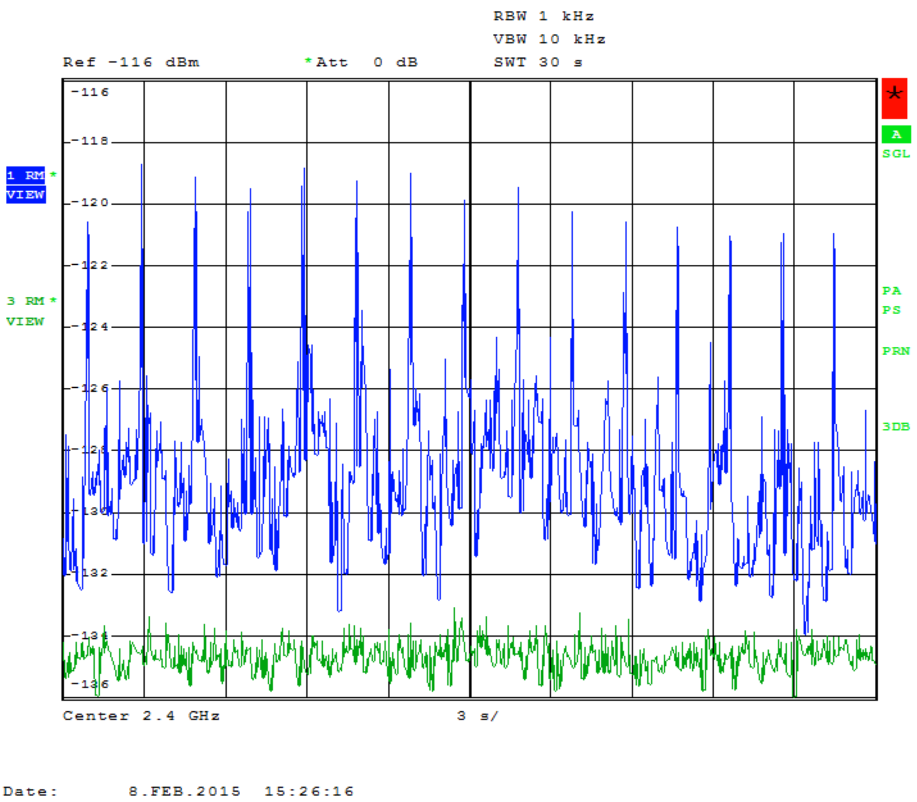
30 cm band



23 cm band



13 cm band



It is clear that levels not only peak and drop at regularly recurring intervals, but also that overlapping effects occur as a result of a number of different interference variables. The specific development of levels also appears to be heavily dependent on the wavelength of the radio signal.

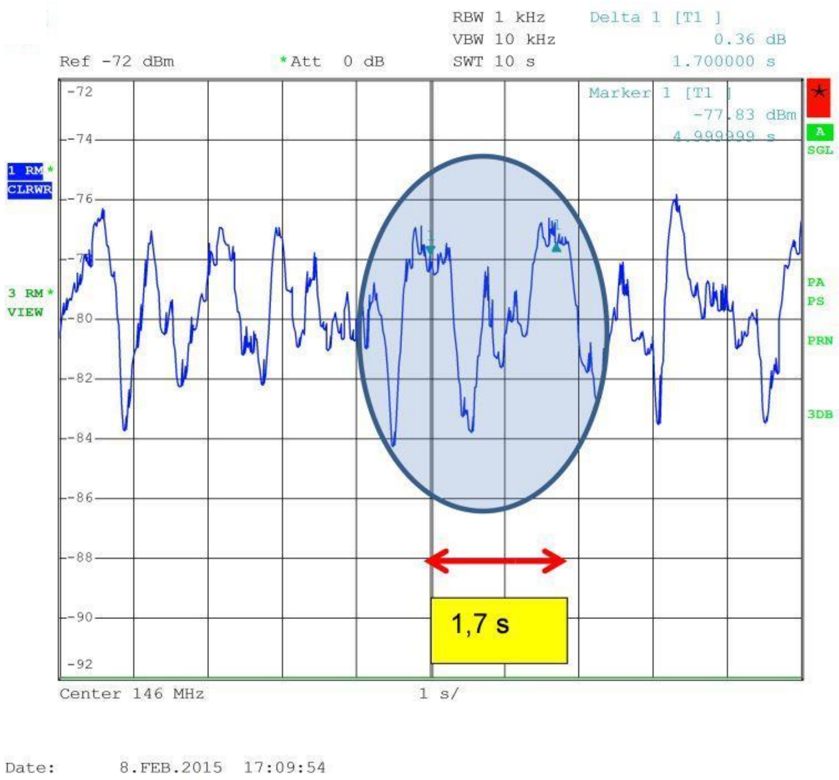
When the distance between individual level peaks is measured, the resulting time difference ranges from 1.7 to 2.16 seconds, which corresponds to a rotor revolution speed of 5.1 to 6.48 seconds (for three-blade turbines). These measured values correspond with the purely visual measurements of rotor revolution speeds of 5.1 to 6.5 seconds taken during the recording of the measured values. This suggests that individual rotor blades on the 29 wind turbines are responsible for these peaks and drops in level. Depending on wavelength, the effects of several rotor blades overlap, causing levels to fluctuate almost chaotically and making it difficult to attribute the fluctuations in level to individual blades. Particularly pronounced time points are marked with triangles.

The difference between the maximum and minimum levels, in this case measured using an RMS detector, is up to 20 dB.

10.3 Level analysis

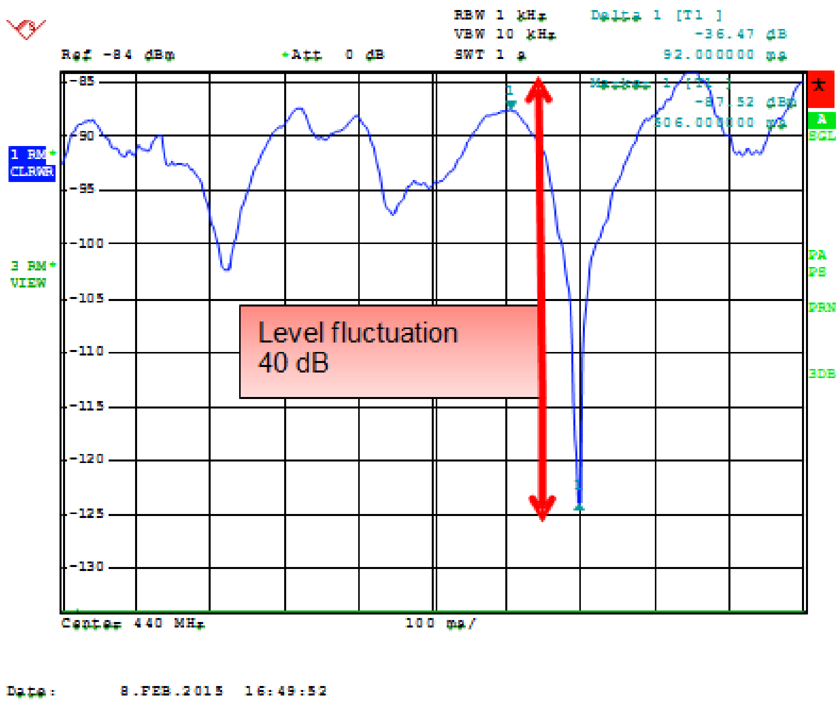
With shorter recording times of ≤ one second, it is even clearer that individual recurring peak levels can be grouped together and attributed to the same cause.

2 m band



At higher measurement rates, the results show that level fluctuations amount to as much as 40 dB. In practical terms, this equates to cancelling each other out.

70 cm band



The temporal development of the received level provides further evidence that drops in level are not caused by the direct shadowing of the radio signal by the rotor blades, which would be impossible in any case since the radio path skirts the periphery of the wind farm. Instead, the rotor blades cause reflections which are constantly overlapping and changing in terms of polarisation and duration, resulting in multipath reception. In the event of the anti-phase superposition of multiple reception paths, the paths almost completely cancel each other out. In principle, therefore, even more pronounced drops in level are possible than those documented here.

Calibrated field strength measurements are no longer possible under the outlined reception conditions. The decoding of digitally modulated signals may no longer be possible.

In any case, a significant loss of sensitivity occurs during the decoding of analogue and digitally modulated signals which cannot be fully compensated for by technical measures (e.g. upgrading to antennas with a higher gain).