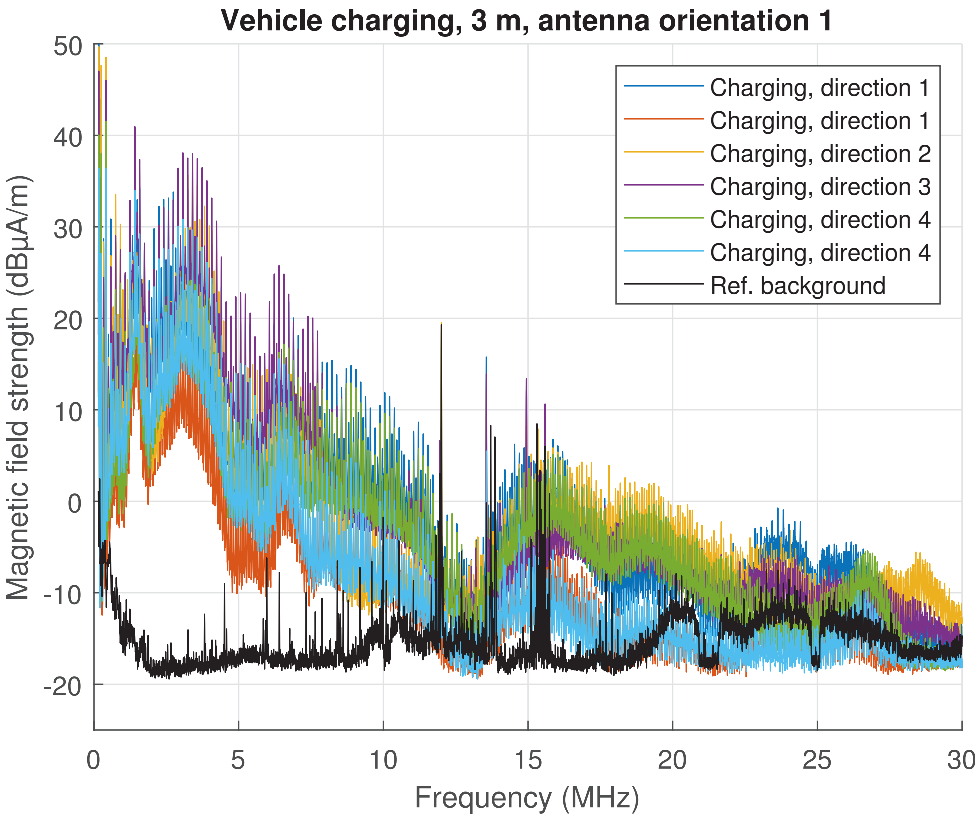
Radio frequency interference measurements of wireless power transfer for electrical vehicles

SOFIA BERGSTRÖM, SARA LINDER, KIA WIKLUNDH



FOI-R--5430--SE
ISSN 1650-1942
Februari 2022

Sofia Bergström, Sara Linder, Kia Wiklundh

Radio frequency interference measurements of wireless power transfer for electrical vehicles

Titel	Mätningar av radiofrekventa störningar från trådlös laddning av fordon
Title	Radio frequency interference measurements of wireless power transfer for electrical vehicles
Rapportnr / Report No.	FOI-R--5430--SE
Månad / Month	Februari
Utgivningsår / Year	2022
Antal sidor / Pages	64
ISSN	hl1650-1942
Kund / Customer	FMV
Forskningsområde	Ledningsteknologi
FoT område	Inget FoT-område
Projektnr / Project No.	E7161643
Godkänd av / Approved by	Christian Jönsson
Ansvarig avdelning	Telekrig

Bild/Cover: FOI

Abstract

Wireless power transfer (WPT) is a collective term for transmitting energy wirelessly. This work is a part of a measurement campaign to measure the electromagnetic emission from potential interference sources, with the long-term goal to assess its impact on radio communication systems nearby. Another goal is to gain knowledge about the emission levels radiated by the WPT station and the characteristics of the potential electromagnetic interference signals. This report presents results for stationary charging of vehicles using inductive wireless charging. The measurements cover 9 kHz-1 GHz, with additional measurement around GPS L1 (1575.42 MHz) and GPS L2 (1227.60 MHz). Measurements are made on five different measurement cases:

- background noise environment,
- charging system in stand-by, but no vehicle charging,
- vehicle (not charging),
- vehicle charging, and
- two vehicles charging simultaneously.

The overall conclusion is that the WPT station is emitting interference, in particular at frequencies up to 30 MHz, when it is charging. The charging frequency at 85 kHz is clearly seen in the measurements and at frequencies between 60 kHz and 30 MHz, a distinct effect from the charging vehicle is evident. There are disturbances at higher frequencies, but the levels are lower and it is not as evident, as for lower frequencies, that they originate from the WPT station.

Keywords: WPT, wireless power transfer, electromagnetic interference, radio frequency interference, interference

Sammanfattning

Wireless power transfer (WPT) är ett samlingsbegrepp för att överföra energi trådlöst. Detta arbete är en del av en mätkampanj för att mäta den elektromagnetiska emissionen från potentiella störningskällor, med det långsiktiga målet att undersöka dess påverkan på radiomottagare i närheten. Målet är också att öka förståelsen för såväl emissionsnivåer som karakteristik hos den eventuella störningssignalen. I denna rapport presenteras mätningar gjorda på infrastruktur kopplat till trådlös stationär laddning av fordon. Mätningarna täcker in frekvensområdet 9 kHz till 1 GHz, med ytterligare mätningar gjorda kring GPS L1 (1575.42 MHz) och GPS L2 (1227.60 MHz). Mätningar har genomförts på fem olika mätfall:

- bakgrundsmiljön,
- då laddinfrastrukturen var påkopplad men inget fordon laddades,
- på fordon som ej laddas,
- då fordonet laddas, och
- samt då två fordon laddas samtidigt.

Den övergripande slutsatsen är att WPT-stationen skapar emission, speciellt på frekvenser upp till 30 MHz, när fordon laddas. Laddningen, som sker på 85 kHz, syns tydligt i mätningarna. I synnerhet på frekvenser mellan 60 kHz och 30 MHz är effekten uppenbar när fordonet laddas. På de högre frekvenserna finns störningar, men störningsnivån är lägre och det är inte lika tydligt, som för de lägre frekvenserna, att dessa kan kopplas till laddningen.

Nyckelord: WPT, trådlös laddning, elektromagnetisk störning, radiofrekvent störning, störning

Contents

1 Introduction 7
1.1 Goal . . . 7
1.2 Prerequisites for the measurement campaign . . . 7
1.3 Outline . . . 7

2 Measurement setup 9
2.1 Measurement cases . . . 9
2.2 Measurement setup and equipment . . . 10
2.2.1 Measurement receiver . . . 10
2.2.2 Antennas . . . 11
2.2.3 Other equipment . . . 11

3 Measurement results 13
3.1 Frequency range 9-150 kHz . . . 13
3.2 Frequency range 150 kHz-30 MHz . . . 18
3.3 Frequency range 30-200 MHz . . . 22
3.3.1 VHF air traffic control band . . . 25
3.4 Frequency range 200 MHz-1 GHz . . . 28
3.4.1 Tetra band . . . 31
3.5 GPS-bands . . . 33
3.5.1 GPS L2 . . . 33
3.5.2 GPS L1 . . . 36

4 Conclusions 39

A Additional measurements cases 41
A.1 9-150 kHz . . . 41
A.2 150 kHz-30 MHz . . . 46
A.3 30-200 MHz . . . 50
A.4 VHF air traffic control band . . . 52
A.5 200 MHz-1 GHz . . . 54
A.6 Tetra band . . . 57

B Antenna and filter measurements 61

1 Introduction

Wireless power transfer to electrical vehicles (WPT-EV) is a new technology application that currently is tested and evaluated. For inductive wireless charging, the frequency band 75-90 kHz can be used to transmit energy from a transmitting coil in the ground to a receiving coil in the vehicle. The measurements presented in this report were carried out 5-7 July 2022 on a system for WPT-EV.

1.1 Goal

The long-term goal of the measurement campaign is to create a basis for assessments of whether or not WPT-EV can cause electromagnetic interference in radio communication systems nearby. Another goal is to gain knowledge about the level of emissions from WPT-EV and the characteristics of the potential electromagnetic interference. This report describes how the measurements were carried out as well as the results of the measurements, which can be used as a basis for future analyses. The measurements cover 9 kHz-1 GHz, with additional measurements around GPS L1 (1575.42 MHz) and GPS L2 (1227.60 MHz).

1.2 Prerequisites for the measurement campaign

As the measurements took place outdoors, the electromagnetic environment of the surroundings also affected the results. The surrounding environment can consist of a number of signals, including strong radio transmitters that can adversely affect the measuring receiver. The surrounding environment is also shifting with time, as other vehicles are passing by or electrical equipment is being switched on and off. There is also a risk that the vehicle itself causes relatively large emissions. In order to be able to distinguish what is caused by the surrounding environment, the vehicle, or the wireless charging, several different measurement cases that distinguish these situations are needed. In these complex measuring situations, there are high performance requirements on measuring equipment. It is therefore important to remember that the measurement results in this report apply to the conditions at the time of the measurement.

1.3 Outline

Chapter 2 presents the measurement setup, including the measurement equipment and measurement settings, as well as the measurement cases. As the measurements were carried out outdoors and thereby running the risk of large variations in the measurements (due to the surrounding signal environment), a large number of measurements were carried out for the various measurement cases. Chapter 3 presents results for the two main measurement cases; the background (when the system is turned off) and when the vehicle is charging. Results for the other measurement cases are found in Appendix A for comparison. Chapter 4 summarizes the conclusions from the measurements. In Appendix B, further details about the measurement equipment can be found.

2 Measurement setup

The measurement cases, the measurement setup and measurement equipment are described in this chapter.

2.1 Measurement cases

The main purpose of the measurement is to gain knowledge of the levels of the emitted electromagnetic field when a vehicle is charged. However, the measurement is made on an outdoor site and will capture other signals in addition to those from the charging of the vehicle. In particular, strong transmitters in the vicinity can cause overload problems in the antennas and in the receiver. The signal environment will also change in time. Disturbance signals, other than those caused by the measuring object, may change during the measurement. There is also a risk that the vehicle itself will create emissions. To differentiate between the emissions from other sources, from the vehicle itself and emissions caused by charging with WPT, several measurement cases have been identified and used. The following cases were measured:

- background noise environment,
- charging system in stand-by, but no vehicle charging,
- vehicle (not charging),
- vehicle charging, and
- two vehicles charging simultaneously.

The measurements was measured at different directions, seen in Figure 2.1, to evaluate if there are spacial differences. The distance to the antenna, 3 or 10 meters, are measured from the charger in any of the four directions. When two cars are charged simultaneously, direction 5 are used.

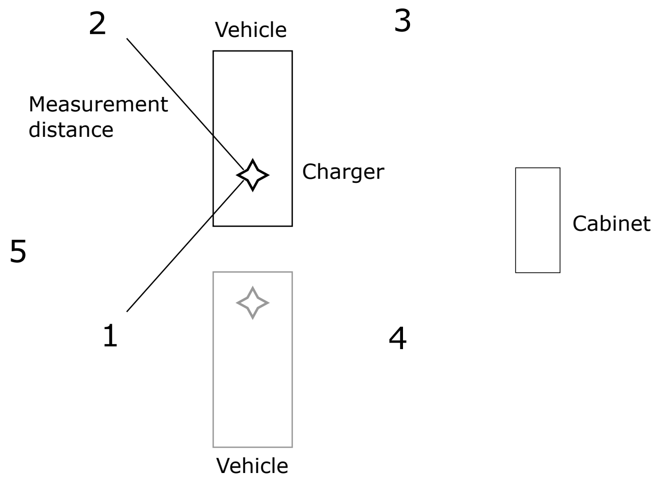


Figure 2.1: Illustration of measurement directions.

2.2 Measurement setup and equipment

The measurement setup consists of an antenna connected to a measurement receiver, ESRP, via a cable of 25 meters. In some of the frequency ranges filters are connected, and in some measurement a pre-amplifier is used. Due to the different attenuation and the whether the pre-amplifier is used or not, the sensitivity of the measurement system can vary. The equipment are more closely described below.

Table 2.1 presents the bandwidths, antennas and filters, and used antenna orientations for the different frequency ranges. Antenna orientations for the loop antenna describe if the loop is perpendicular to the direction of charger (1) or is facing the charger (2), see Figure 2.2. For the other antennas, the antenna polarisation is stated by H, horisontal, or V, vertical.

Table 2.1: Resolution bandwidth (RBW), antenna and filter and antenna orientation used in the measurements.

Frequency range	RBW [Hz]	Antenna and filter	Antenna orientations
9-150 kHz	300	Loop antenna	1 & 2
150 kHz-30 MHz	10k	Loop antenna	1 & 2
30-200 MHz	100k	Biconical antenna,	H & V
200 MHz-1 GHz	100k	Log-periodic antenna (HL023)	V
1.2-1.25 GHz (GPS L2)	100k	Log-periodic antenna (HL040), L2 filter	V
1.55-1.6 GHz (GPS L1)	100k	Log-periodic antenna (HL040), L1 filter	V
108-140 MHz (VHF COM)	10k	Log-periodic antenna (HL040), VHF filter	H & V
370-470 MHz (Tetra)	10k	Biconical antenna, FM filter	V

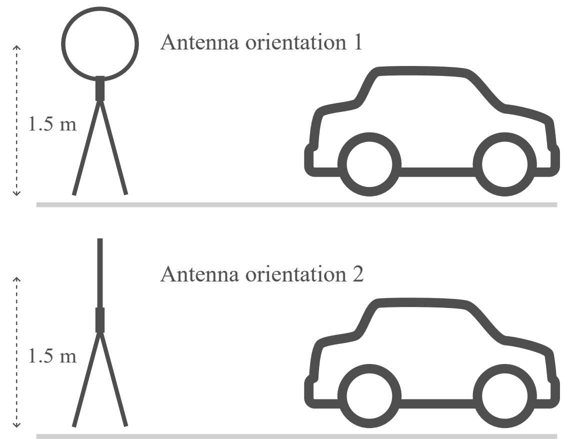


Figure 2.2: The two antenna orientations for the loop antenna where the vehicle is placed in the same plane as the paper. (Car icon image design by vectorstock)

2.2.1 Measurement receiver

The measuring receiver used is of type ESRP from R&S, with serial number 1316-4500K03-101591. The measuring receiver is used in receiver mode, which means that preselection filters are used to filter out interference from other frequency bands. The receiver was used in time-domain mode which is based on FFT (fast Fourier transform), which measures several frequencies simultaneously. The receiver automatically divides the current frequency range into several sub-bands that are measured sequentially. The measurement time were 100 ms per sub-band. The FFT method usually leads to considerably shorter measurement times than frequency-sweeping measurements. This also means that the measurement of all sub-bands does not take place simultaneously and since the measured signal can vary rapidly, measurements of different sub-bands can have abrupt shifts in signal level. Similar problems exist, of course, for a sweeping spectrum analyzer as well, but then the change takes place continuously over frequency, which does not create as abrupt shifts in signal level.

The ESRP was controlled from a program on a connected laptop. For each measurement, the frequency range was measured a number of times, usually 10 times, and the result was saved both as a spectrogram and in a text file. The spectrogram consists of several sweeps for the peak detector, for example for 10 sweeps. In the result file, the max hold was saved for the detectors peak and RMS, which means that the highest value during the different sweeps was saved for each frequency and detector. Clear write for the peak detector (i.e. the last sweep) was also saved as well as the current settings used in the measurement.

2.2.2 Antennas

Below is a list of the antennas used to measure field strength in each frequency range, as well as their sensitivity. The frequency range in parentheses is the range in which the antenna is used in the measurements. The antennas are calibrated measuring antennas with known antenna factors.

Loop antenna: For the lower frequencies, an active loop antenna from Rohde & Schwarz of type HFH2-Z2E was used. The antenna covers the frequency range 9 kHz to 30 MHz and is powered by a IN600 Bias Unit from Rohde & Schwarz. The antenna factor is presented in Figure B.1 in appendix from the calibration at Rohde & Schwarz 2021-04-30.

Biconical antenna: For frequencies between 30 and 200 MHz, a antenna from ETS Lindgren of type 3104C was used. The antenna factor is shown in Figure B.2 in appendix.

Log-periodic antenna, R&S HL023-A1: For frequencies above 200 MHz a log-periodic antenna from Rohde & Schwarz of type HL023-A1 was used. The antenna factor is shown in Figure B.3 in appendix.

Log-periodic antenna, R&S HL040: For frequencies above 1 GHz a log-periodic antenna from Rohde & Schwarz of type HL040 was used. The antenna factor is shown in Figure B.4 in appendix.

2.2.3 Other equipment

In some of the measurements, other equipment such as pre-amplifier, current probe and a filter were used. These are presented here.

Preamplifier: A broadband preamplifier from Schwarzbeck of the type BBV-9744 was used in some of the measurements with the passive antennas for frequencies above 30 MHz. The preamplifier has a frequency range of 9 kHz-6 GHz.

FM filter: When measuring emission in the frequency band 30-200 MHz, an FM filter was used to filter out strong radio transmissions to avoid that the preamplifier or measuring receiver was overloaded. The filter used was an NSBP-108 + band stop filter 88-108 MHz from Mini-Circuits. Gain for the filter is shown in Figure B.5 in appendix.

GNSS L1 filter: To be able to measure the noise floor in the otherwise quite GPS band a passband filter is used with centerfrequency at GPS L1. The used filter was L1FM-HR-E-TF from GPS Source. Gain for the filter is shown in Figure B.6 in appendix.

GNSS L2 filter: The 20 MHz bandpass filter used at GPS L3 was a Palsternack PE8704. Gain for the filter is shown in Figure B.7 in appendix.

VHF COM filter: A bandpass filter 3527 from Rockwell International covering 118-136 MHz. Gain for the filter is shown in Figure B.8 in appendix.

Cables: Coaxial cable was used between antennas and measuring receivers. Losses for these cables have been measured and the presented results are compensated with these losses.

3 Measurement results

The measurement results are presented in this chapter. The results are divided into the different frequency ranges, given by Table 2.1. For each range, one representative measurement with the WPT-EV system off, has been selected, shown in black in the figures. The purpose of the background measurements is to find a representative level that can be used as comparisons to the emission levels that occur when the vehicle is charged. Since the measurements are made outdoors, the so-called background contains signals from the surrounding and is site-dependent. Hence, the measured background environment are rather noisy. The curves are illustrating the trends and the measurement levels should be compared with caution. In some of the figures there are several measurements with the same settings. The difference between these measurements demonstrates that uncontrolled variables in the surroundings can affect the measurements.

3.1 Frequency range 9-150 kHz

Figure 3.1 shows the background in four different measurements for the frequency range 9-150 kHz, all at a distance of 3 meters and measured at direction 1. One representative measurement with background has been selected, shown in black in the figure.

Figure 3.2, 3.3, 3.4 and 3.5 presents the measurement at a distance of 3 and 10 meters for two antenna orientations when the vehicle is charging, which theoretically should have the highest levels. There is a high peak at 83.025 kHz in all of the curves, which comes from the charging frequency. The height of the peak is at most 81 dBµA/m but varies, see Table 3.1. Within the same measurement, i.e. 1 second, the peak has a constant height, see spectrogram in Figure 3.6. Figure 3.2 and 3.3 shows the results at a distance of 3 meters and there is a clear difference to the background above 70 kHz. In Figure 3.4 and 3.5, the results at a distance of 10 meters, there are lower levels but still a visible difference around 80 kHz.

Figure 3.7 shows the vehicle when it is almost fully charged. The height of the charging peaks at 83 kHz are between 38.4 and 46.9 dBµA/m. This can be compared to Figure 3.4 with the same distance and antenna orientation.

In appendix A.1, there are measurements of only the vehicle (Figure A.1, A.2, A.3 and A.4), the system in stand-by without vehicle (Figure A.5, A.6 and A.7) and when two vehicles are charging simultaneously (Figure A.8). In some of the measurements of the vehicle when it is not charging there is a peak at 85.5 kHz. This corresponds to the guiding frequency of the charging device, used to help the vehicle to find the correct charging position. It is seen in six of the curves, and in all of these the signal is present in all sweeps in the measurement.

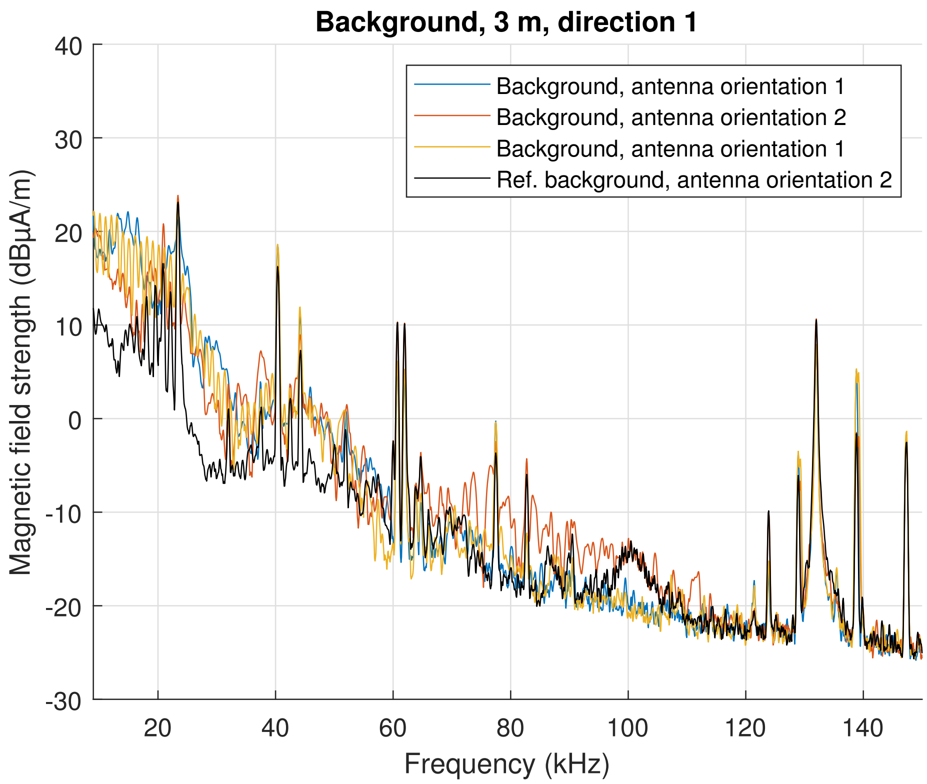


Figure 3.1: Measurement of the background in the frequency range 9-150 kHz at a distance of 3 meters and measured at direction 1 where the selected background measurement is shown in black.

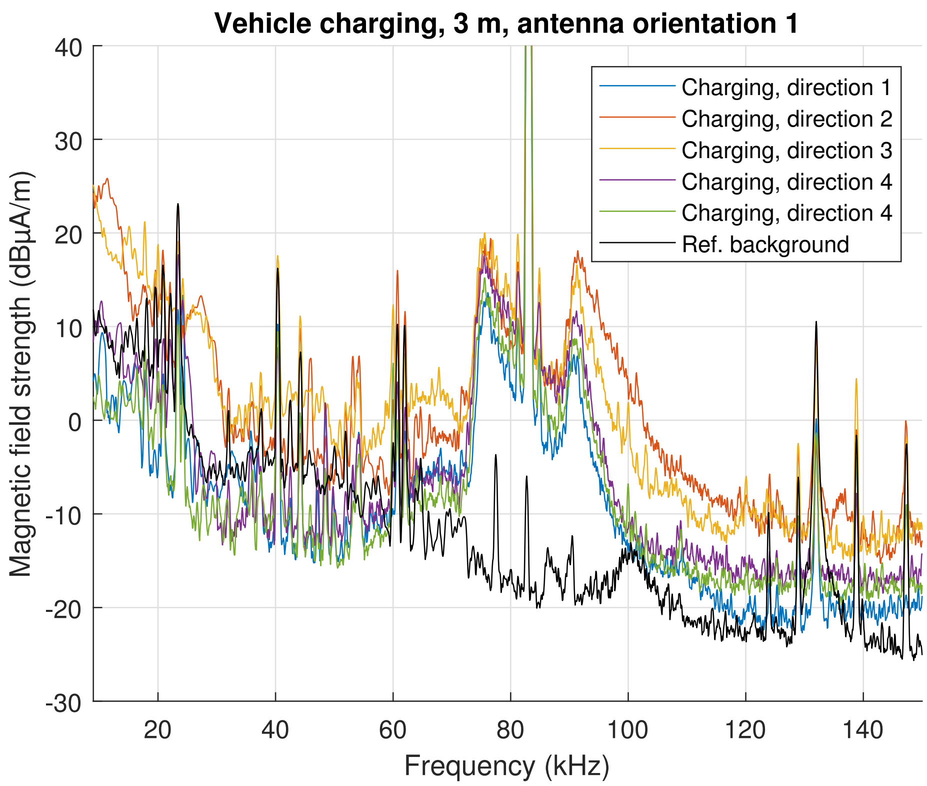


Figure 3.2: Measurement of vehicle charging at a distance of 3 meters and with antenna orientation 1 for the frequency range 9-150 kHz. The reference background is shown in black.

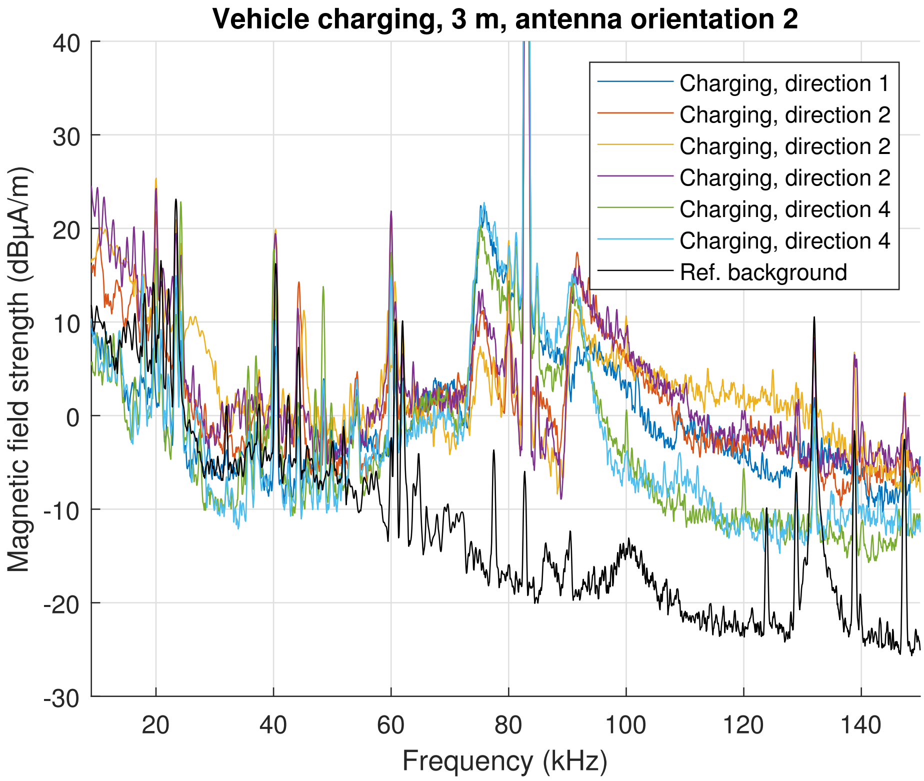


Figure 3.3: Measurement of vehicle charging at a distance of 3 meters and with antenna orientation 2 for the frequency range 9-150 kHz. The reference background is shown in black.

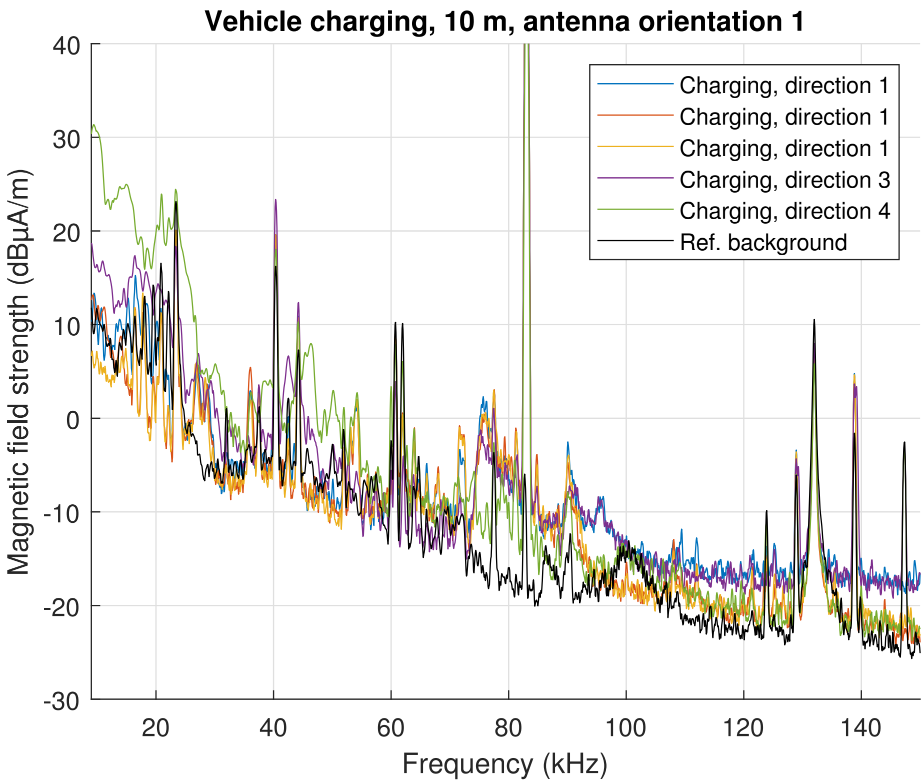


Figure 3.4: Measurement of vehicle charging at a distance of 10 meters and with antenna orientation 1 for the frequency range 9-150 kHz. The reference background is shown in black.

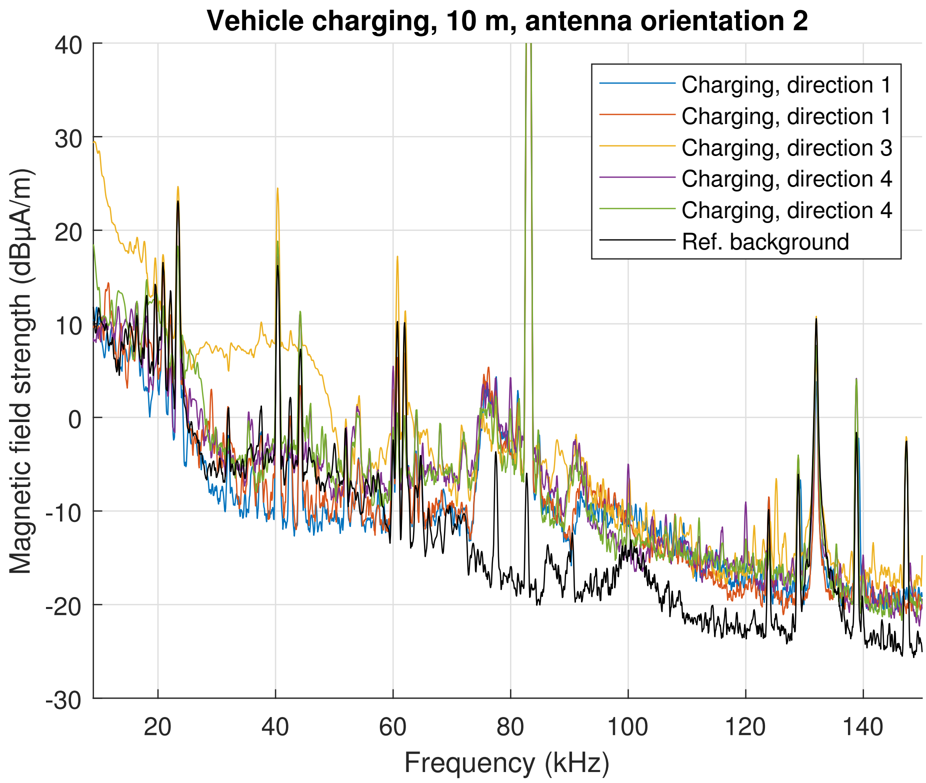


Figure 3.5: Measurement of vehicle charging at a distance of 10 meters and with antenna orientation 2 for the frequency range 9-150 kHz. The reference background is shown in black.

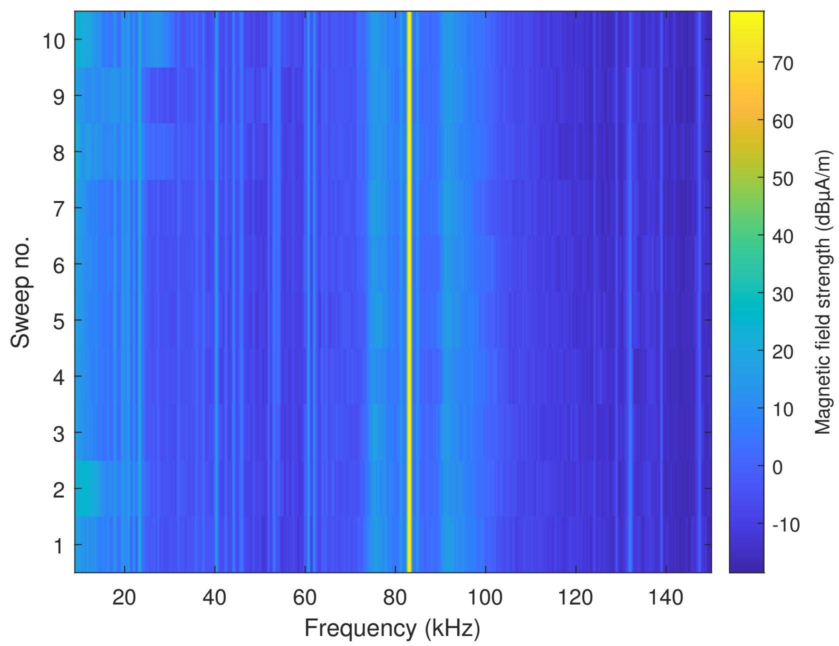


Figure 3.6: Spectrogram representation vehicle charging at a distance of 3 meter with antenna orientation 1 and direction 1.

Table 3.1: Values of the peak at 83.025 kHz for case when vehicle is charging.

Distance	Antenna orientation	Direction	Peak value [dBμA/m]
3 m	1	1	71.4
3 m	1	2	78.8
3 m	1	3	81.2
3 m	1	4	75.5
3 m	1	4	71.7
3 m	2	1	78.7
3 m	2	2	64.3
3 m	2	2	64.3
3 m	2	2	64.6
3 m	2	4	78.8
3 m	2	4	79.8
10 m	1	1	58.7
10 m	1	1	58.7
10 m	1	1	58.5
10 m	1	3	58.6
10 m	1	4	51.1
10 m	2	1	61.1
10 m	2	1	61.0
10 m	2	1	62.3
10 m	2	3	64.4
10 m	2	4	64.9

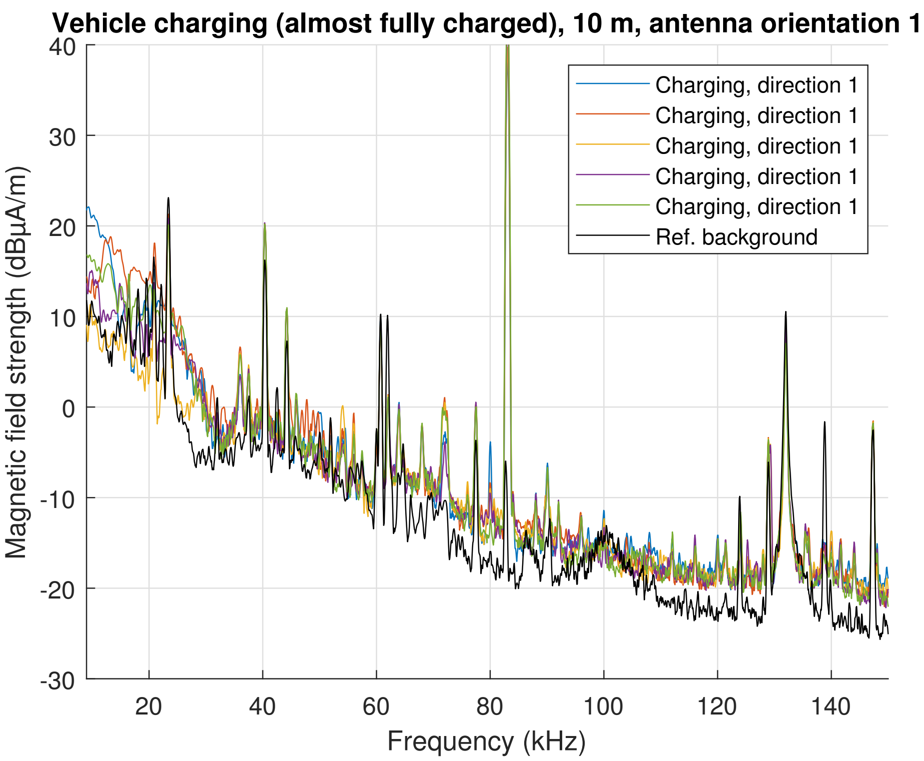


Figure 3.7: Measurement of vehicle charging, when the vehicle is almost fully charged, at a distance of 10 meters and with antenna orientation 1 for the frequency range 9-150 kHz. The reference background is shown in black.

3.2 Frequency range 150 kHz-30 MHz

Figure 3.8 shows six different background measurements at a distance of 3 meters. One representative measurement has been selected, shown in black in the figure, is used as comparison for the other measurement cases within this frequency range. All measurements contains many small peaks between 5-15 MHz. This is probably some of the many radio system working in this range, possibly at a far distance. The 'hills' in the right of the figure, around 20-25 MHz, can on the other hand be some closer disturbers. The distance between the peaks are around 200 kHz.

Figure 3.9, 3.10, 3.11 and 3.12 presents the measurement, at a distance of 3 and 10 meters and for two antenna orientations, of the frequency range 150 kHz-30 MHz when the vehicle is charging. Figure 3.13 is zoomed in at 1-6 MHz when the vehicle is charging at a distance of 3 meters and with antenna orientation 1, but the same pattern are seen in all said figures. The distance in frequency between the high peaks are 166 kHz and between a high peak and its smaller neighbour peak 83 kHz. This indicates it comes from the charging frequency. Figure 3.14 shows an example of the spectrogram for charging the vehicle and it can be seen the levels are constant over the measurement time of 1 second.

In appendix A.2, there are measurements of only the vehicle (Figure A.9, A.10, A.11 and A.12), the system in stand-by without vehicle (Figure A.13, A.14 and A.15) and when two vehicles are charging simultaneously (Figure A.16). Notable from the graphs with vehicle without charging is that there is an increased level from five of ten of the measurement cases at a distance of 10 meters, which is not seen at a distance of 3 meters. The measurements with higher level had no obvious connection in time and was measured during two different days. The distance between the high peaks to the left in the figures are 171 kHz which most likely are related to the guiding frequency of 85.5 kHz. At the peak around 20 MHz there are a frequency component of 57.0 kHz which can not be explained by any signal in the measurements from 9-150 kHz.

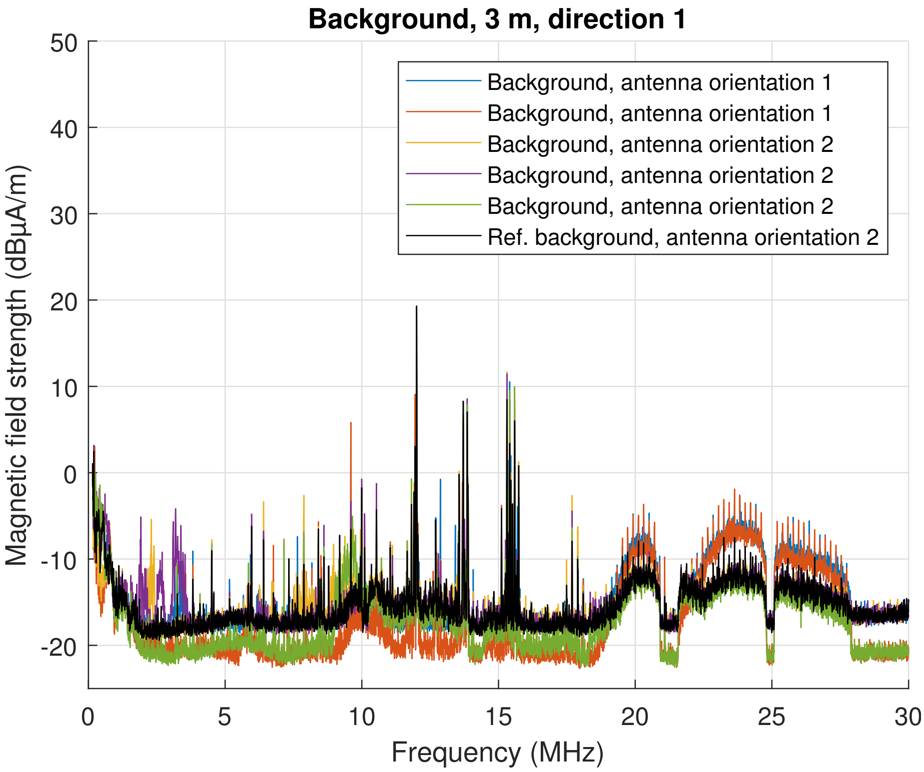


Figure 3.8: Measurement of the background in the frequency range 150 kHz-30 MHz where the selected background measurement is shown in black.

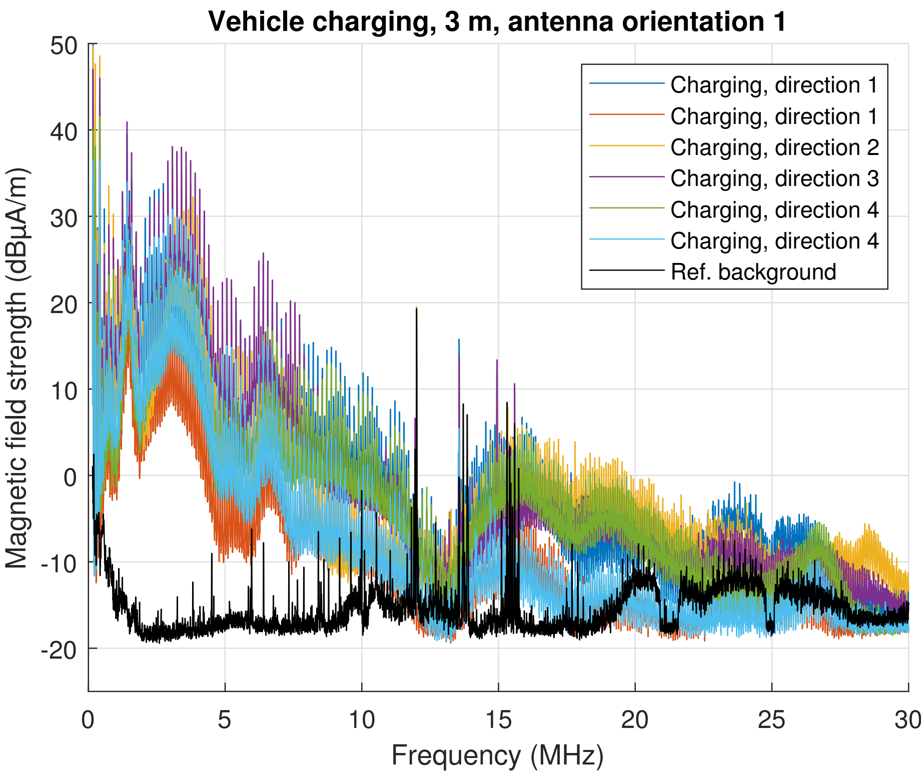


Figure 3.9: Measurement of vehicle charging at a distance of 3 meters and with antenna orientation 1 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

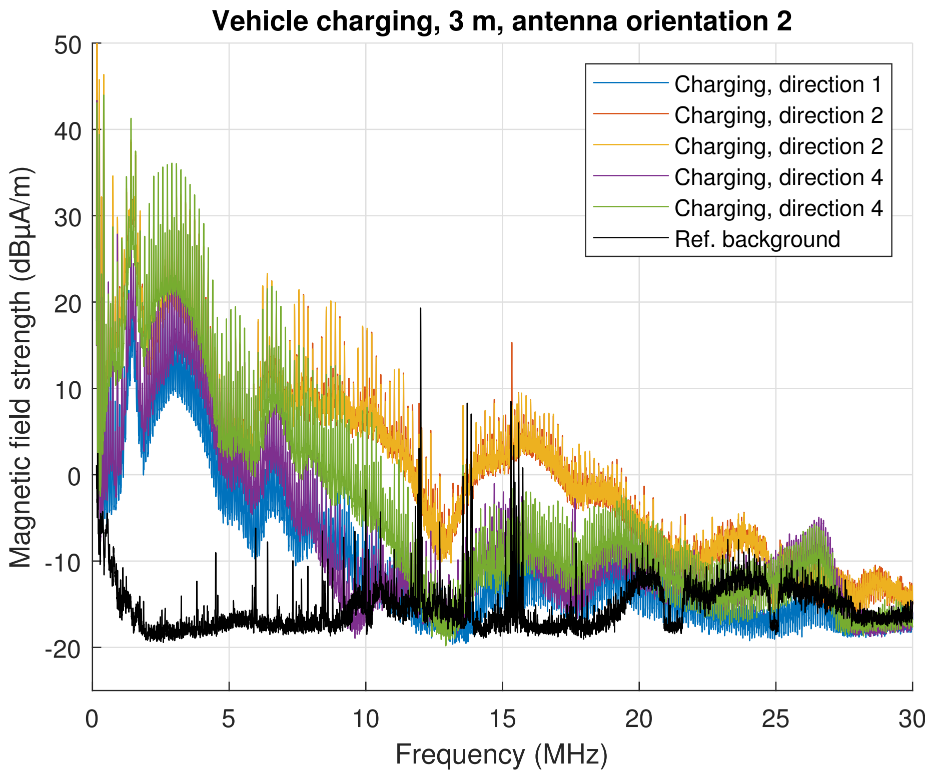


Figure 3.10: Measurement of vehicle charging at a distance of 3 meters and with antenna orientation 2 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

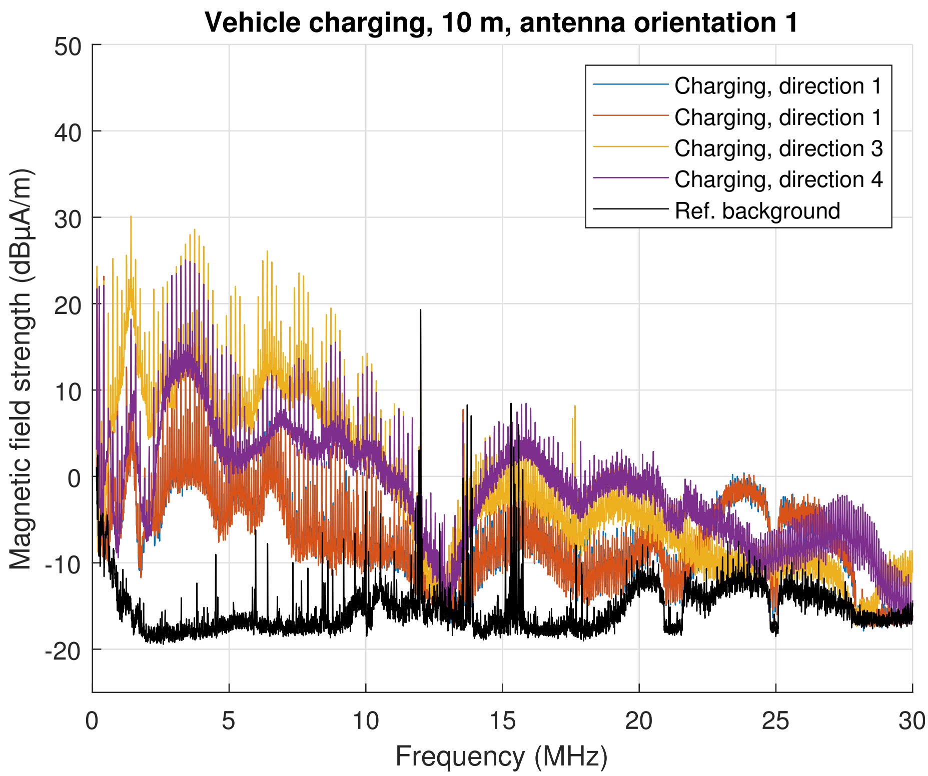


Figure 3.11: Measurement of vehicle charging at a distance of 10 meters and with antenna orientation 1 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

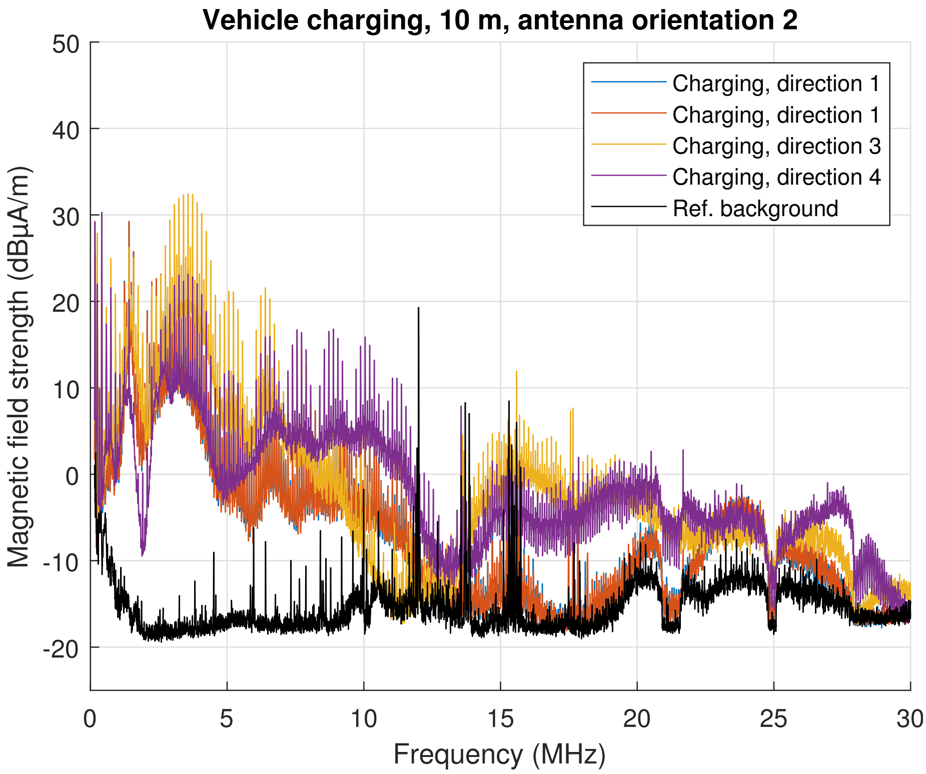


Figure 3.12: Measurement of vehicle charging at a distance of 10 meters and with antenna orientation 2 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

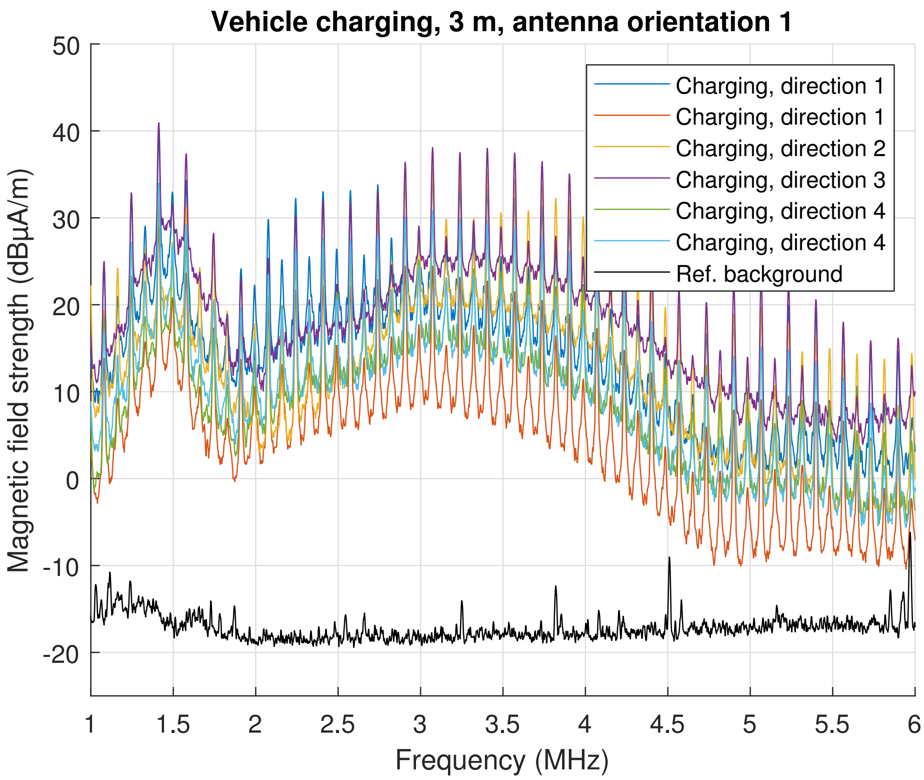


Figure 3.13: The measurements zoomed in at 1-6 MHz when the vehicle is charging at a distance of 3 meters with antenna orientation 1.

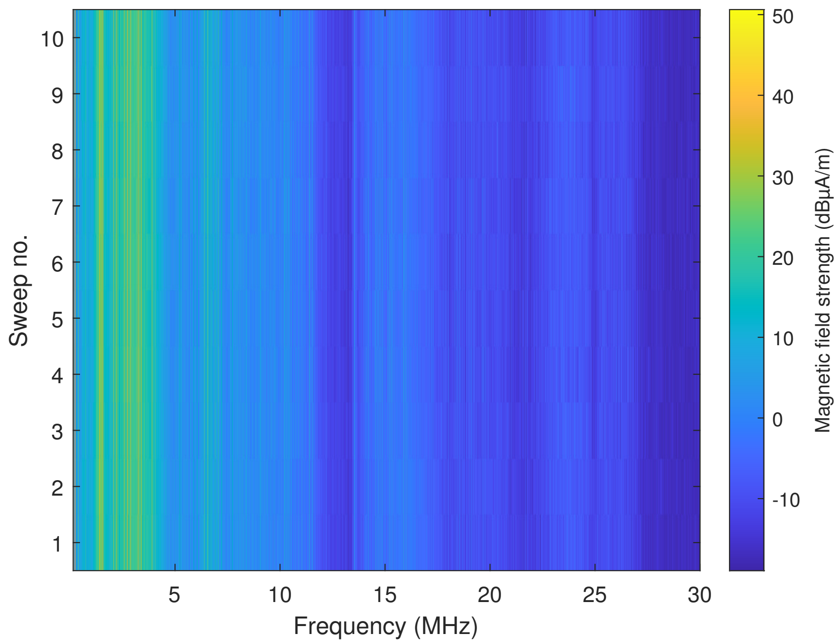


Figure 3.14: Spectrogram representation vehicle charging at a distance of 3 meter with antenna orientation 1 and direction 1.

3.3 Frequency range 30-200 MHz

Figure 3.15 shows nine different background measurements at a distance of 3 meters. One representative measurement with low level has been selected, shown in black in the figure, are used as comparison for the other measurement cases within this frequency range. In general, the background varies between the measurements and are rather noisy.

At the measurements in this frequency band, a band stop filter was used over 88-108 MHz to filter out the FM radio transmission. This can still be seen in the figures due to the post processing, hence should these frequencies be ignored in the analysis. The frequency range 108-156 MHz cover among others the VHF air traffic control radio and is more closely examined in Section 3.3.1.

Figure 3.16, 3.17, 3.18 and 3.19 presents the measurement of the frequency range 30-200 MHz when the vehicle is charging, which theoretically should have the highest levels. It is hard to point out frequency components that are related to changing due to the varying background, but one peak at 40.7 MHz is only present in one of ten background measurements, but is distinct in all measurement containing charging. At this frequency there is an ISM-band, perhaps used by communication related to the charger.

In appendix A.3, there are measurements of only the vehicle (Figure A.17) and when two vehicles are charged simultaneously (Figure A.18 and A.19).

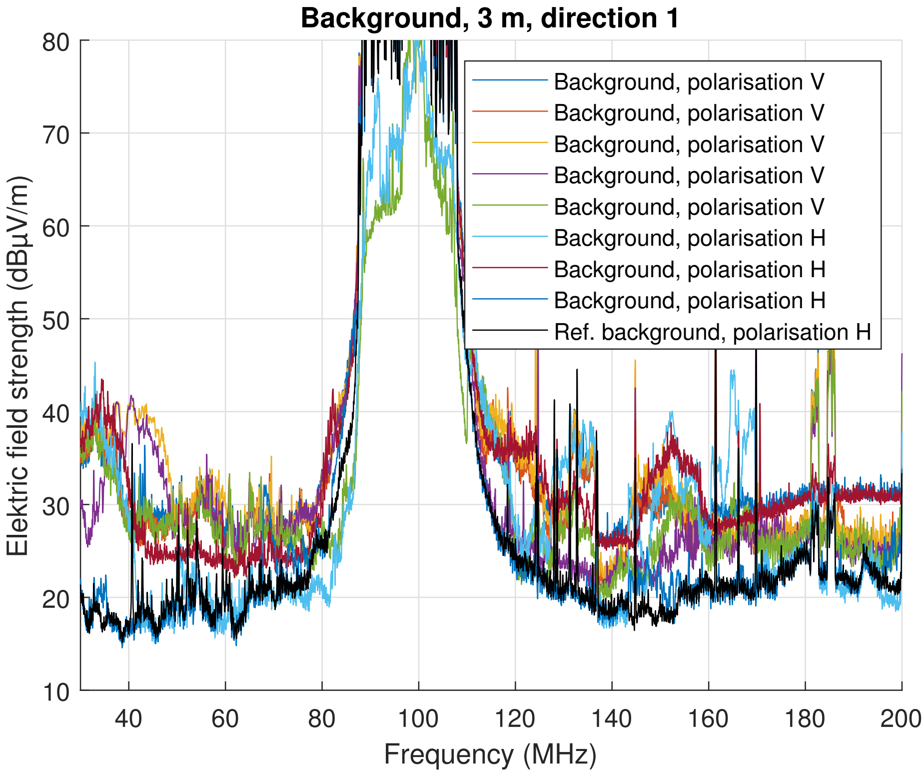


Figure 3.15: Measurement of the background in the frequency range 30-200 MHz where the selected background measurement is shown in black.

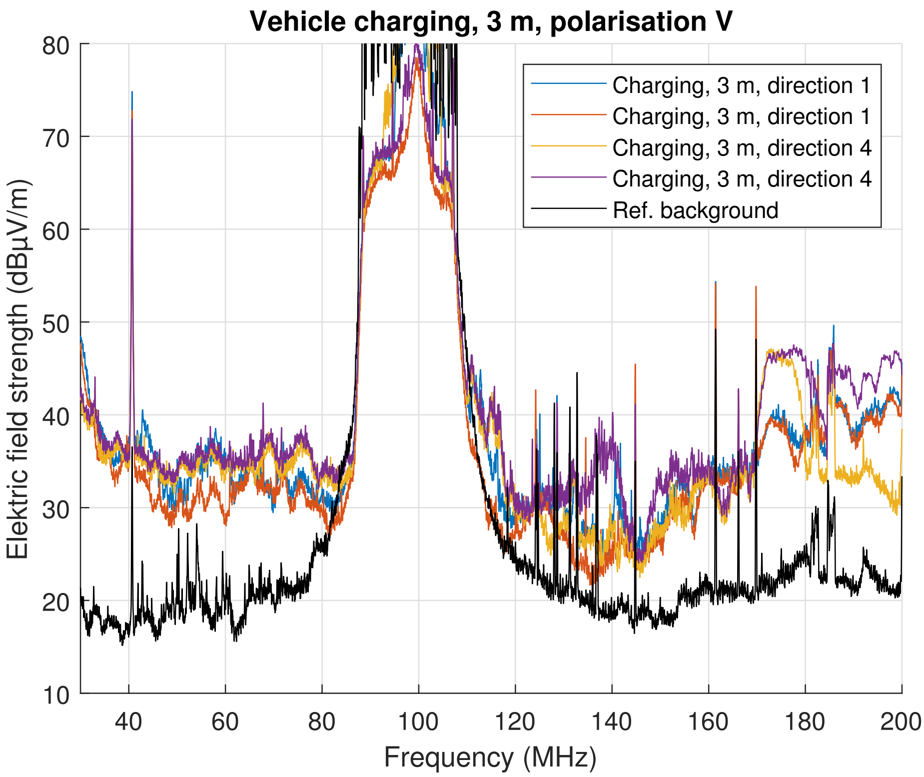


Figure 3.16: Measurement of vehicle charging at a distance of 3 meters and with vertical polarisation for the frequency range 30-200 MHz. The reference background is shown in black.

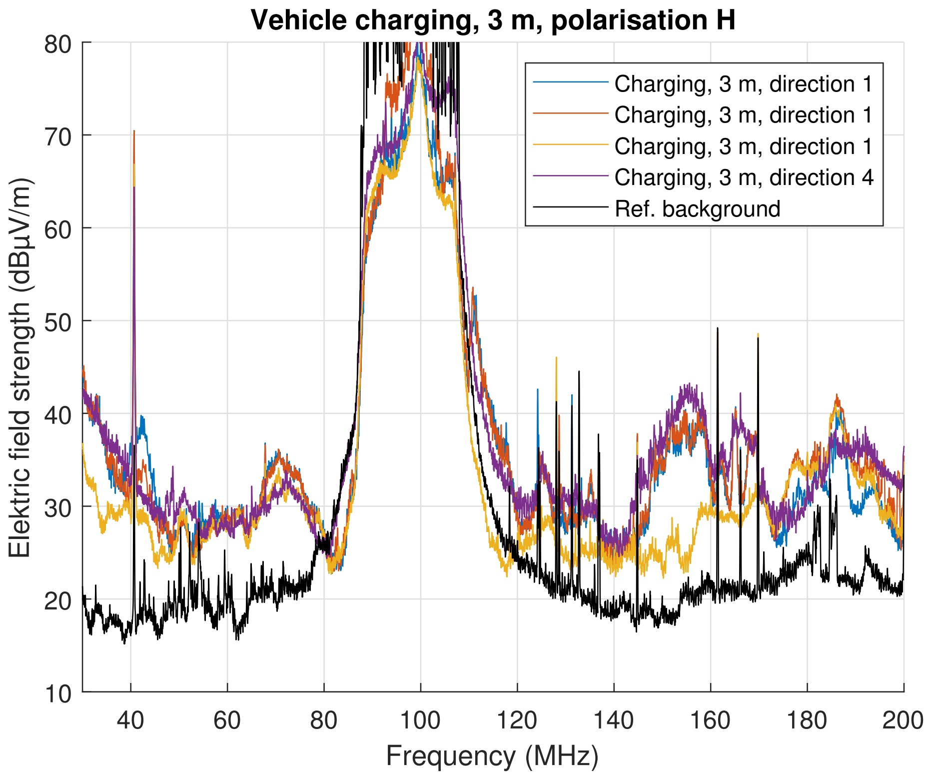


Figure 3.17: Measurement of vehicle charging at a distance of 3 meters and with horizontal polarisation for the frequency range 30-200 MHz. The reference background is shown in black.

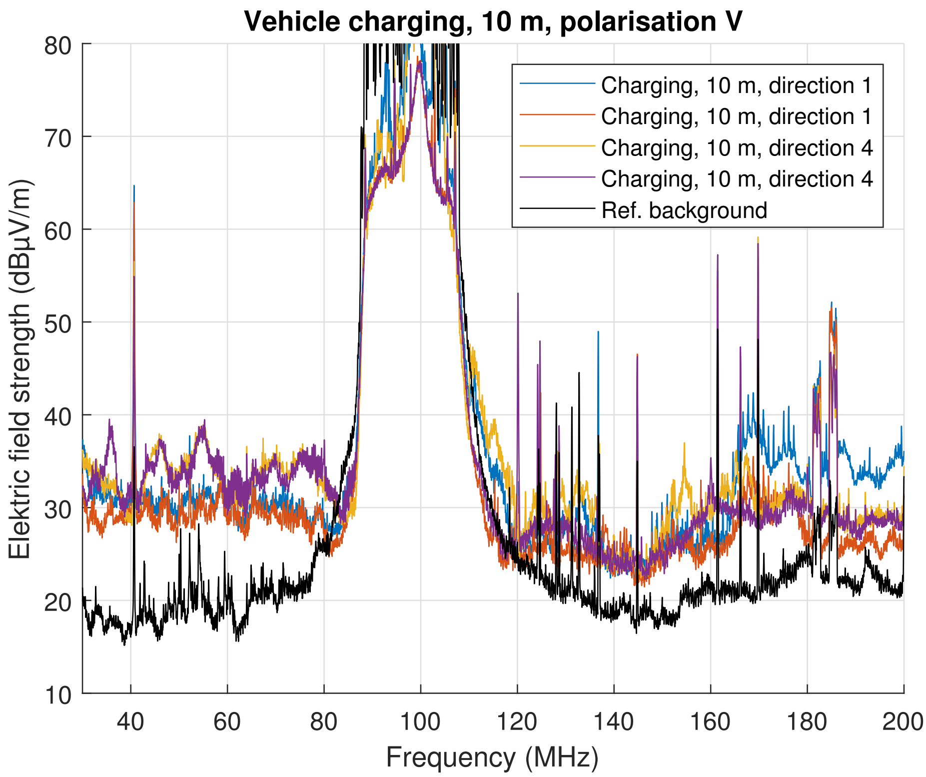


Figure 3.18: Measurement of vehicle charging at a distance of 10 meters and with vertical polarisation for the frequency range 30-200 MHz. The reference background is shown in black.

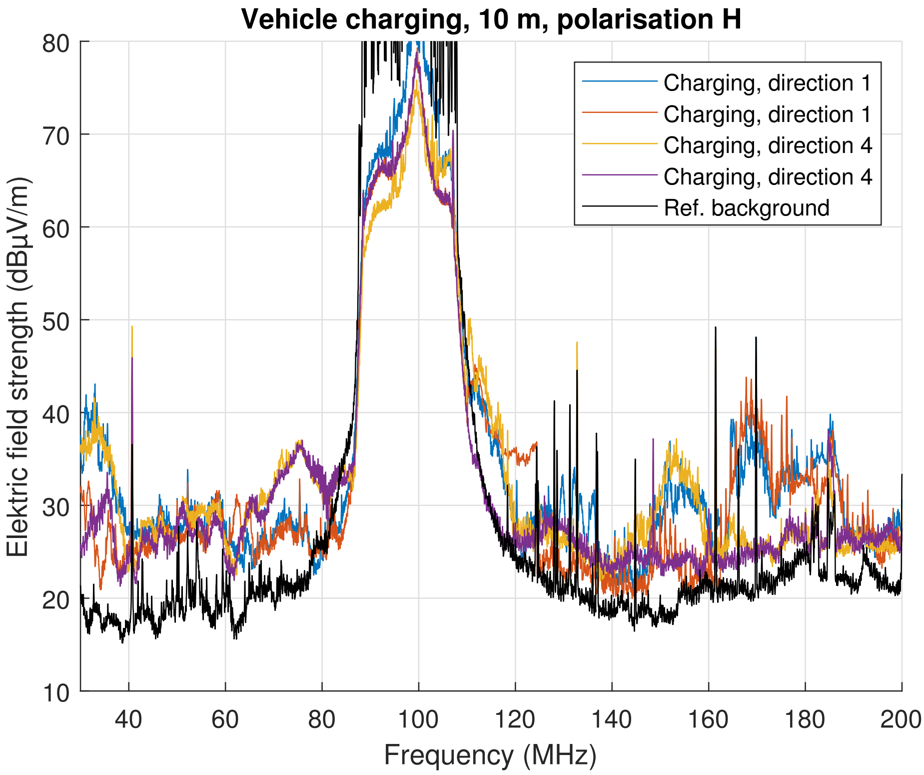


Figure 3.19: Measurement of vehicle charging at a distance of 10 meters and with horizontal polarisation for the frequency range 30-200 MHz. The reference background is shown in black.

3.3.1 VHF air traffic control band

The air traffic control radio is a critical infrastructure consisting of the communication between airplane and air traffic control tower. Therefore an extra measurement in the range 105-140 MHz has been made with a resolution bandwidth of 10 kHz, chosen to be comparable with a radio receiver for air traffic control. Figure 3.20 shows three different measurements of the background, where the black one is selected as reference background. All three measurements show sign of some disturbance.

Figure 3.21 shows a charging vehicle at 3 meters and with vertical polarisation. Since the background is noisy it is hard to say anything regarding the impact of the charging. Figure 3.22, two vehicles simultaneously charging at a distance of 3 meters and Figure 3.23, which is the same figure but zoomed in over 128-144 MHz, has some periodic peaks. The thin peaks around 128-135 MHz has a distance in frequency of 750 kHz. The thicker peak to the right in the figure has a distance of around 610 kHz.

In appendix A.4, there are measurements of only the vehicle (Figure A.20 and A.21), the system in stand-by without vehicle (Figure A.22) and when two vehicles are charging simultaneously (Figure A.23).

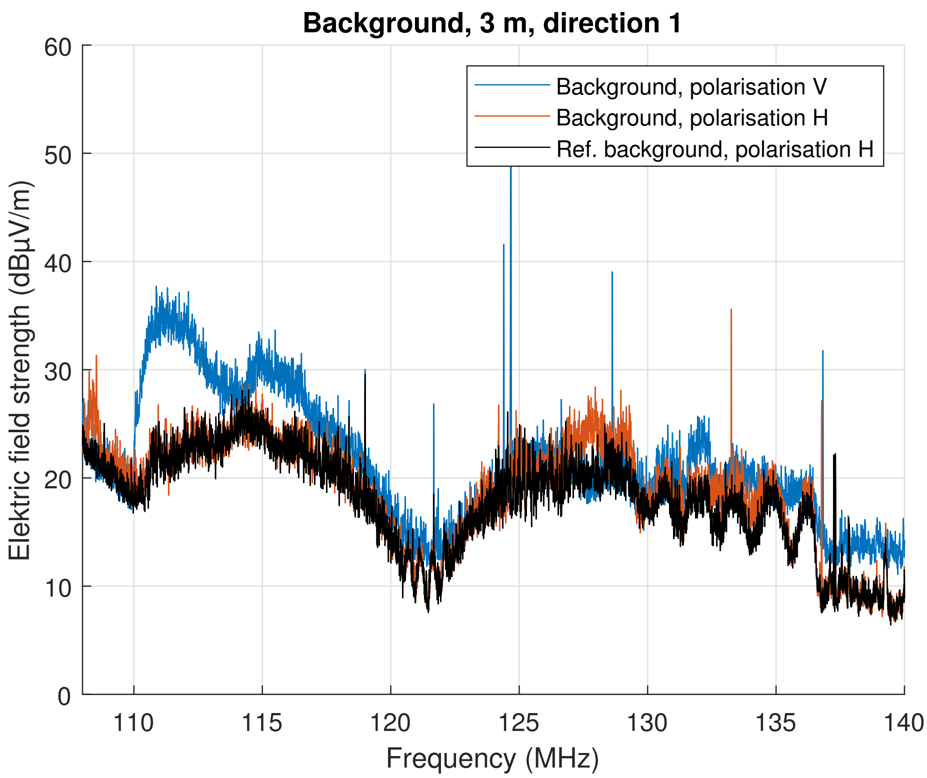


Figure 3.20: Measurement of the background where the selected background measurement is shown in black.

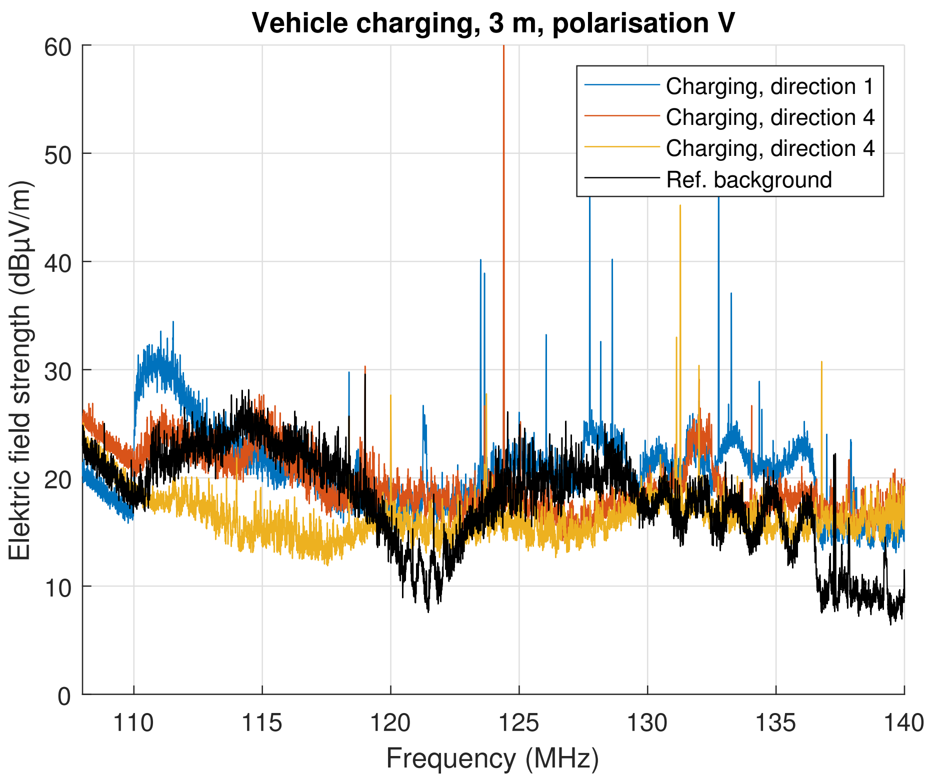


Figure 3.21: Measurement of vehicle charging at a distance of 3 meters and with vertical polarisation for the frequency range 105-140 MHz. The reference background is shown in black.

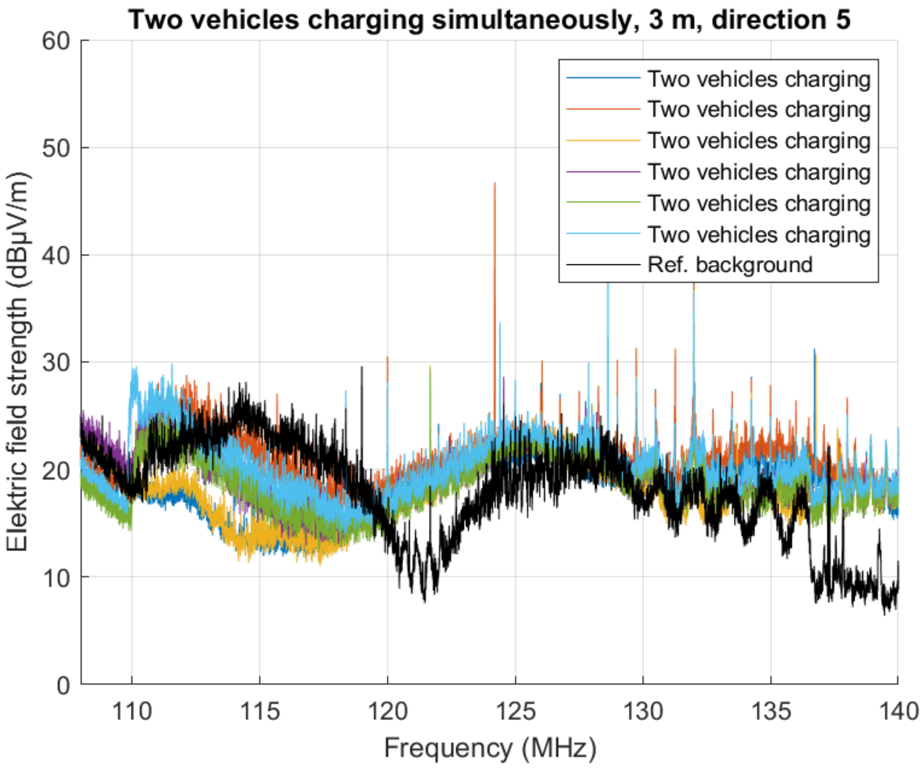


Figure 3.22: Measurement when two vehicles are charging at a distance of 3 meters for the frequency range 105-140 MHz. The reference background is shown in black.

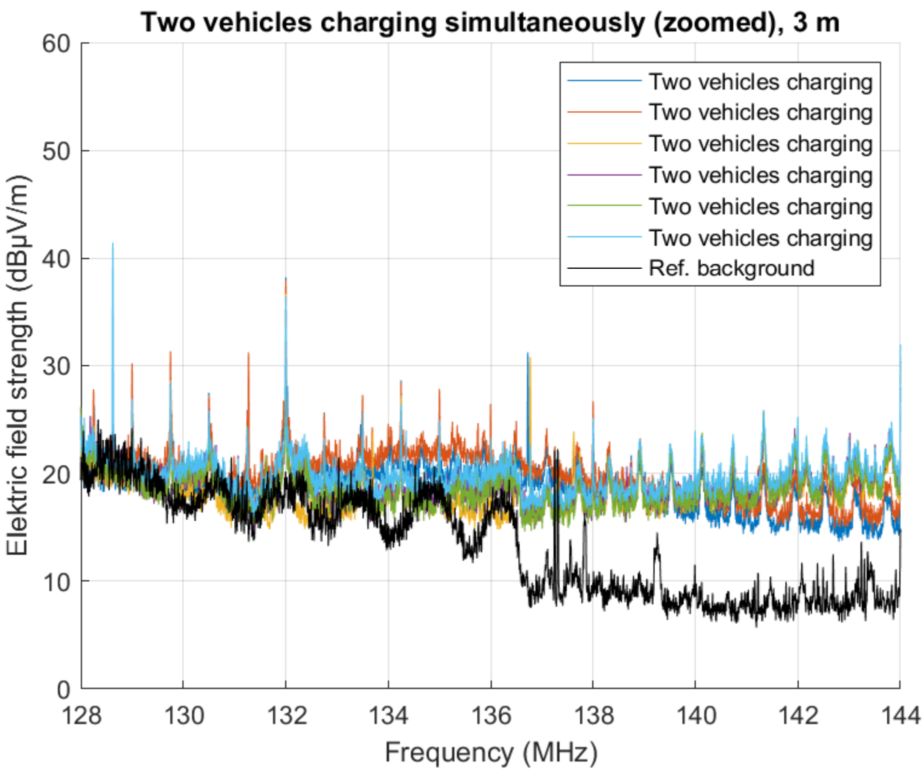


Figure 3.23: The measurements zoomed in at 128-146 MHz when two vehicles are charging at a distance of 3 meters.

3.4 Frequency range 200 MHz-1 GHz

Figure 3.24 shows two different background measurements at a distance of 3 meters. One measurement with low level has been selected, shown in black in the figure, that is used as comparison for the other measurement cases within this frequency range. The background has many peaks compared to the noise floor, which probably correspond to the numerous systems working in this range. In the range 380-430 MHz there are frequencies dedicated to the emergency services which are discussed in Section 3.4.1.

Figure 3.25 shows the results when the vehicle is charging at a distance of 3 meters. Note here that some of the measurements has a higher noise floor than the background. The different sensitivity levels are due to the different attenuation settings and whether the antenna pre-amplifier is used or not. However the peak levels are not affected by this, only the noise floor. Figure 3.26, showing measurement of the vehicle when it is not charging, has the same disturbances in around 400 MHz as in Figure 3.25, suggesting this disturbances come from the car and not from the charging.

In appendix A.5, there are measurements of the vehicle charging at a distance of 10 meters (Figure A.24), of only the vehicle at a distance of 10 meters (Figure A.25), the system in stand-by without vehicle (Figure A.26) and when two vehicles are charged simultaneously (Figure A.27 and A.28).

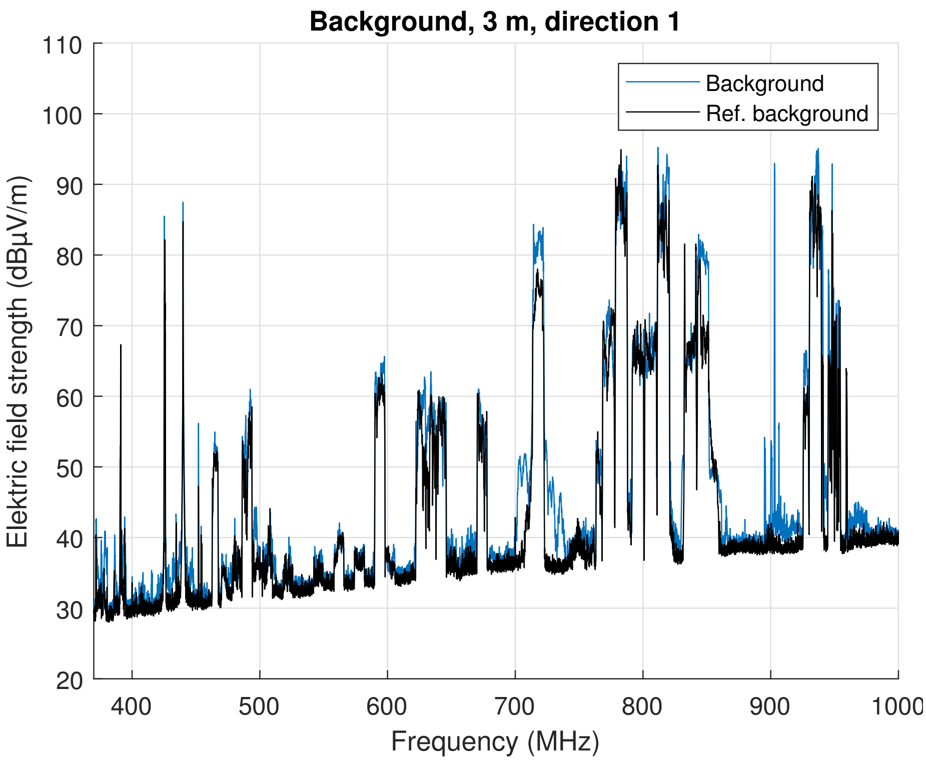


Figure 3.24: Measurement of the background in the frequency range 200 MHz-1 GHz where the selected background measurement is shown in black.

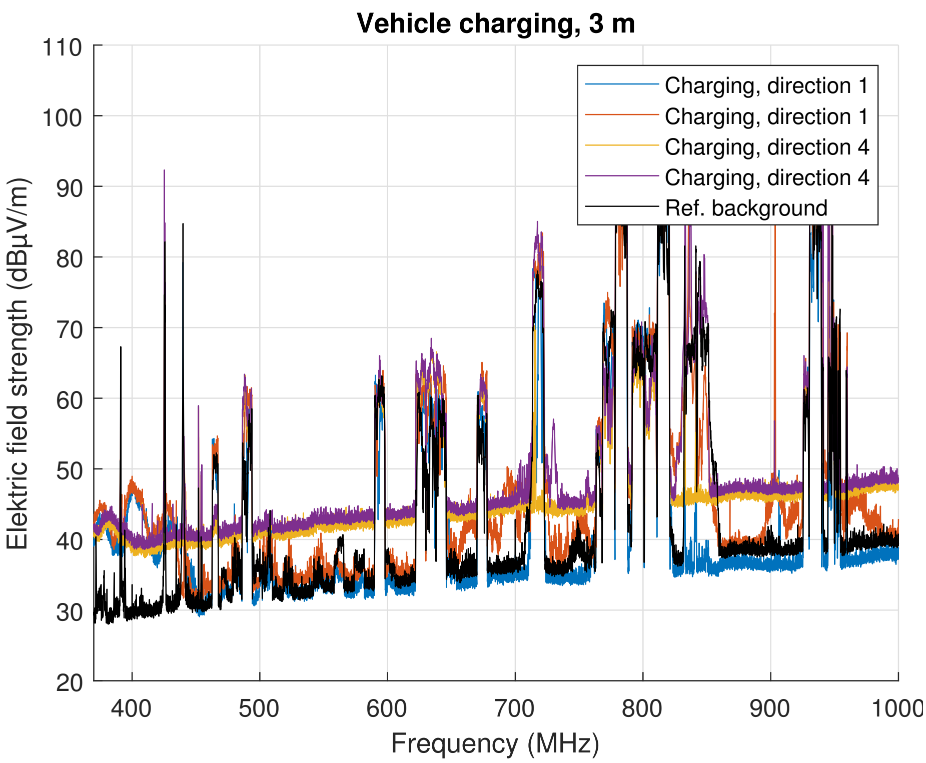


Figure 3.25: Measurement of vehicle charging at a distance of 3 meters and with vertical polarisation for the frequency range 200 MHz-1 GHz. The reference background is shown in black.

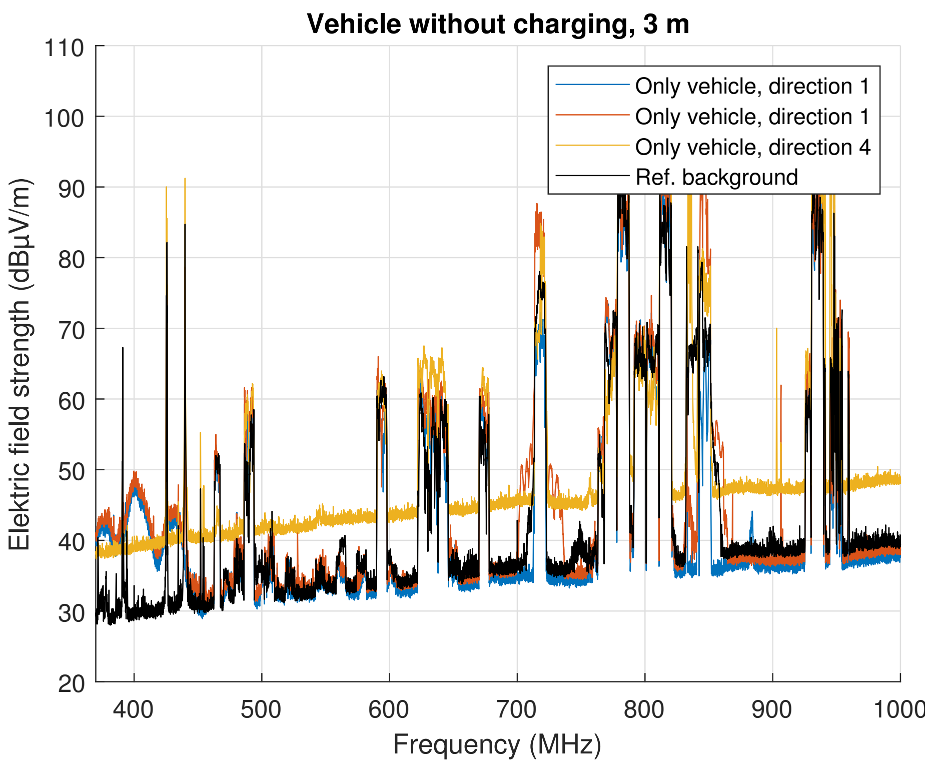


Figure 3.26: Measurement of only the vehicle at a distance of 3 meters and with vertical polarisation for the frequency range 200 MHz-1 GHz. The reference background is shown in black.

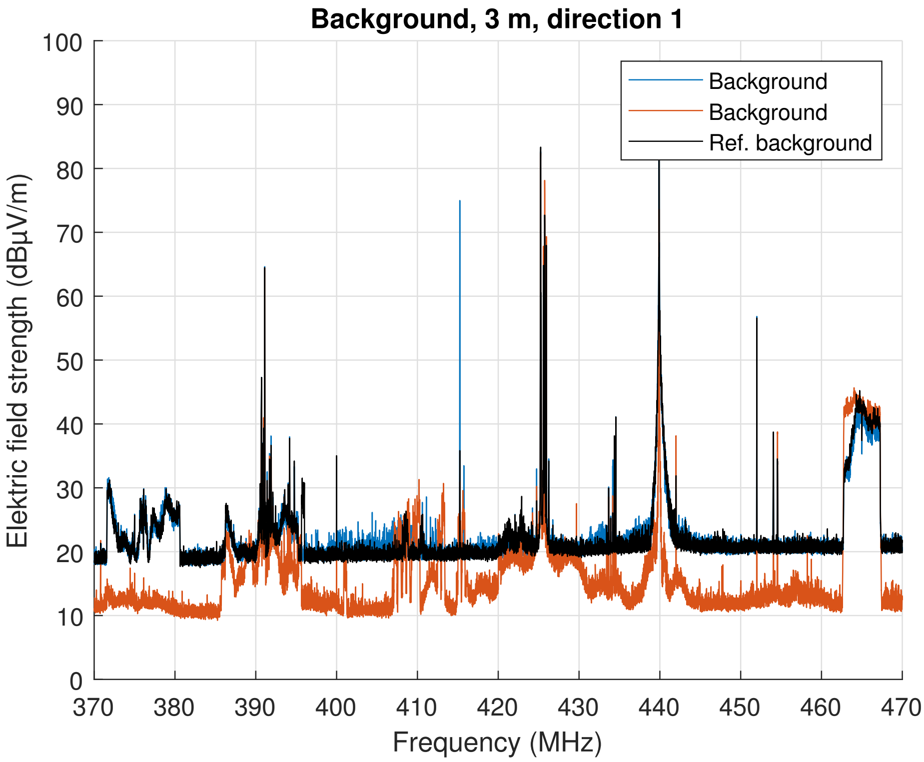


Figure 3.27: Measurement of the background in the frequency range 370-470 MHz where the selected background measurement is shown in black.

3.4.1 Tetra band

There are frequencies designated to emergency services, for example Rakel, in the range 380-430 MHz, therefore an extra measurement in 370-470 MHz was made with a resolution bandwidth of 10 kHz. Figure 3.27 shows three different measurements. One representative measurement of the background has been selected, shown in black in the figure, are used as comparison for the other measurement cases within this frequency range. The different sensitivity in the figure is a result of different measurement receiver attenuation and the use of the pre-amplifier.

Figure 3.28 and 3.29 presents the measurement at a distance of 3 and 10 meters of the frequency range 370-470 MHz when the vehicle is charging. For a distance of 3 meters there are undulating values below 440 MHz. This is probably not a coincident since the same pattern can also be seen some of the measurements in Figure 3.25 and A.24. One of the measurements from 10 meters have higher values than the corresponding curves from a distance of 3 meters. This measurement may be a result of an overload in the pre-amplifier, but are still included.

In appendix A.6, there are measurements of only the vehicle (Figure A.29 and A.30), the system in stand-by without vehicle (Figure A.31) and when two vehicles are charged simultaneously (Figure A.32 and A.33).

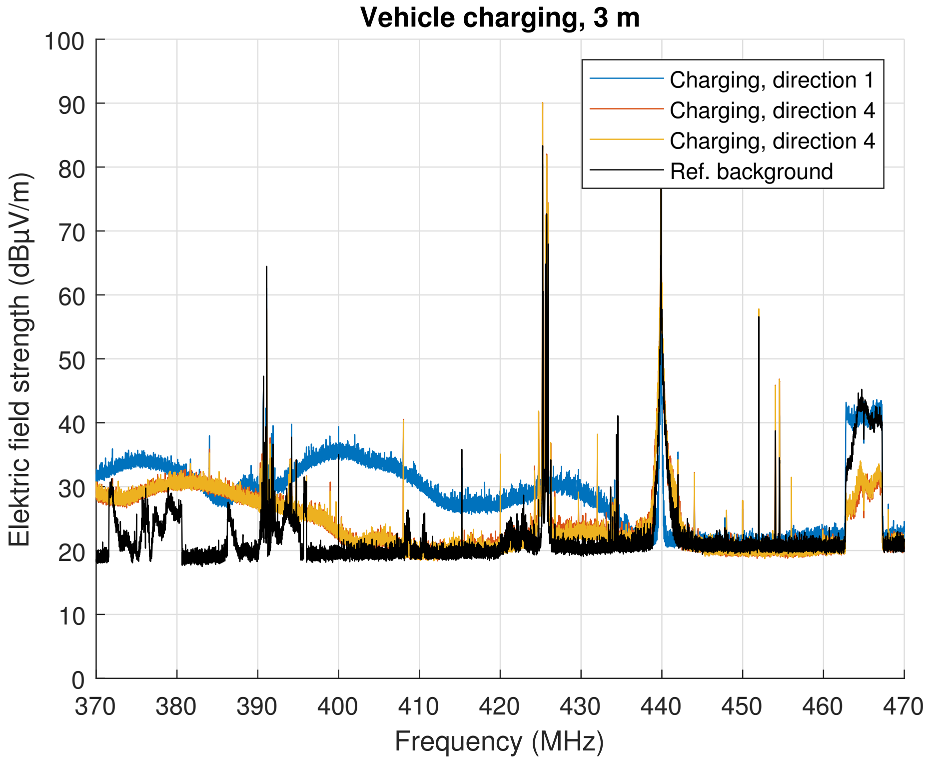


Figure 3.28: Measurement of vehicle charging at a distance of 3 meters for the frequency range 370-470 MHz. The reference background is shown in black.

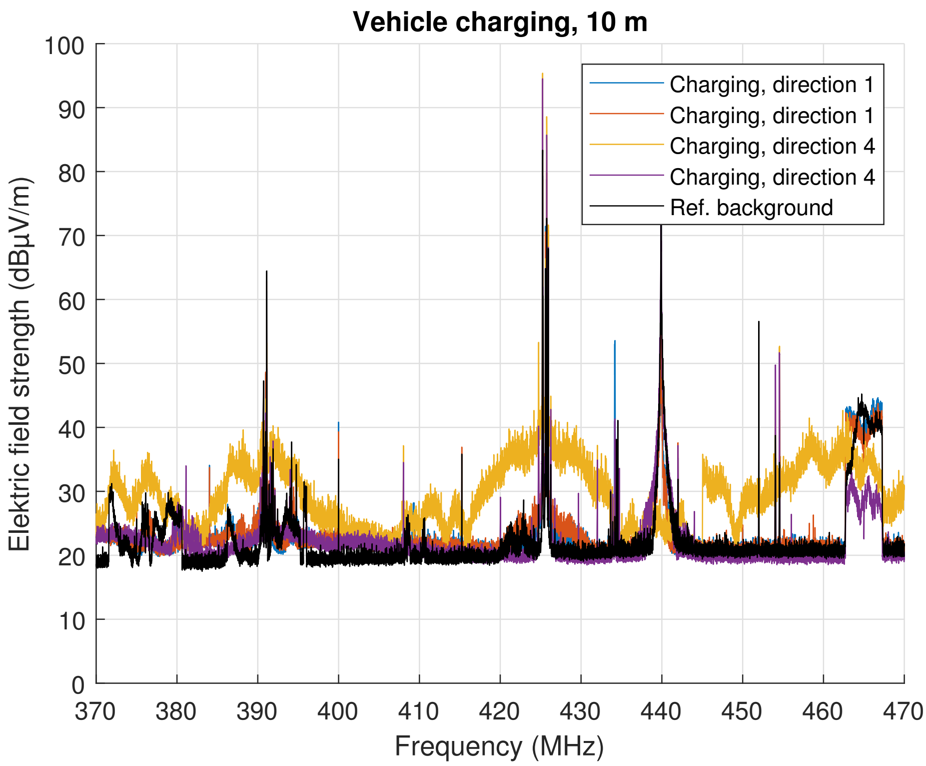


Figure 3.29: Measurement of vehicle charging at a distance of 10 meters for the frequency range 370-470 MHz. The reference background is shown in black.

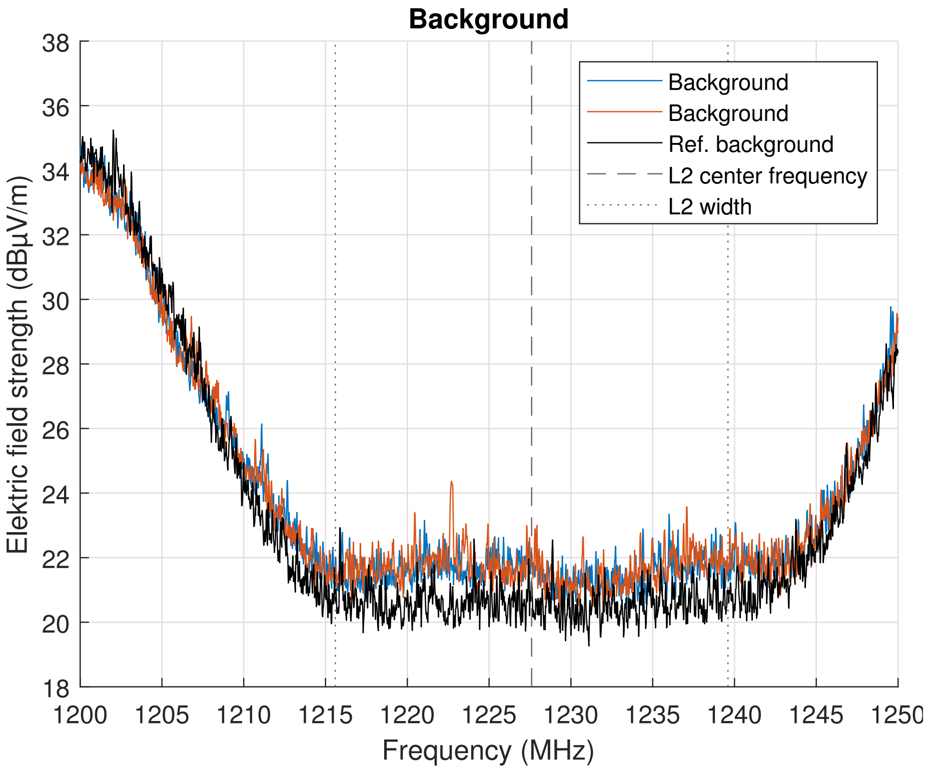


Figure 3.30: Measurement of the background in the frequency range 1.20-1.25 GHz where the selected background measurement is shown in black. All measured at a distance of 3 meters and with vertical polarisation.

3.5 GPS-bands

Extra measurements has been made in the GPS L1 och GPS L2 bands, since Global Navigation Satellite System (GNSS) is critical infrastructure. It is important that these bands are quiet, since the GNSS signals are below the noise floor. The GPS L2 and GPS L1 has center frequencies at 1227.60 MHz respectively 1575.42 MHz. Both GPS band consist of signals with bandwidths up to 24 MHz. All measurement are made at a distance of 3 meters, with vertical polarisation and at direction 1.

3.5.1 GPS L2

Figure 3.30 shows three different background measurements around the GPS L1-band. One representative measurement with low level has been selected, shown in black in the figure. The background levels follows the bowl-shape form from the correction of the L2-filter.

Figure 3.31 and 3.32 consist of measurements of the vehicle charging and measurements of only the vehicle. Deviation from the background can be seen at some frequencies. Most distinctive is the peak around 1.233 GHz which is within the bandwidth of GPS L2. There are also an increased noise level in the frequencies below the GPS L2 center frequency. The increased level around 1.216 GHz is stable during all sweeps, but the rest of the peaks above the noise floor are varying and only appearing during some of the sweeps.

In Figure 3.33, system in stand-by, the red curve is higher than the rest for the highest frequency band. This signal only occur a short period of time, see Figure 3.34, but since the value shown is the max hold value, it can be seen for this frequency range. The signal is most likely present also below 1233 MHz but due to the measurement method and the short time period of the disturbance, this is not seen.

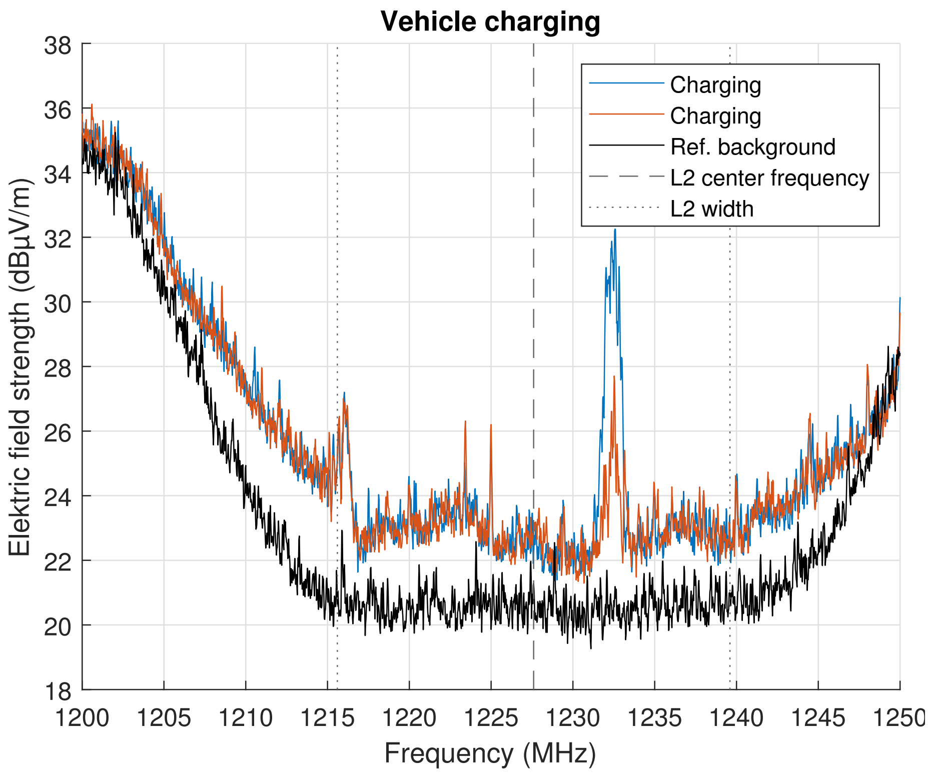


Figure 3.31: Measurement of vehicle charging at a distance of 3 meters and with vertical polarisation for the frequency range 1.2-1.25 GHz, where GPS L2 is located. The reference background is shown in black.

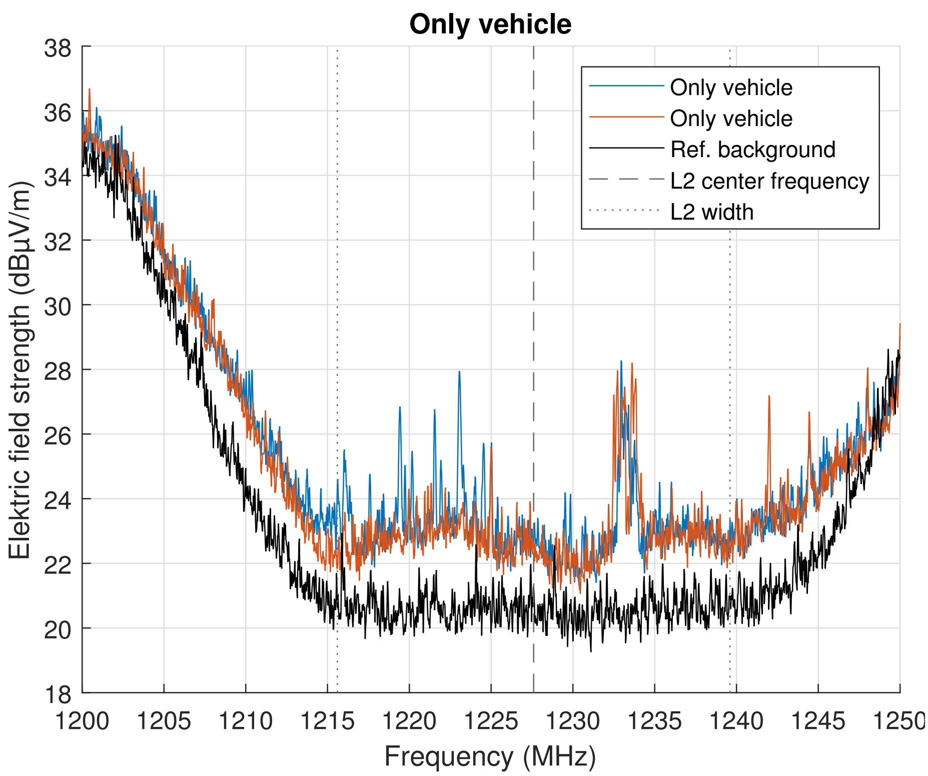


Figure 3.32: Measurement of only the vehicle at a distance of 3 meters and with vertical polarisation for the frequency range 1.2-1.25 GHz, where GPS L2 is located. The reference background is shown in black.

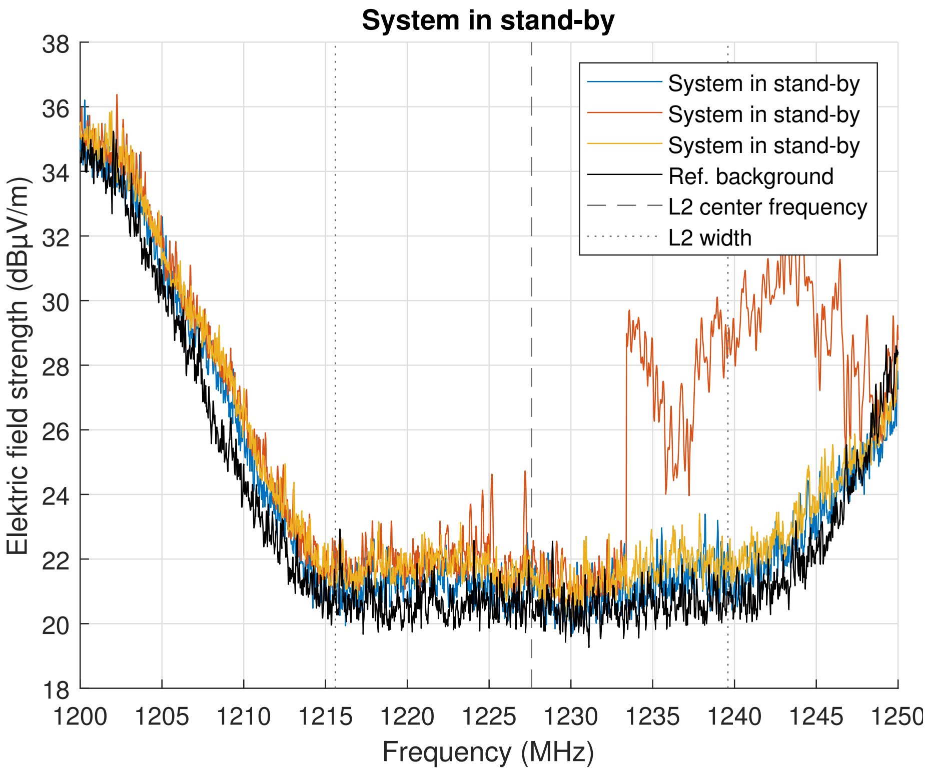


Figure 3.33: Measurement of the system in stand-by at a distance of 3 meters and with vertical polarisation for the frequency range 1.2-1.25 GHz, where GPS L2 is located. The reference background is shown in black.

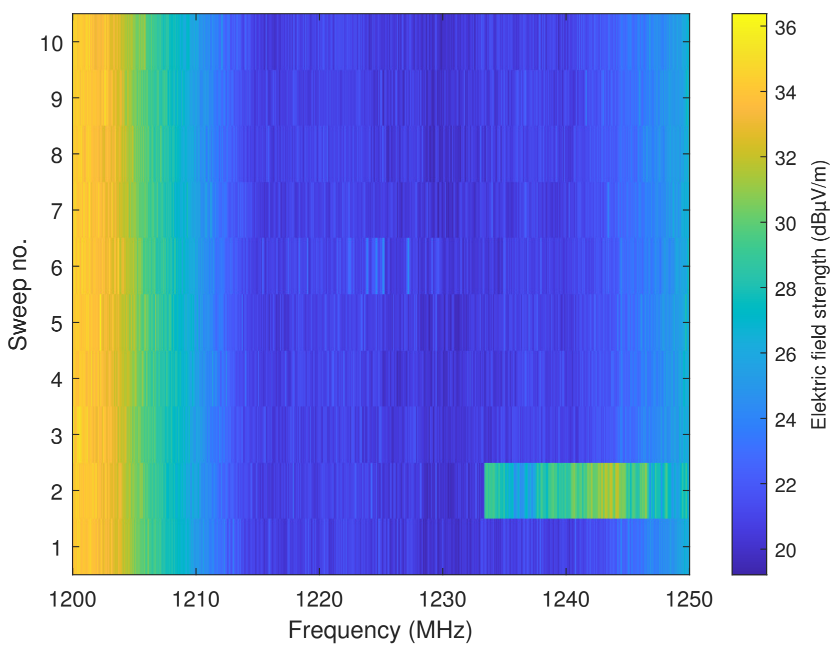


Figure 3.34: Spectrogram of the system is in stand-by, showing the red curve from Figure 3.33.

3.5.2 GPS L1

Figure 3.35 shows measurements of the GPS L1-band, all measured at a distance of 3 m and with vertical polarisation. The background measurement are seen as the two lowest measurements. These two are lower due to a different level of attenuation in the measurement system. The figure also consist of measurements of vehicle charging, the system in stand-by and the vehicle when not charging. The curvature of all measurements comes from the correction of the L1-filter.

The GPS L1-band is quiet, except for some peaks visible in the 'only vehicle'-measurement. The peaks was only seen in one of ten sweeps in the spectrogram.

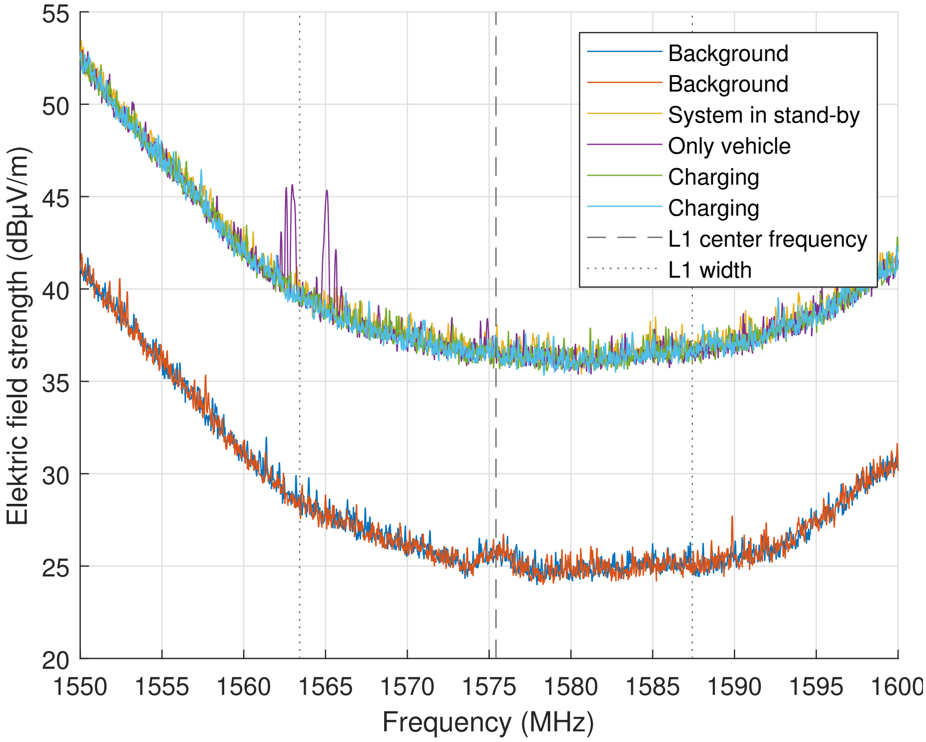


Figure 3.35: Measurement at a distance of 3 meters and with vertical polarisation for the frequency range 1.55-1.6 GHz, where GPS L1 is located.

4 Conclusions

This report presents results from measurements of the emission from a charging infrastructure with the purpose to wirelessly and stationary charge a vehicle. The measurements have taken place outdoors, in an industrial environment, where other activities have run in parallel. Hence, the measurement results may include signals originating from the surrounding environment. In the evaluation of the emission levels, the measurements of the background are used as a comparison. For the lower frequency bands and up to the high frequency (HF) band (1-30 MHz), the measurements are, with the measurement distances of 3 and 10 m, partly conducted in the near field. Altogether, the measurement levels should be compared with caution. The overall conclusions are derived from trends that can be seen in several measurements.

The results show that the WPT station is emitting interference, in particular at frequencies up to 30 MHz, when it is charging. The charging frequency, at 83 kHz, can clearly be seen in the results. The guiding frequency, used to help the vehicle to find the correct charging position, can be seen in some of the measurement at 85.5 kHz. In some frequency bands, especially in 9 kHz to 30 MHz, high emission levels can be seen when the vehicle is charging. The periodicity of the peaks in this frequency band also indicates that it is originating from the charging frequency.

In the frequency range 30-200 MHz, the emission from the background itself is varying during the measurements. Hence, no clear impact from the charging can be seen, except for one high peak at 40 MHz, which is present in all measurements when charging, but only in one of ten background measurements. This may originate from an application in the charging system that is using the industrial, scientific and medical (ISM) band around 40 MHz.

In the frequency range 200 MHz to 1 GHz, there are many wireless systems operating. One impact, possibly related to the charging infrastructure, is some emissions below 440 MHz, also seen in the dedicated measurements of the Tetra band.

Measurements have also been made at the GPS L1 and L2 frequencies. It is important that these bands are quiet, since the GNSS signals are below the noise floor and easily disturbed. For GPS L2, the measurement results indicate that there are emissions from both the charging and from the vehicle itself. In one of the measurements, a high broadband disturbance are seen during a short period of time, possibly covering the whole band. The measurements in the GPS L1 band were mostly quiet, beside some temporary peaks at the edge of the band.

Finally, no clear consistent influence of the measurement direction or antenna orientation can be seen on the measured levels.

A Additional measurements cases

A.1 9-150 kHz

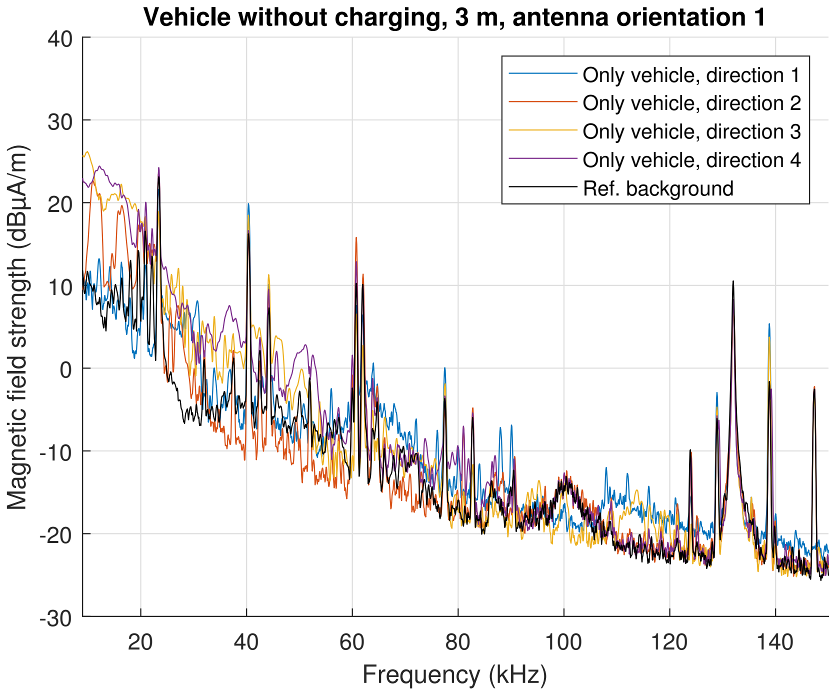


Figure A.1: Measurement of the vehicle at a distance of 3 meters and with antenna orientation 1 for the frequency range 9-150 kHz. The reference background is shown in black.

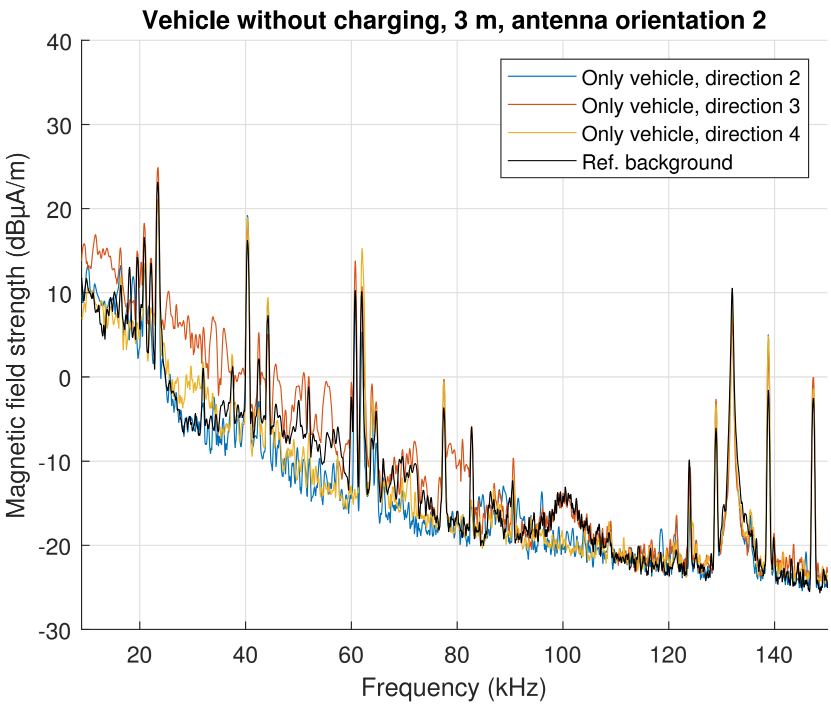


Figure A.2: Measurement of the vehicle at a distance of 3 meters and with antenna orientation 2 for the frequency range 9-150 kHz. The reference background is shown in black.

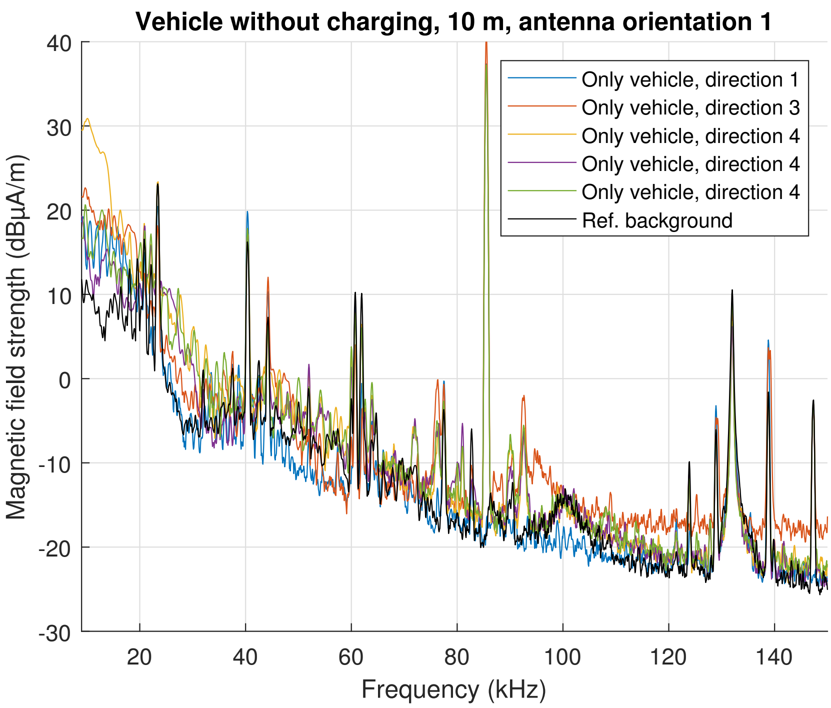


Figure A.3: Measurement of the vehicle at a distance of 10 meters and with antenna orientation 1 for the frequency range 9-150 kHz. The reference background is shown in black.

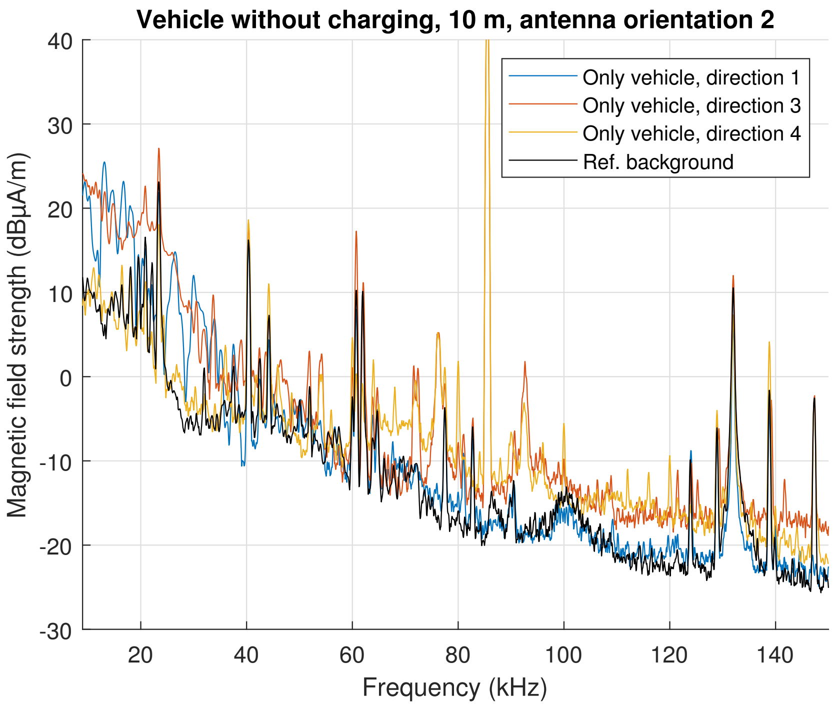


Figure A.4: Measurement of the vehicle at a distance of 10 meters and with antenna orientation 2 for the frequency range 9-150 kHz. The reference background is shown in black.

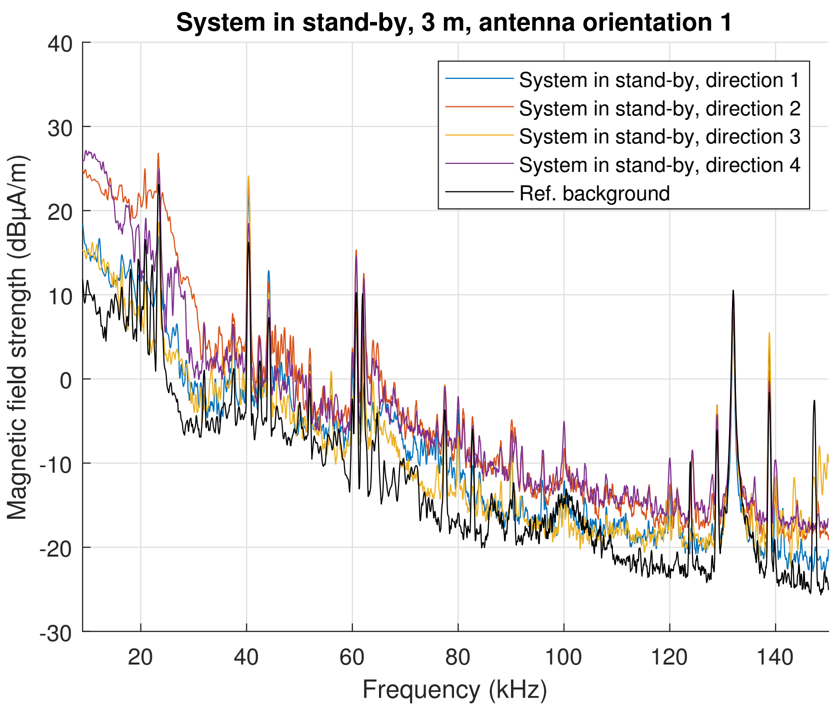


Figure A.5: Measurement when the system is in stand-by at a distance of 3 meters and with antenna orientation 1 for the frequency range 9-150 kHz. The reference background is shown in black.

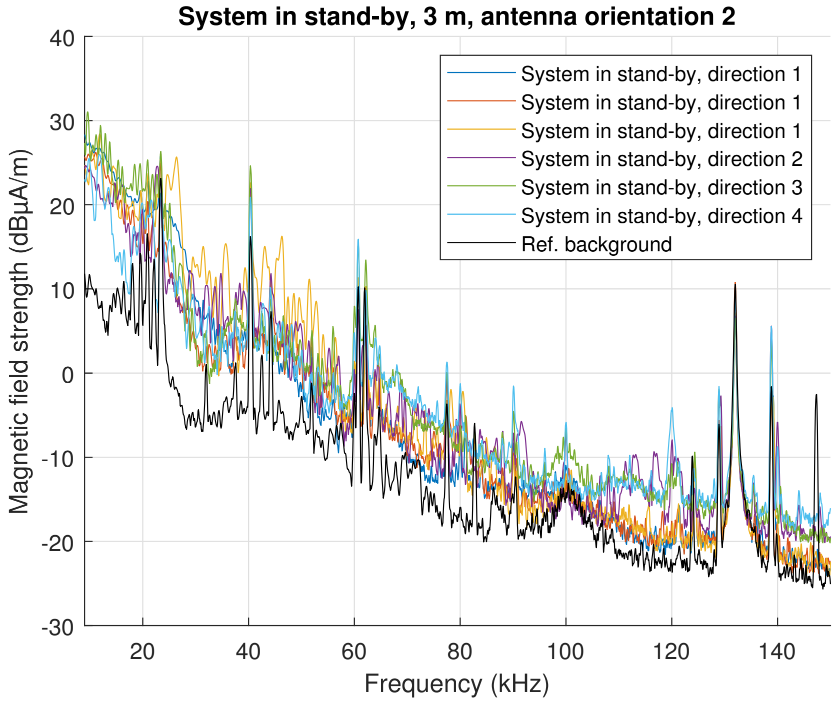


Figure A.6: Measurement when the system is in stand-by at a distance of 3 meters and with antenna orientation 2 for the frequency range 9-150 kHz. The reference background is shown in black.

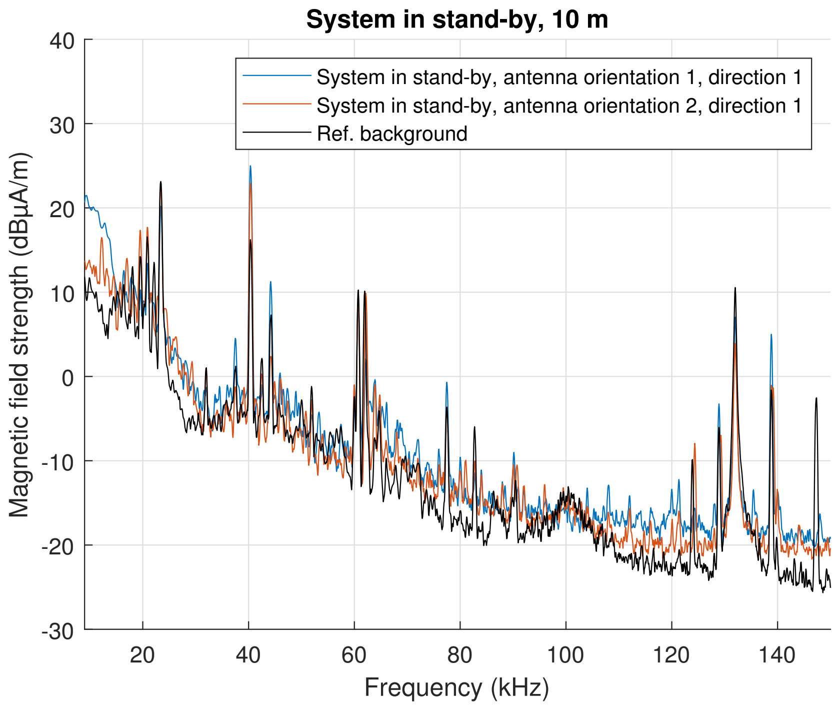


Figure A.7: Measurement when the system is in stand-by at a distance of 10 meters for the frequency range 9-150 kHz. The reference background is shown in black.

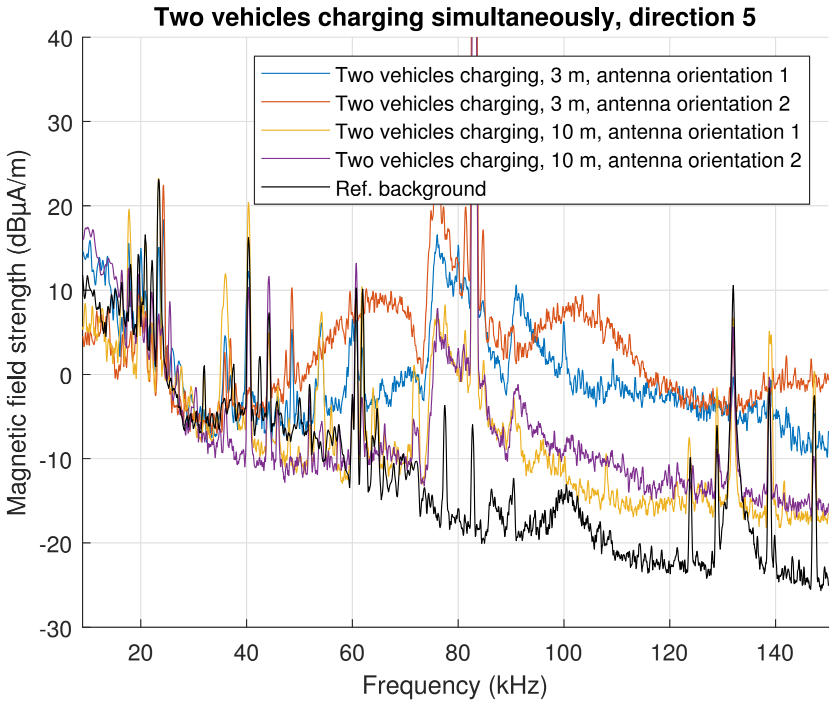


Figure A.8: Measurement when two vehicles are charging for the frequency range 9-150 kHz. The reference background is shown in black.

A.2 150 kHz-30 MHz

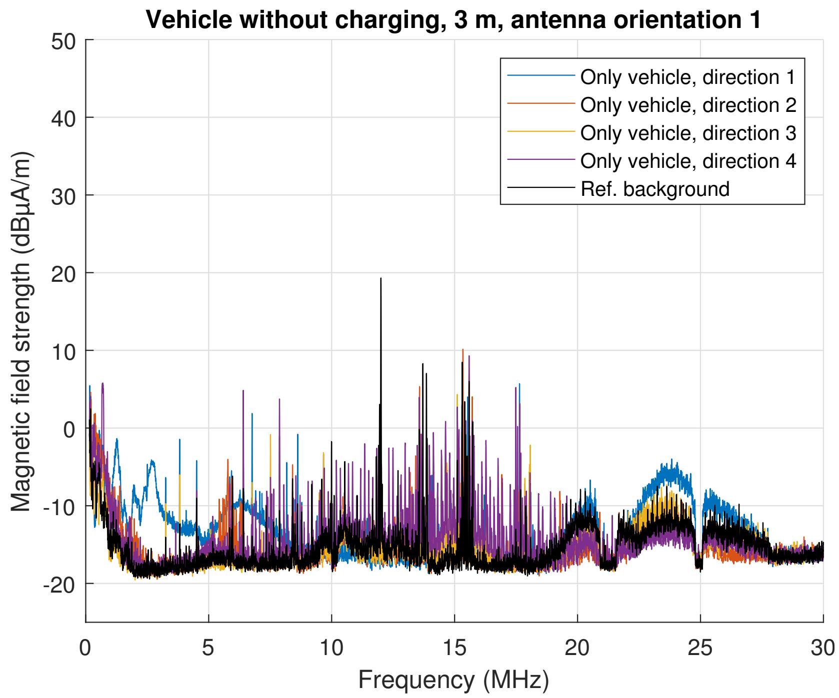


Figure A.9: Measurement of the vehicle at a distance of 3 meters and with antenna orientation 1 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

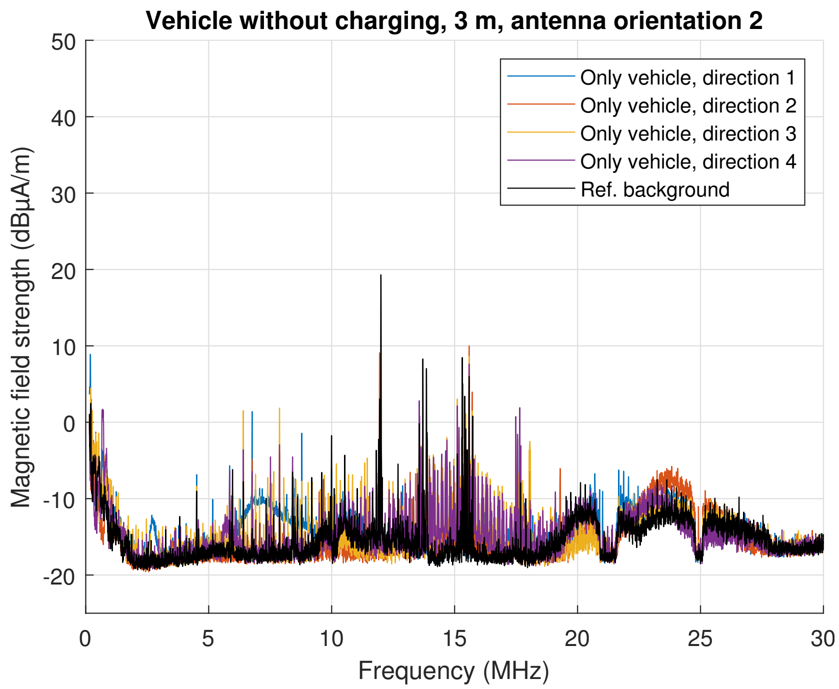


Figure A.10: Measurement of the vehicle at a distance of 3 meters and with antenna orientation 2 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

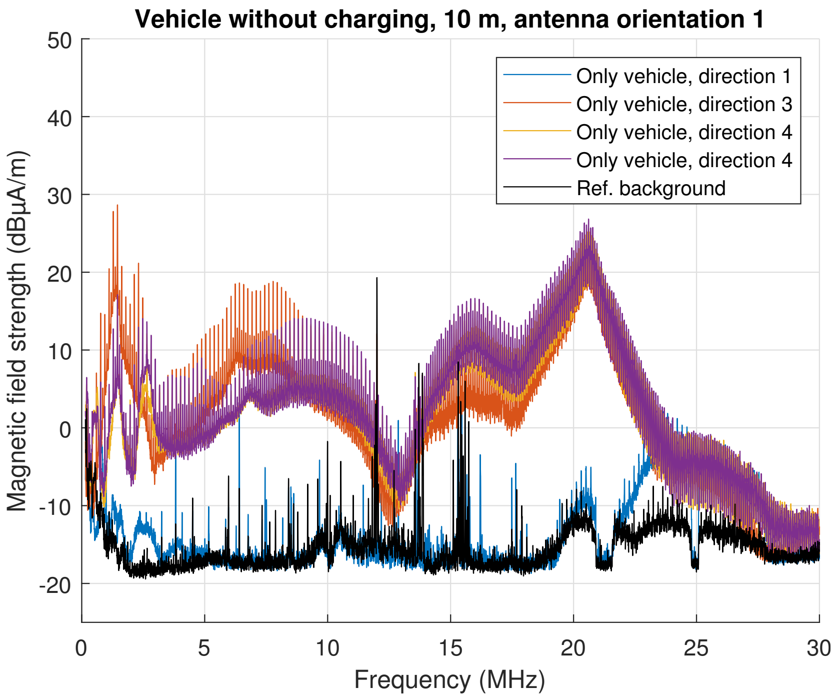


Figure A.11: Measurement of the vehicle at a distance of 10 meters and with antenna orientation 1 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

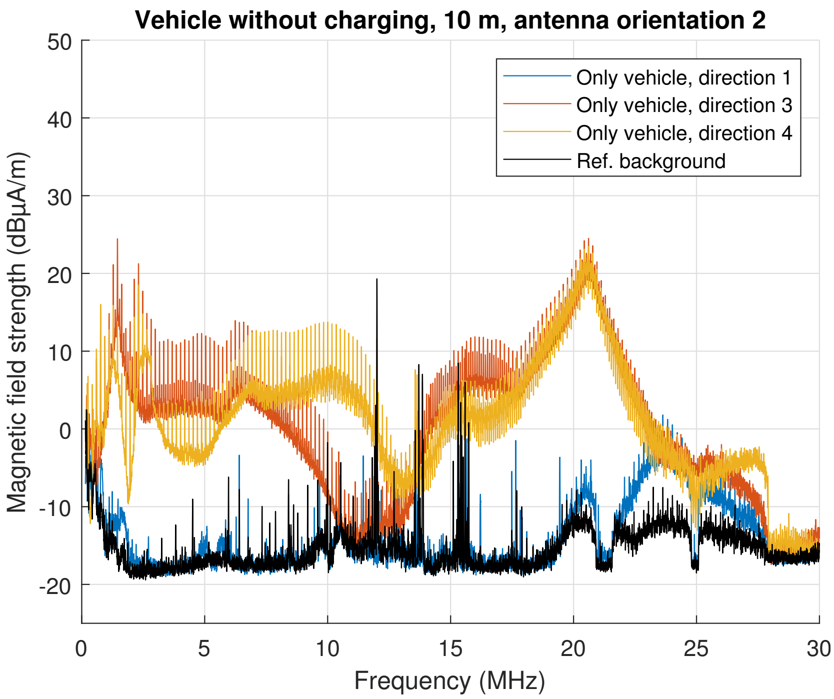


Figure A.12: Measurement of the vehicle at a distance of 10 meters and with antenna orientation 2 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

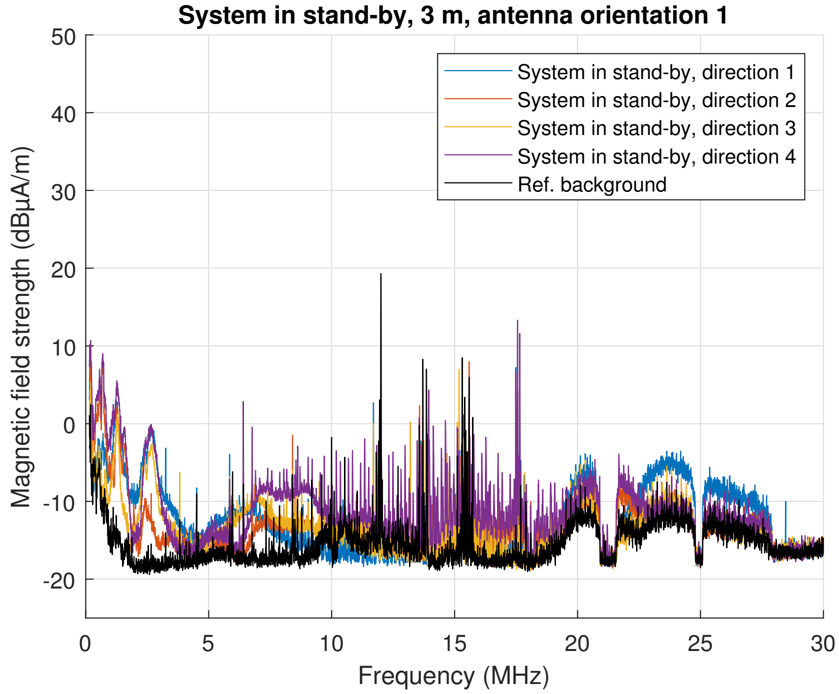


Figure A.13: Measurement of the system in stand-by at a distance of 3 meters and with antenna orientation 1 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

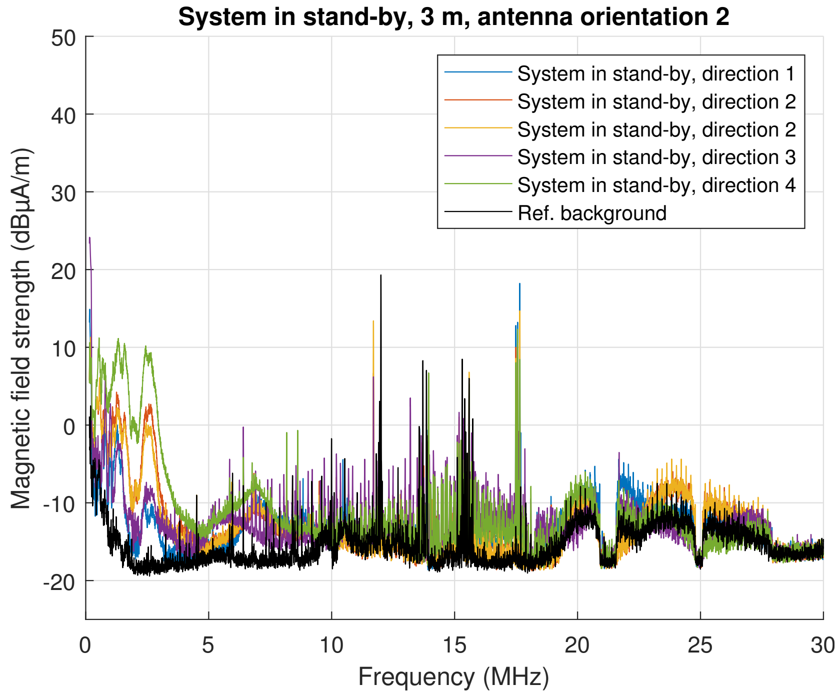


Figure A.14: Measurement of the system in stand-by at a distance of 3 meters and with antenna orientation 2 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

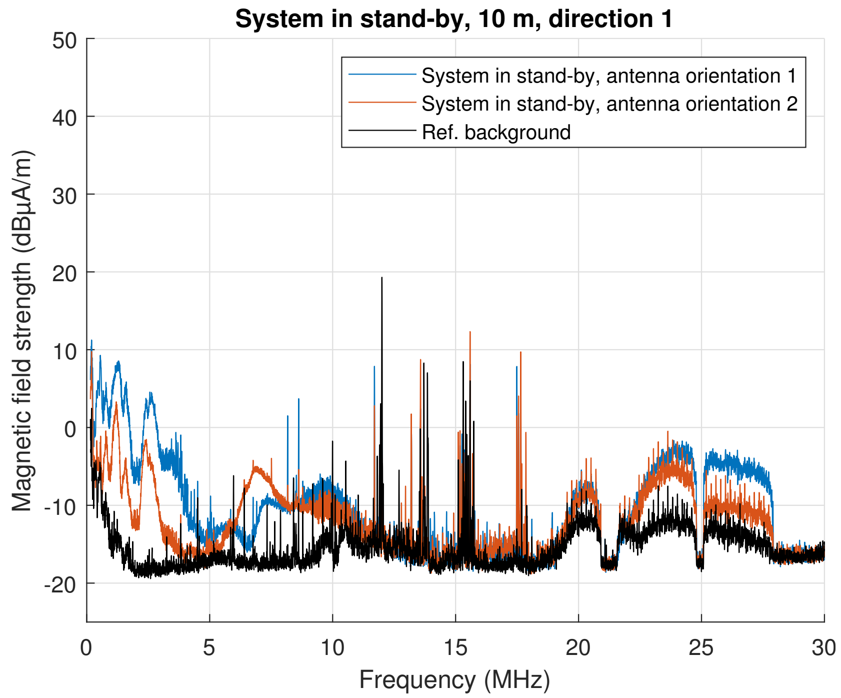


Figure A.15: Measurement of the system in stand-by at a distance of 10 meters and with antenna orientation 1 for the frequency range 150 kHz-30 MHz. The reference background is shown in black.

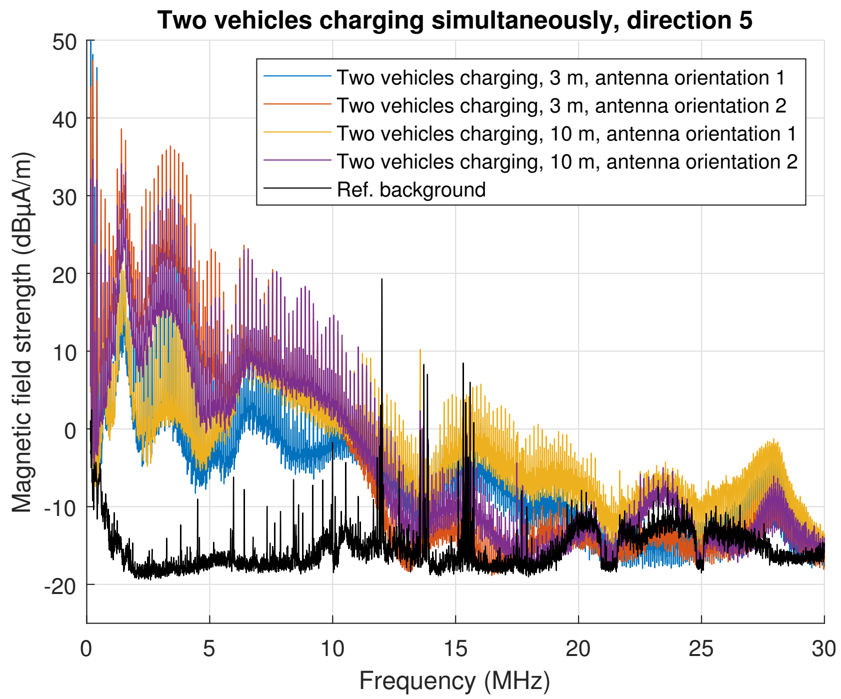


Figure A.16: Measurement when two vehicles are charging simultaneously. The reference background is shown in black.

A.3 30-200 MHz

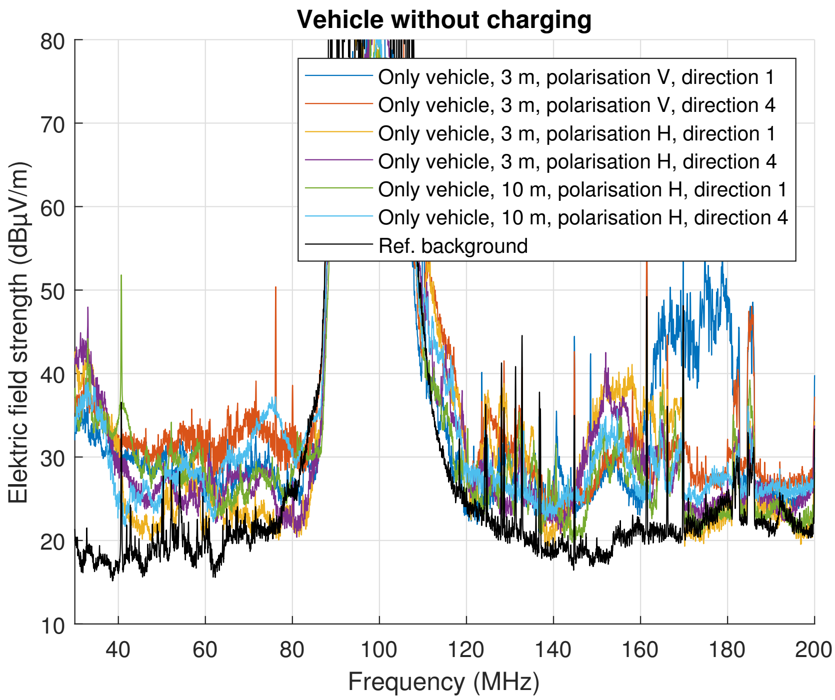


Figure A.17: Measurement of the vehicle for the frequency range 30-200 MHz. The reference background is shown in black.

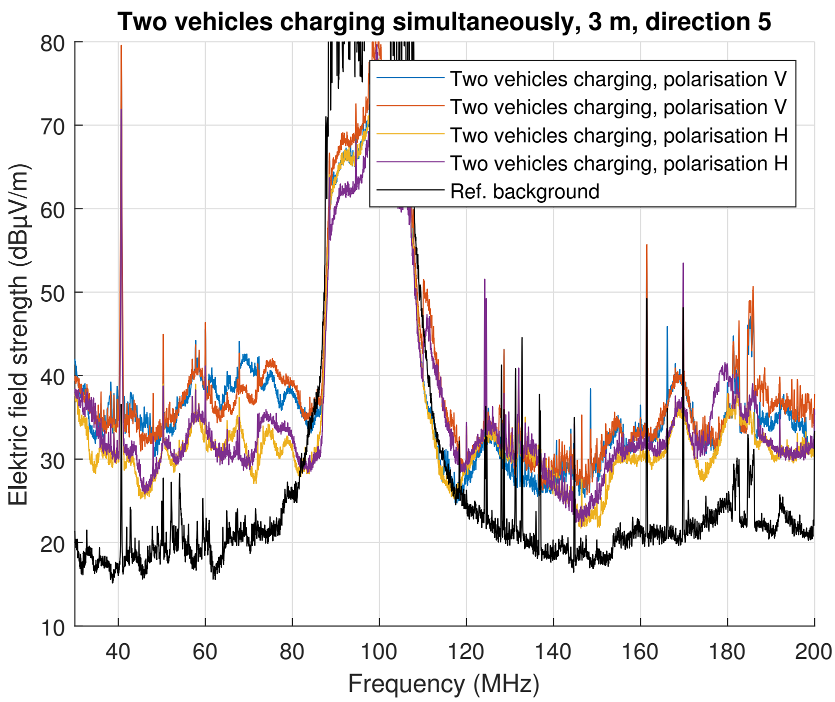


Figure A.18: Measurement when two vehicles are charging at a distance of 3 meters for the frequency range 30-200 MHz. The reference background is shown in black.

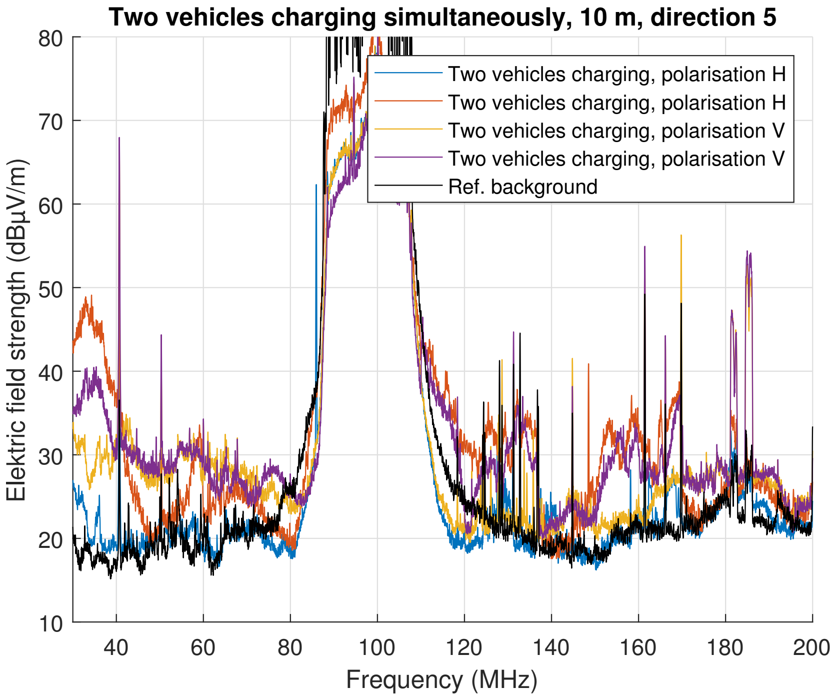


Figure A.19: Measurement when two vehicles are charging at a distance of 10 meters for the frequency range 30-200 MHz. The reference background is shown in black.

A.4 VHF air traffic control band

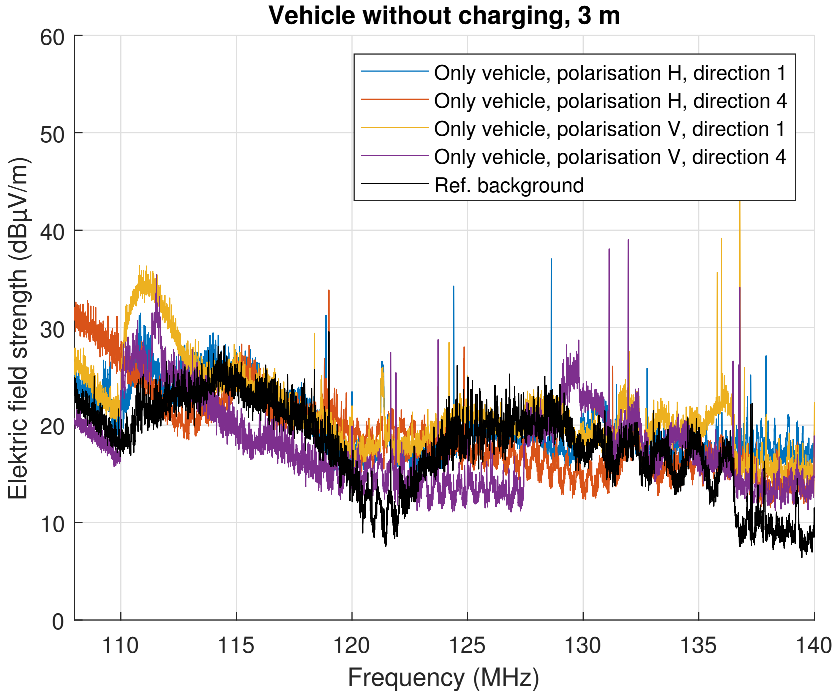


Figure A.20: Measurement of the vehicle at a distance of 3 meters for the frequency range 105-140 MHz. The reference background is shown in black.

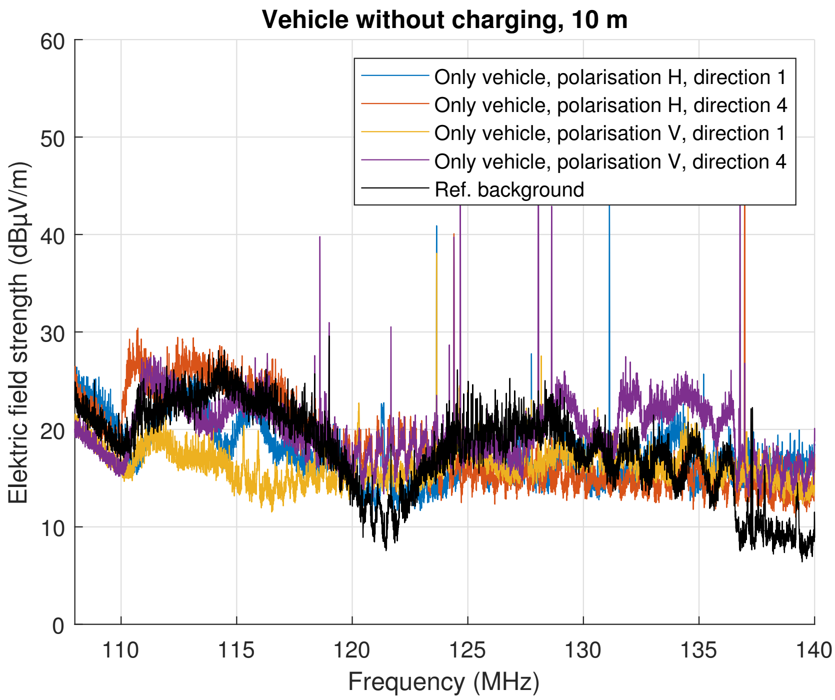


Figure A.21: Measurement of the vehicle at a distance of 10 meters for the frequency range 105-140 MHz. The reference background is shown in black.

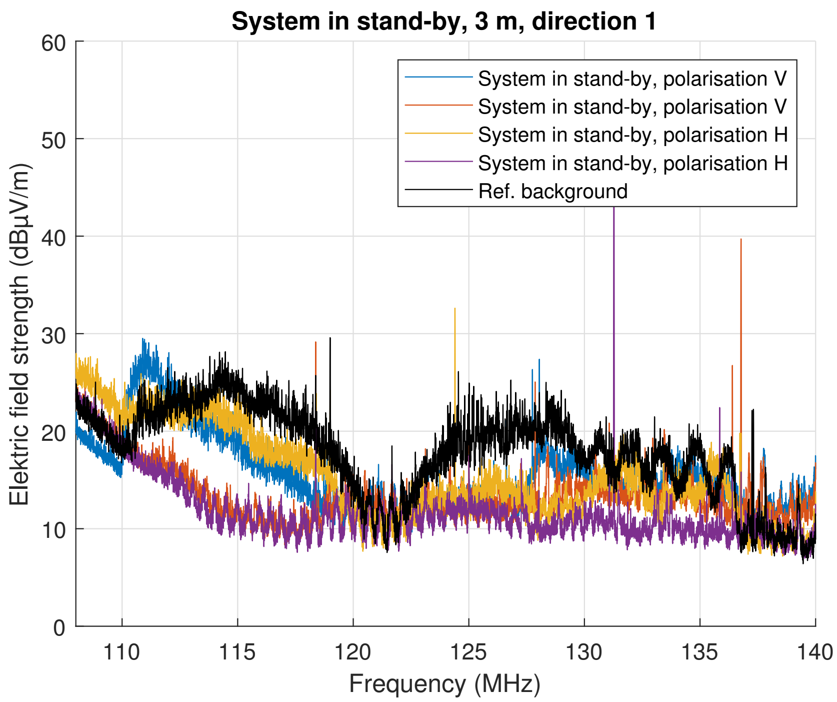


Figure A.22: Measurement of the system in stand-by at a distance of 3 meters for the frequency range 105-140 MHz. The reference background is shown in black.

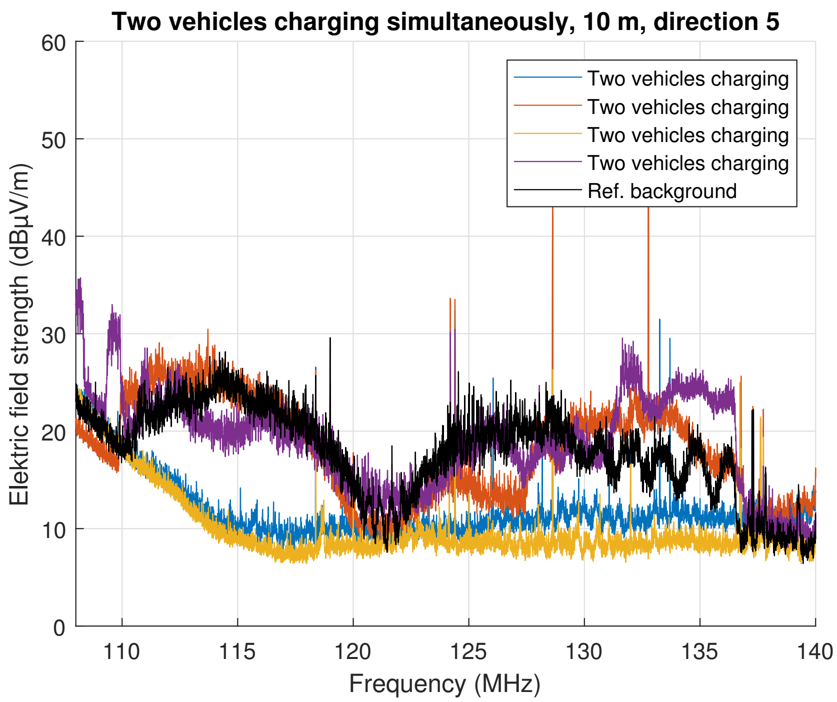


Figure A.23: Measurement when two vehicles are charging at a distance of 10 meters for the frequency range 105-140 MHz. The reference background is shown in black.

A.5 200 MHz-1 GHz

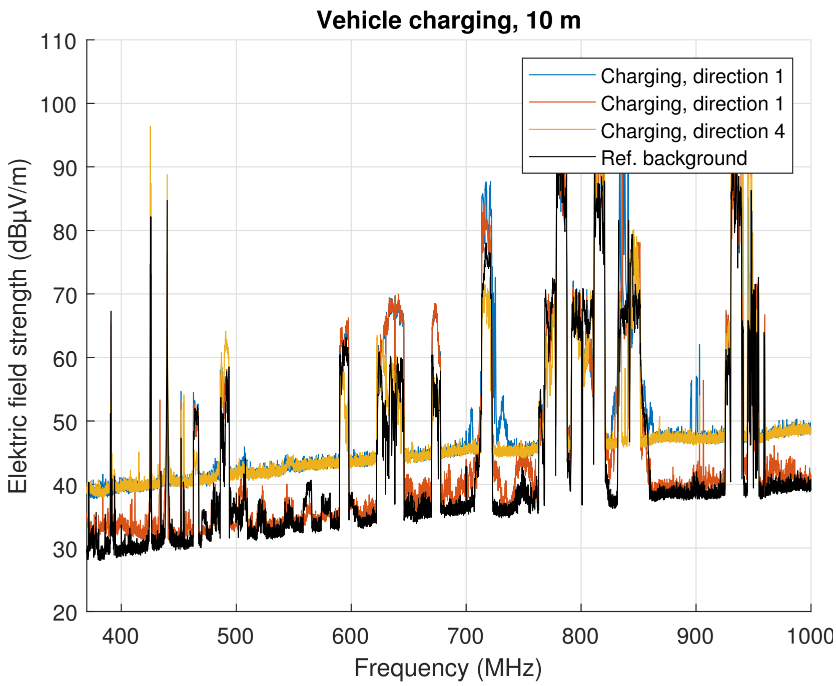


Figure A.24: Measurement of a vehicle charging at a distance of 10 meters for the frequency range 200 MHz-1 GHz. The reference background is shown in black.

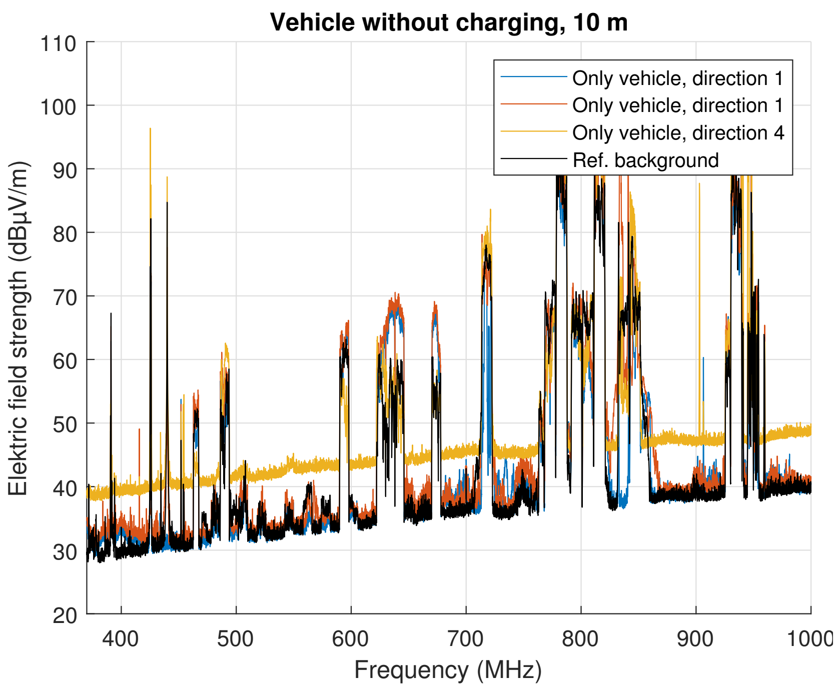


Figure A.25: Measurement of a vehicle charging at a distance of 10 meters for the frequency range 200 MHz-1 GHz. The reference background is shown in black.

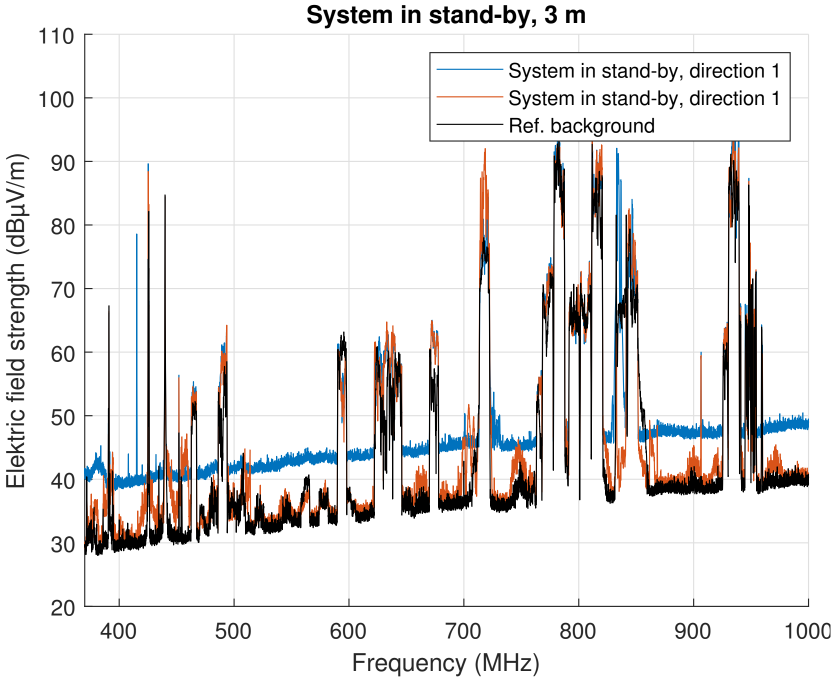


Figure A.26: Measurement of the system in stand-by at a distance of 3 meters for the frequency range 200 MHz-1 GHz. The reference background is shown in black.

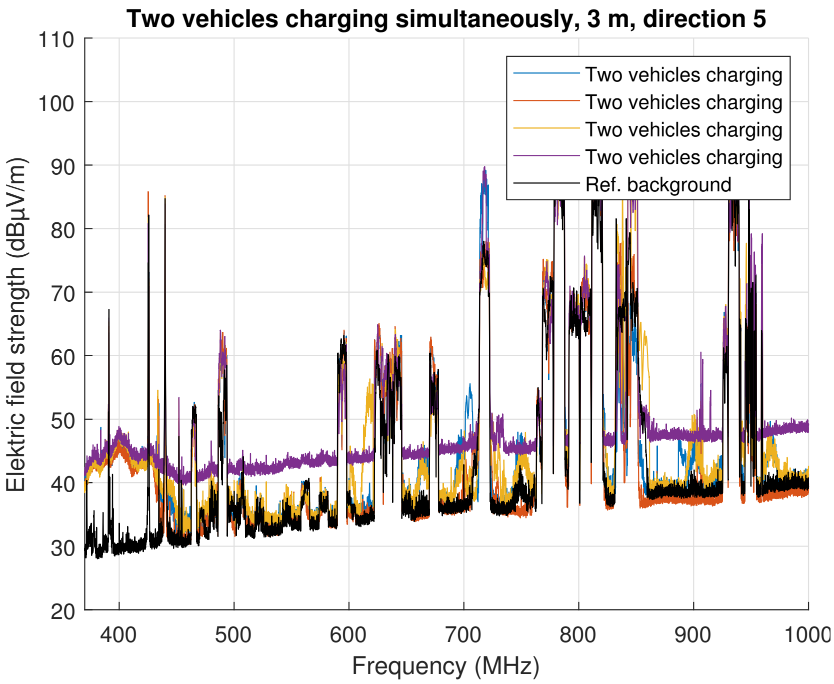


Figure A.27: Measurement when two vehicles are charging at a distance of 3 meters for the frequency range 200 MHz-1 GHz. The reference background is shown in black.

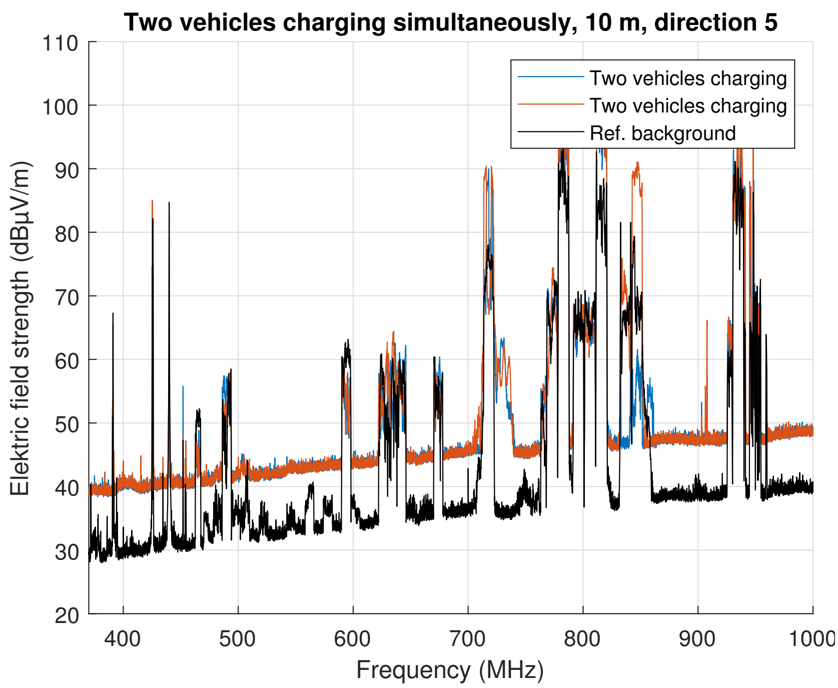


Figure A.28: Measurement when two vehicles are charging at a distance of 10 meters for the frequency range 200 MHz-1 GHz. The reference background is shown in black.

A.6 Tetra band

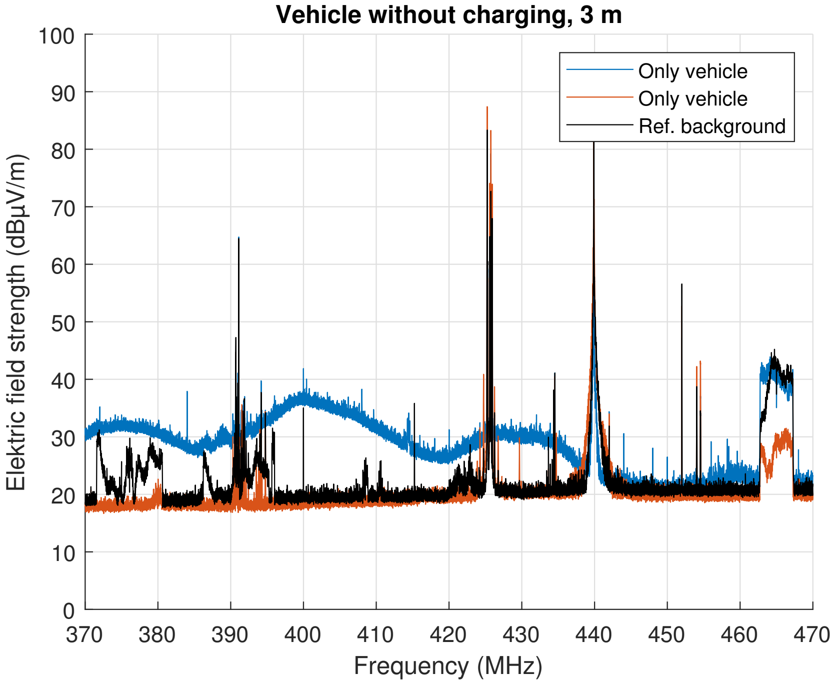


Figure A.29: Measurement of a vehicle at a distance of 3 meters for the frequency range 370-470 MHz. The reference background is shown in black.

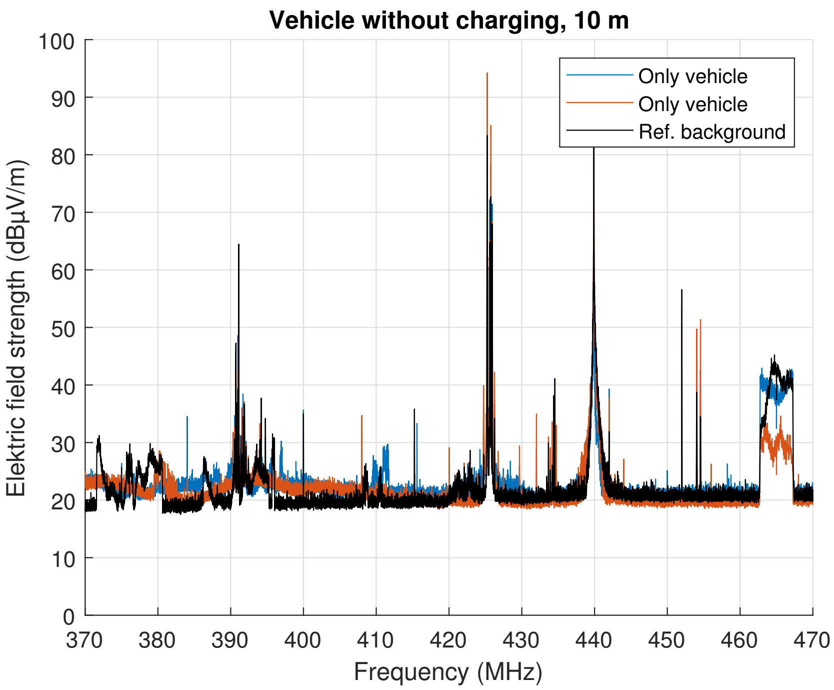


Figure A.30: Measurement of a vehicle at a distance of 10 meters for the frequency range 370-470 MHz. The reference background is shown in black.

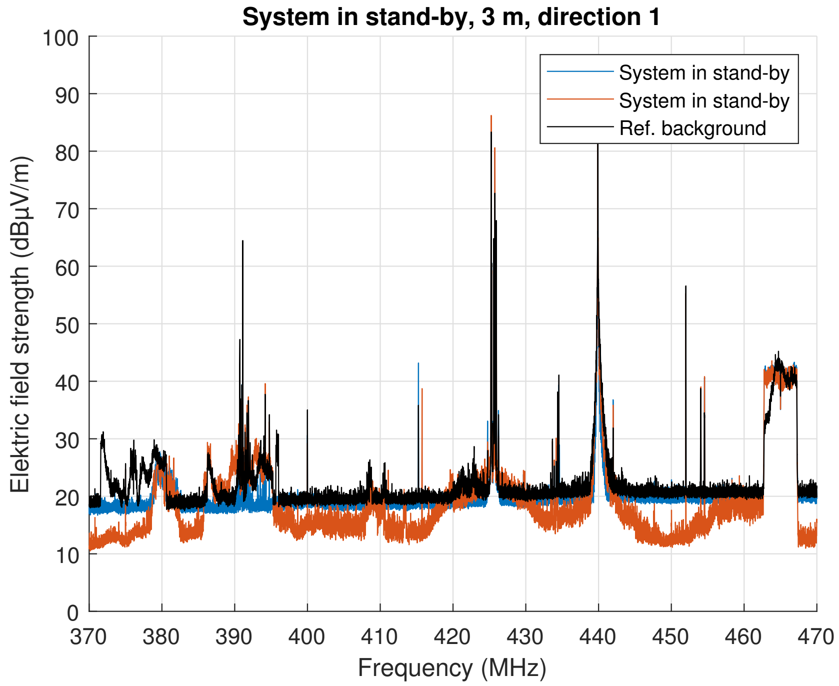


Figure A.31: Measurement of the system in stand-by at a distance of 3 meters for the frequency range 370-470 MHz. The reference background is shown in black.

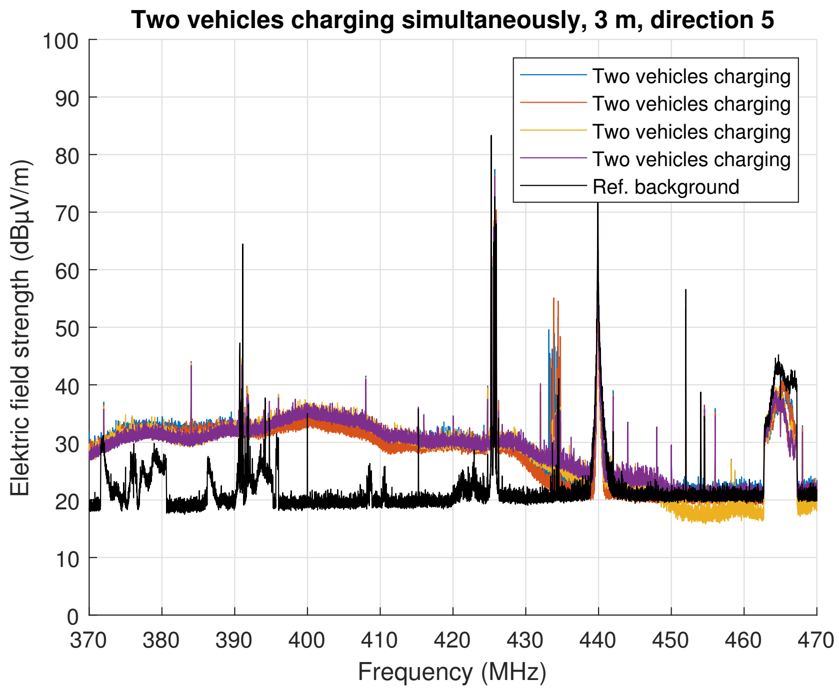


Figure A.32: Measurement when two vehicles are charging at a distance of 3 meters for the frequency range 370-470 MHz. The reference background is shown in black.

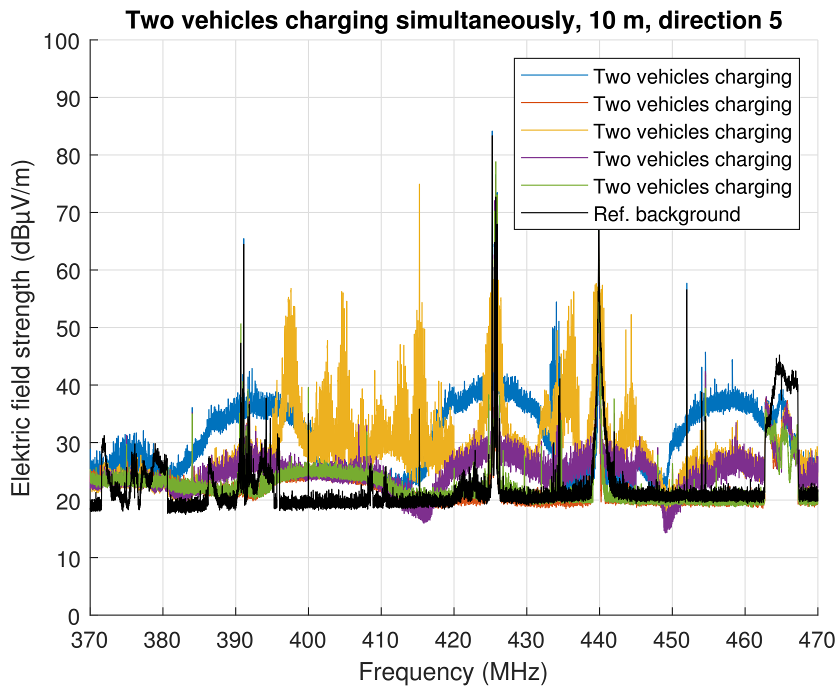


Figure A.33: Measurement when two vehicles are charging at a distance of 10 meters for the frequency range 370-470 MHz. The reference background is shown in black.

B Antenna and filter measurements

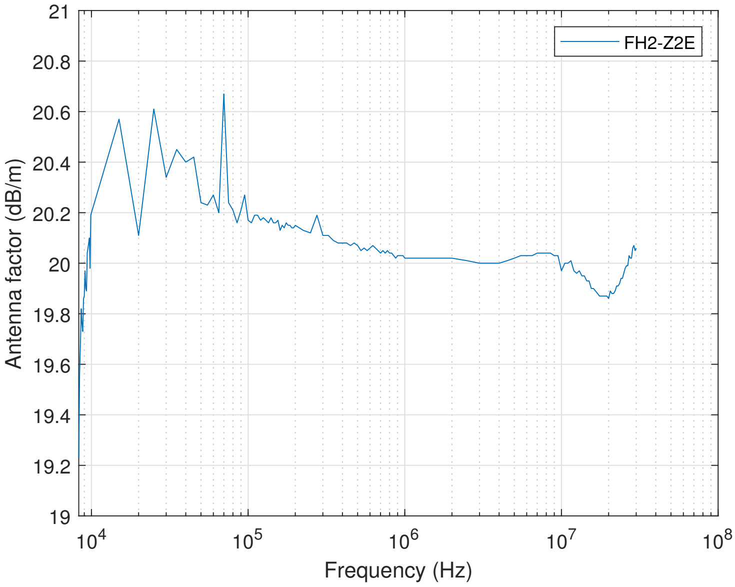


Figure B.1: Antenna factor for the loop antenna HFH2-Z2E.

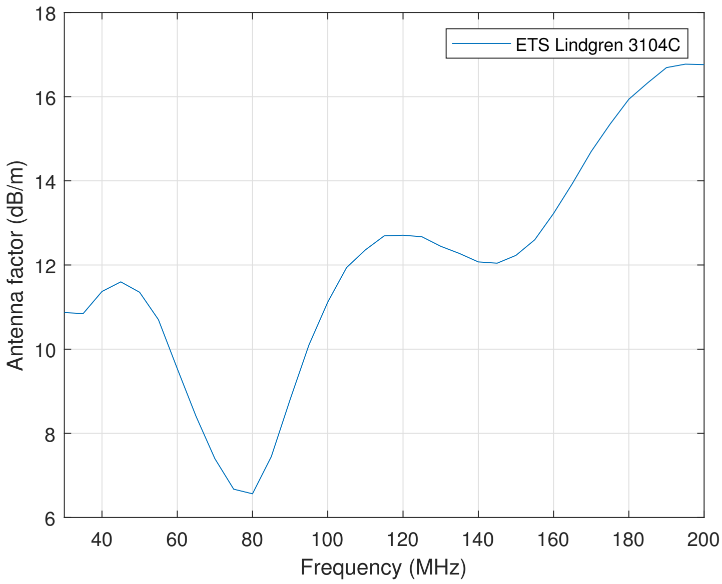


Figure B.2: Antenna factor for the biconical antenna ETS Lindgren 3104C.

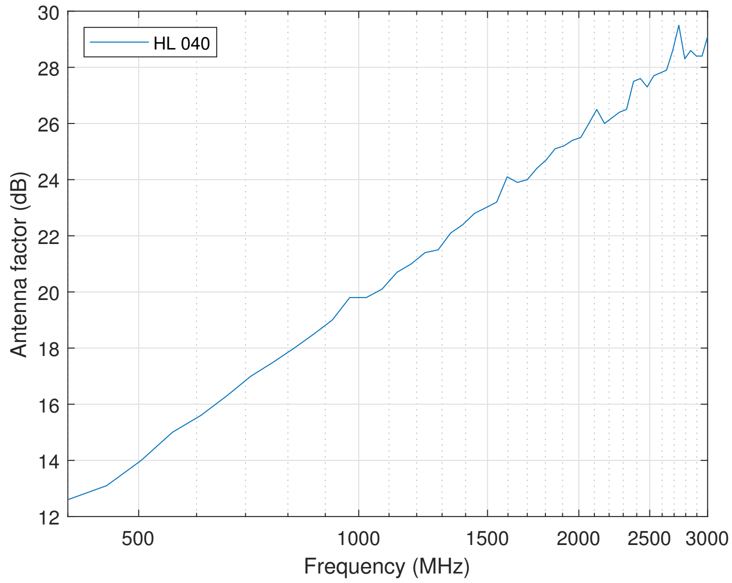


Figure B.3: Antenna factor for the log-periodic antenna HL023.

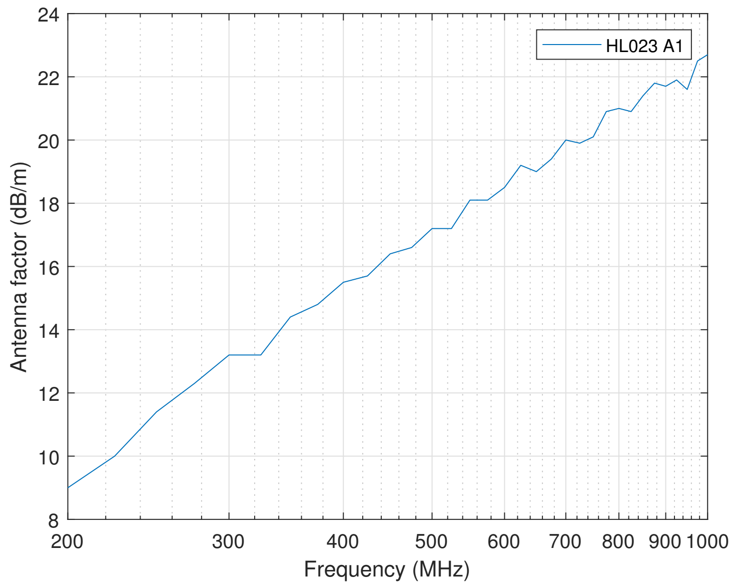


Figure B.4: Antenna factor for the log-periodic antenna HL023 A1.

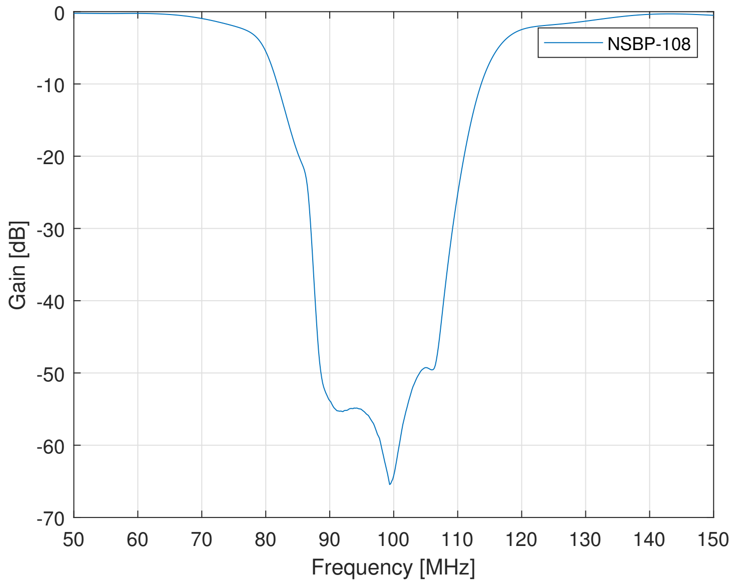


Figure B.5: Gain for the FM filter NSBP-108.

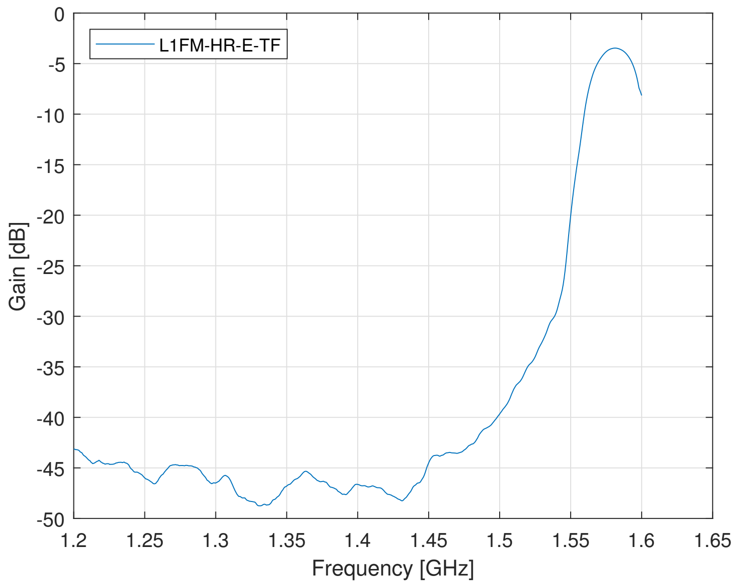


Figure B.6: Gain for the GPS L1 filter L1Fm-HR-E-TF.

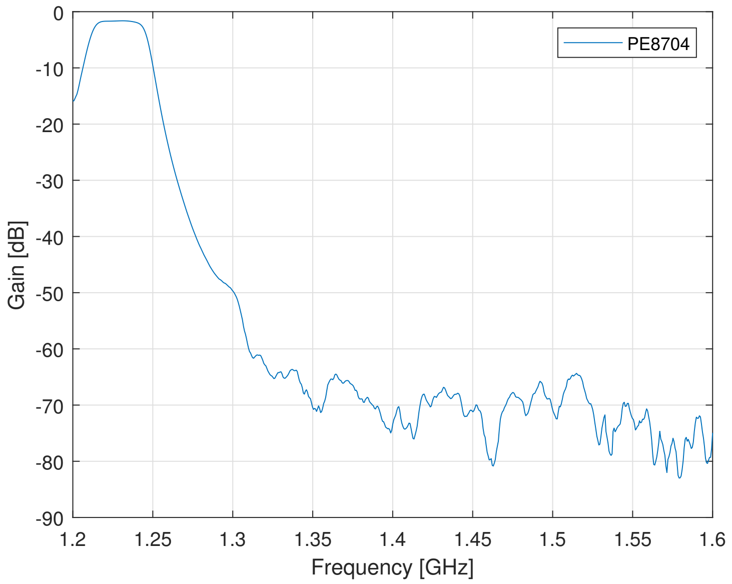


Figure B.7: Gain for the GPS L2 filter PE8704.

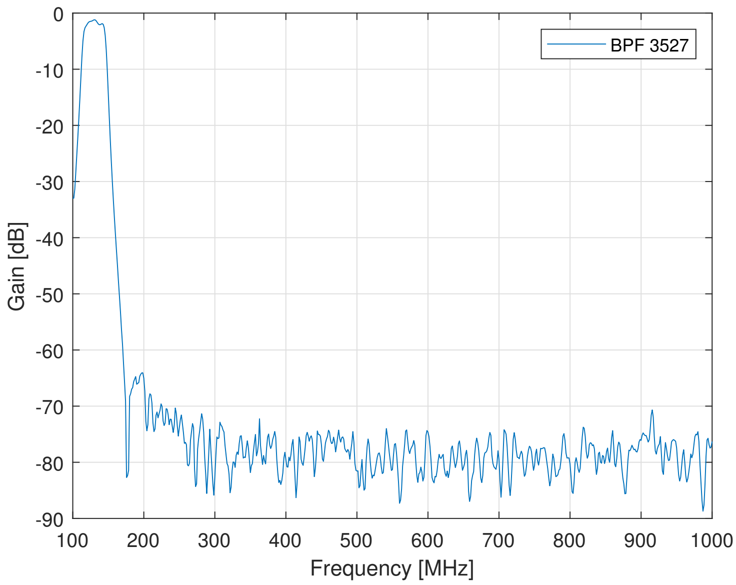


Figure B.8: Gain for the air aviation band pass filter 3527.

FOI
Defence Research Agency
SE-164 90 Stockholm

Phone: +46 8 555 030 00
Fax: +46 8 555 031 00

www.foi.se