# ETSI TR 103 086 V1.1.1 (2013-03)

**Technical Report**

**Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Conformance test procedure for the exterior limit tests in EN 302065-3 UWB applications in the ground based vehicle environment**

Reference

DTR/ERM-TGUWB-021

Keywords

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***ETSI***

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - NAF 742 C
Association à but non lucratif enregistrée à la
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# Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM).

# 1 Scope

The present document specifies a measurement procedure for the exterior limit for road and rail vehicle applications defined in ECC DEC (06)04 [i.2] from 2011. The procedure is intended to be used in the upcoming standard EN 302 065-3 [i.8].

The measurement procedure has been developed based on an extensive measurement campaign with a full car inside a semi-anechoic chamber, in which the radio channel from the inside to the outside, from the transmission of the surface, from below the car and from the tyre are studied in detail.

# 2 References

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

Referenced documents which are not found to be publicly available in the expected location might be found at http://docbox.etsi.org/Reference.

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## 2.1 Normative references

The following referenced documents are necessary for the application of the present document.

## 2.2 Informative references

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] ETSI EN 302 065 V1.2.1 (2010-10): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD) using Ultra Wide Band technology (UWB) for communications purposes; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive".

[i.2] ECC Decision (06) 04 of 24 March 2006 amended 15 December 2011 on the harmonised conditions for devices using Ultra-Wideband (UWB) technology in bands below 10,6 GHz.

[i.3] F. Berens, H. Dunger, S. Czamecki, T. Bock, R. Reuter, S. Zeisberg, J. Weber and J.F. Guasch: "UWB car attenuation measurements", 16th IST Mobile and Wireless Communications Summit, 2007.

[i.4] R. Zetik, A. P. Garcia Ariza, R. Thomä, W. Kotterman:"Application-specific MIMO-UWB channel measurements and parameter extraction: Integrated Project - EUWB", Deliverable D3.1.2b, 2009.

[i.5] ETSI TS 102 883 (V1.1.1): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD) using Ultra Wide Band (UWB); Measurement Techniques".

[i.6] ECC TG3: "UWB Screening Attenuation of Cars", TG3#16-21R0, European Commission JRC, Ispra, Italy, 2006.

[i.7] M. Cheikh, J. David, J.-G. Tartarin, S. Kessler, A. Morin:"RF source characterization of Tire Pressure Monitoring System"; 2nd European Wireless Technology Conference, 2009 (EuWIT 2009), Rome, Page(s): 176 - 179.

[i.8] ETSI EN 302 065-3: "Electromagnetic compatibility and Radio spectrum Matters (ERM) Short Range Devices (SRD) using Ultra Wide Band technology (UWB) for communications purposes; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive Part 3: Requirements for UWB devices for road and rail vehicles".

# 3 Definitions, symbols and abbreviations

## 3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

**equivalent isotropically radiated power (e.i.r.p.):** product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain) (RR 1.161)

## 3.2 Symbols

For the purposes of the present document, the following symbols apply:

| | |
|---|---|
| $d$ | Distance |
| $\Theta$ | Elevation angle |
| $\delta$ | Loss factor |
| $\varepsilon_r$ | Dielectric constant |
| $f$ | Frequency |
| $\Gamma_{RX}$ | Receive antenna reflection coefficient |
| $\Gamma_{TX}$ | Transmit antenna reflection coefficient |
| $G_{RX}$ | Receive antenna gain |
| $G_{TX}$ | Transmit antenna gain |
| $\lambda$ | Wavelength |
| $L_{RX,cable}$ | Receive cable losses |
| $L_{TX,cable}$ | Transmitter cable losses |
| [illegible] | Azimuth angle |
| $P_{RX}$ | Receive power |
| $P_{out}$ | Signal generator output power |
| $\sigma_r$ | Conductivity |
| $\rho_{RX}$ | Direction of the received electrical field |
| $\rho_{TX}$ | Direction of the transmitted electrical field |

## 3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

| | |
|---|---|
| BW | BandWidth |
| CW | Continuous Wave |
| DAA | Detect And Avoid |
| DIT | Device Inside the Tire |
| DUT | Device Under Test |
| e.i.r.p. | equivalent isotropically radiated power |
| EM | ElectroMagnetic |
| GTX | Gain Transmitter |
| LACE | Laboratory of Antennas and Electromagnetic Compatibility |
| LAN | Local Area Network |
| LDC | Low Duty Cycle |
| LNA | Low Noise Amplifier |
| LOS | Line Of Sight |
| ML | MessLabor |
| NF | Noise Figure |
| PEC | Perfect Electric Conductor |

| | |
|---|---|
| PSD | Power Spectral Density |
| RAM | Radar Absorbing Material |
| RF | Radio Frequency |
| RMS | Root Mean Square |
| RX | Receiver / Receive |
| SNR | Signal to Noise Ratio |
| TPC | Transmit Power Control |
| TX | Transmitter / Transmit |
| UWB | Ultra WideBand |

# 4 Summary Of ECC Consideration

The considerations defined in ECC/DEC/(06)04 [i.2] allow, besides general cases, the usage of Ultra Wideband (UWB) devices installed in road and rail vehicles, where special limits apply for the bands 3,1 GHz to 4,8 GHz, 6 GHz to 8,5 GHz and 8,5 GHz to 9 GHz if mitigation techniques are implemented.

Operation is permitted with a maximum mean e.i.r.p. spectral density ($PSD_{mean}$) of -41,3 dBm/MHz and a maximum peak e.i.r.p. ($PSD_{peak}$) of 0 dBm defined in 50 MHz if:

- within the bands 3,1 GHz to 4,8 GHz and 6 GHz to 8,5 GHz Low Duty Cycle (LDC) and an exterior limit ($PSD_{ext}$) of -53,3 dBm/MHz are implemented; or
- within the bands 3,1 GHz to 4,8 GHz and 8,5 GHz to 9 GHz Detect And Avoid (DAA), Transmit Power Control (TPC) and an exterior limit of -53,3 dBm/MHz are implemented; or
- within the band 6 GHz to 8,5 GHz Transmit Power Control (TPC) and an exterior limit of -53,3 dBm/MHz are implemented.

The exterior limit is valid above 0 degree, whereas the reference plane for the 0 degree is the sensor mounting height. Figure 1 shows the principle of these considerations.

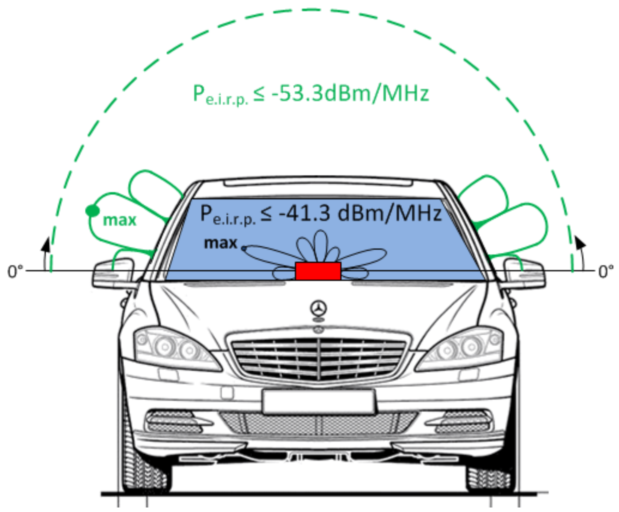



**Figure 1: Principle of the considerations**

NOTE: The exterior limit refers to the maximum mean e.i.r.p. spectral density measured outside the vehicle and every local maximum is below the limits.

# 5 Fundamental Channel Measurements

This clause presents channel measurements, which are used to clarify fundamental issues, i.e. to evaluate the maximum measureable distance and to study the influence of the car. Based on these results the measurement concept for the exterior car limit in EN 302 065-3 [i.8] is developed.

The measurement campaign was performed at a semi-anechoic chamber at the Messlabor (ML) Kolberg of the Bundesnetzagentur in Germany. First test and calibration measurements were performed without a car in an anechoic chamber. As the semi-anechoic chamber shows a measurement uncertainty of ± 6 dB, the measurements are compared to full anechoic chamber measurement from a previous measurement campaign at BOSCH. This shows the influence of the chamber.

Next the channel was characterized from the inside to the outside of the car and from application relevant locations on its surface.

# 5.1 Calibration and Test Measurement

## 5.1.1 Measurement Setup

The measurement setup of the calibration measurements is shown in the next figures. A microwave generator produces a continuous wave (CW) at frequencies between 3 GHz and 5 GHz with a step size of 500 MHz and from 6 GHz to 9 GHz with a step size of 1 GHz. The signal is transmitted by a Vivaldi antenna and is received at 10 meters distance by a calibrated log periodic receiver (RX) antenna. The signal is amplified by a low noise amplifier (LNA) and is measured with a spectrum analyzer. The settings of the spectrum analyzer are shown in table 1. A detailed description of the measurement hardware can be found in table A.1.

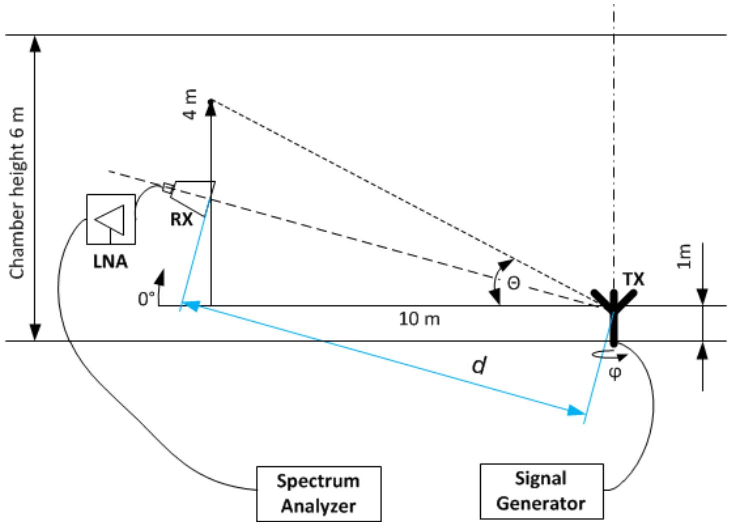
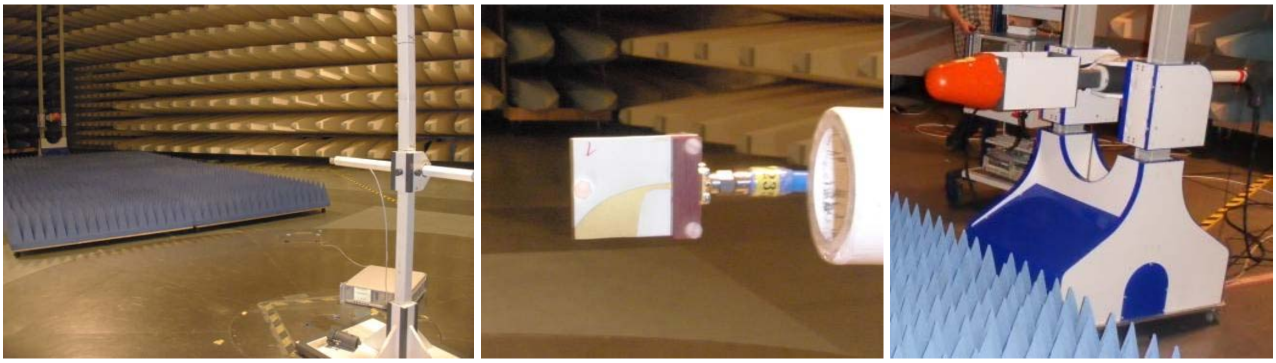



**Figure 2: Antenna Pattern Calibration Measurement Setup**



(a) Setup (b) Vivaldi TX Antenna (c) Log-periodic RX antenna

**Figure 3: Antenna Pattern Calibration Measurement Setup: Photos**

**Table 1: Spectrum analyzer settings according to EN 302 065 [i.1]**

| Parameter | Value |
|---|---|
| Start Frequency | 2 GHz |
| Stop Frequency | 10 GHz |
| Resolution BW | 1 MHz |
| Video BW | 3 MHz |
| Detector Mode | RMS |
| Averaging time | 1ms (per point on spectrum analyser scan) |

The transmitter (TX) antenna is continuously rotated about the vertical axis and the received power is calculated back to the transmitted e.i.r.p. The calibration measurements were performed only for the vertical polarization corresponding to the polarization of the TX antenna.

## 5.1.2 Antenna Pattern Analysis

As the transmitter antenna gain in the transmit path are unknown and the transmit e.i.r.p. has to be known, they were determined by calibration measurements. This is done by calculation of the e.i.r.p. from the received power $P_{RX}(f,d)$ using Friis law where f is the frequency and d is the distance. The Friis equations in dB is given by:

$$P_{RX}(f,d) = P_{out} - L_{TX\,cable}(f) + G_{TX}(\varphi,\theta,f) + G_{RX}(\varphi,\theta,f) - L_{RX\,cable}(f) + 20\log\left(\frac{\lambda}{4\pi d}\right) + G_{LNA}(f)$$

where $P_{out}$ is the output power of the signal generator, $L_{TX\,cable}$ and $L_{RX\,cable}$ are the TX and RX cable losses, $G_{TX}$ and $G_{RX}$ are the TX and RX antenna gains, and $G_{LNA}$ is the LNA gain. As e.i.r.p. is given by:

$$\text{e.i.r.p.}(\varphi,\theta,f) = P_{out} - L_{TX\,cable}(f) + G_{TX}(\varphi,\theta,f),$$

where ⍰ is the azimuth and Θ is the elevation angle, it follows that:

$$\text{e.i.r.p.}(\varphi,\theta,f) = P_{RX}(f,d) - G_{RX}(\varphi,\theta,f) - G_{LNA}(f) + 20\log\left(\frac{4\pi d}{\lambda}\right) + L_{RX\,cable}.$$

where λ is the wavelength. All parameters are known except $G_{TX}$ can be calculated straight forward by:

$$G_{TX}(\varphi,\theta,f) = \text{e.i.r.p.}(\varphi,\theta,f) - P_{out} + L_{TX\,cable}(f).$$

The measured antenna gain including the cable losses are shown in figure 4.

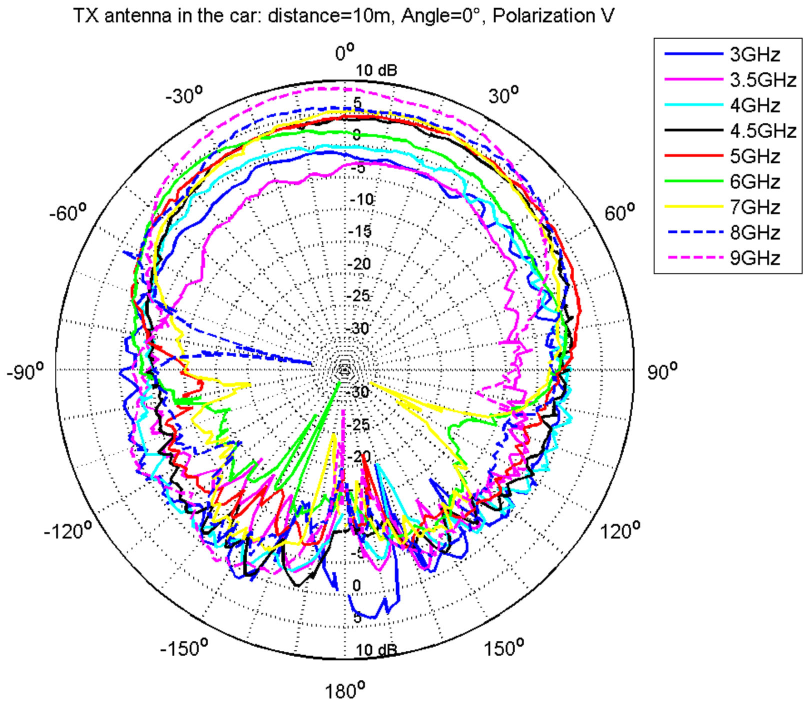



**Figure 4: TX antenna pattern (measured)**

We can see that the antenna gain between -60° and 75° is approx. constant, but the gain is frequency dependent and achieves values between -5 dB and +9 dB. The peak at 170° occurs from the measurement cable, this can be observed if the plot is compared to the reference antenna pattern (see figure 5).

## 5.1.3 Reference Antenna Pattern

The real antenna pattern was previously measured in a full anechoic chamber at BOSCH. Figure 5 shows the frequency dependency of the Vivaldi antenna. The nominal gain at azimuth angle 0° and the maximum gain are shown in table 2. Furthermore the TX cable losses are shown for the calculation of e.i.r.p.

A comparison of figures 4 and 5 shows that the patterns are very similar, but due to measurement uncertainties (mainly from diffraction and reflections) the maximum gain can differ up to 4 dB for specific frequencies.

The real antenna gain is used for the calculation of the e.i.r.p. values.

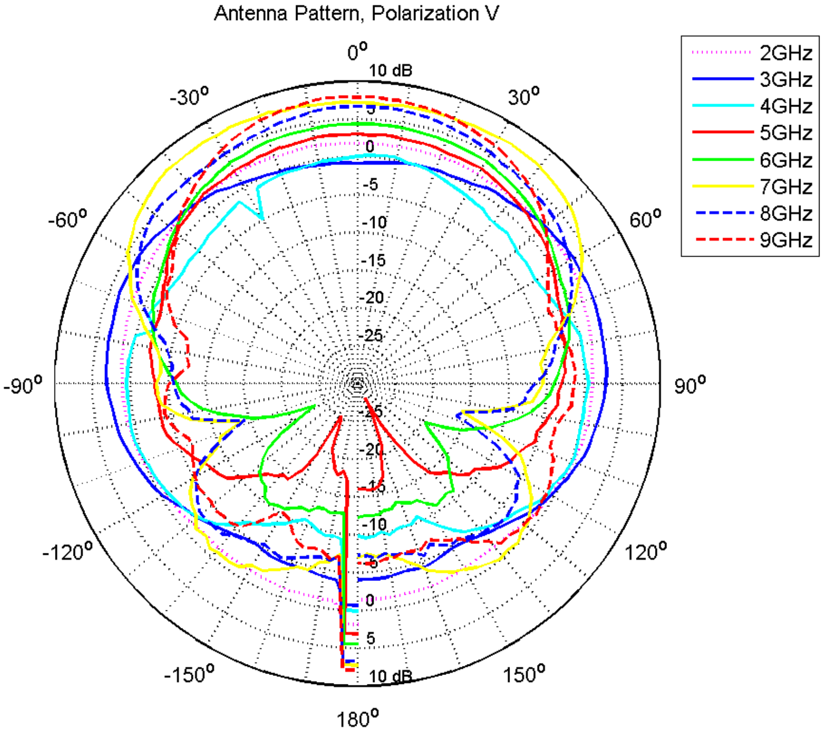



**Figure 5: TX antenna pattern (real – measured in full anechoic chamber)**

**Table 2: Nominal and maximum gain of the antenna pattern**

| Frequency [GHz] | Nominal angle [deg] | Nominal gain [dBi] | Max. gain angle [deg] | Max. gain [dBi] | TX Cable losses |
|---|---|---|---|---|---|
| 2 | 0 | 1,7 | 45 | 2,2 | 0,57 |
| 3 | 0 | -0,9 | -81 | 3,6 | 0,66 |
| 3,5 | 0 | -0,45* | | 2,1* | 0,74 |
| 4 | 0 | 0 | 78 | 0,5 | 0,79 |
| 4,5 | 0 | 1,5* | | 1,8* | 0,82 |
| 5 | 0 | 3 | -21 | 3,0 | 0,86 |
| 6 | 0 | 4,3 | -9 | 4,4 | 0,95 |
| 7 | 0 | 7,1 | -39 | 7,8 | 1,02 |
| 8 | 0 | 6,6 | -6 | 6,7 | 1,1 |
| 9 | 0 | 7,8 | -18 | 7,9 | 1,19 |
| NOTE: * Linear interpolated. | | | | | |

For all measurements where the transmit power is set to a specific e.i.r.p. level, the output level of the signal generator $P_{out}$ is given by

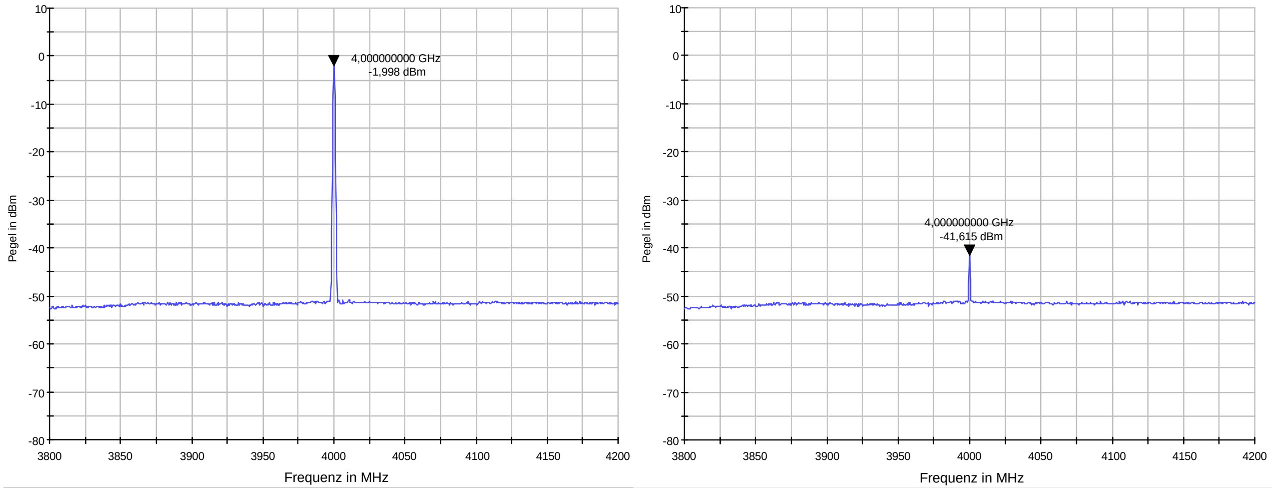
$$P_{out} = \text{e.i.r.p.}(\varphi,\theta,f) + L_{TX\ cable}(f) - G_{TX}(\varphi,\theta,f)$$

and $G_{TX}(\varphi,\theta,f)$ is set to the max. antenna gain (f) of table 2.

## 5.1.4 Maximum Measureable Distance

The necessary SNR for an accurate measurement is approximately 10 dB. Thus, we can calculate the maximum measureable distance for UWB transmission levels, if typical high performance measurement equipment is used.

The measurements were done at a distance of 10 m with $\varphi = \theta = 0°$ and $P_{out}$ was reduced from 0 dBm to -50 dBm in 10 dB steps.




(a) $P_{out} = 0\text{dBm}$ (b) $P_{out} = -40\text{dBm}$

**Figure 6: Measured TX power for SNR analysis**

Figure 6 shows that an e.i.r.p. of -41,3 dBm is measureable at a distance of 10 m with sufficient SNR, but the exterior limit of -53,3 dBm/MHz is below the noise floor. Therefore a maximum measureable distance can be calculated where the attenuation is 12 dB less using Free space equation. A maximum measurable distance of 2,5 m is obtained. As the car is very close if the distance is only 2,5 m, we decided to go to 3 m which decreases the SNR by 1,5 dB, but it is the minimum practical distance.

Note, the noise floor is -52 dBm/MHz, because the received noise power is calculated for e.i.r.p. Thus the correction is done accounting for the free space loss, cable losses, antenna gains, and the LNA gain.

Note, the measured SNRs correspond perfectly with the expected ones from the link budget in table A.2. A direct comparison can be done if 6 dB will be subtracted from the 2 GHz value to obtain the corresponding 4 GHz value.

The next measurements were performed at 3 m and e.i.r.p.=-53,3 dBm. The results are summarized in table 3.

**Table 3: Measured SNR at 3m using e.i.r.p. = -53,3 dBm**

| f [GHz] | $G_{TX}$ [dB] | $P_{out}$ [dB] | e.i.r.p[dB] | SNR [dB] |
|---|---|---|---|---|
| 3,0 | -0,9 | -52,3 | -53,4 | 11,0 |
| 3,5 | -0,3 | -53,0 | -53,9 | 9,0 |
| 4,0 | -0,6 | -52,7 | -53,3 | 8,0 |
| 4,5 | 1,7 | -55,0 | -52,8 | 8,0 |
| 5,0 | 2,9 | -56,2 | -52,5 | 7,0 |
| 6,0 | 3,1 | -56,4 | -51,0 | 4,2 |

We can see that the expected SNR matches very well the measured one (SNR = 8,5 dB at 4 GHz). Obviously it is not possible to measure -53,3 dBm at the higher frequencies with the current high performance setup. Thus a more sensitive measurement setup has to be chosen for the higher frequencies, which could be achieved e.g. by using a higher RX antenna gain (> 7 dBi) or a lower noise figure of the LNA (< 2,6 dB).

For the measurement at 10 GHz additional 10,5 dB gain are needed in comparison to 3 GHz. Horn antenna gains are available on the market up to 14 dBi to16 dBi.

### Conclusions:

The current measurement equipment with a measurement antenna with 7 dB gain and an LNA with 28 dBgain/2,6 dB noise figure, was sufficiet to measure signals at 3 m with e.i.r.p.=-41,3 dBm/MHz. But the exterior limit of -53,3 dBm/MHz was not measureable at the higher frequencies, thus higher antenna gains or lower NFs are necessary. The proposed parameters for the measurement equipment are shown in table 4.

**Table 4: Recommended Hardware**

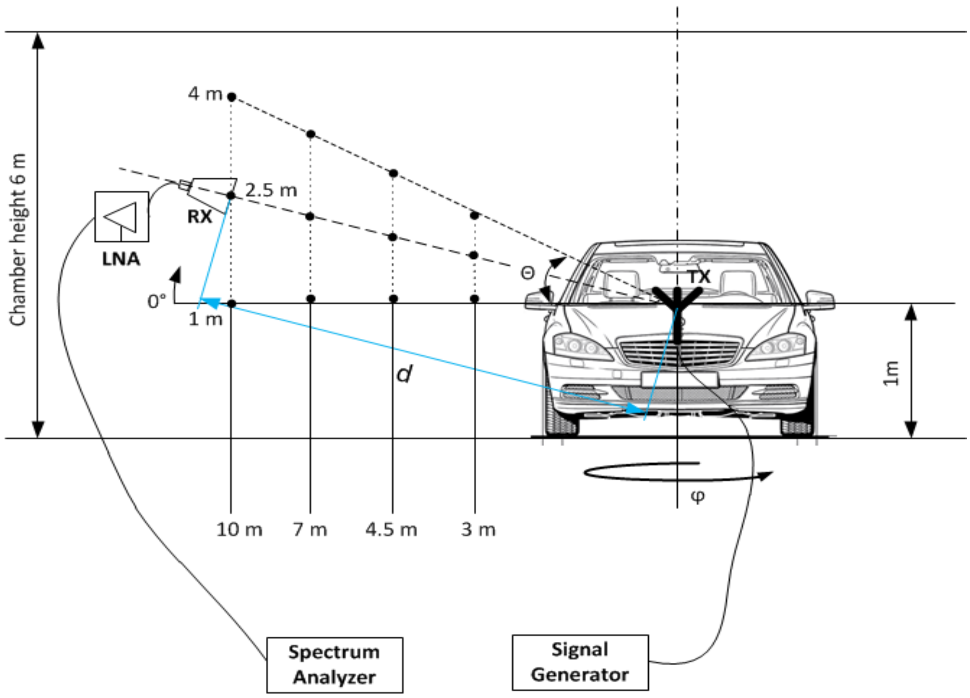
| Device | Parameter | Value |
|---|---|---|
| LNA | NF | < 2 dB |
| LNA | Gain | > 30 dB |
| RX Horn Antenna | Gain (10 GHz) | > 16 dB |
| RX Horn Antenna | Gain (8 GHz) | > 14 dB |
| RX Horn Antenna | Gain (6 GHz) | > 12,5 dB |
| RX Horn Antenna | Gain (2 GHz to 5 GHz) | > 10 dB |
| Cables | Shielding | > 60 dB |
| Cable | Losses | Take losses into account for total gain calculations |
| NOTE: The noise floor of the combined equipment should be at least 6 dB but 10 dB would be optimal. | | |

## 5.2 Car shielding/car influence measurement

The goal of these measurements is to study the impact of the car on the measured/calculated transmit power (e.i.r.p.). First, the TX antenna is placed in the middle of the car and in the centre of the rotating plate. Then the car is rotated by 360° and the received power is measured at 10 m. The measurement is repeated for several RX antenna heights (see figure 7). This allows the detection of the peak power spots. The measurements were repeated for several distances and a comparison of the measured powers allows a fading analysis. The minimum distance is evaluated at which the fading does not significantly influence the estimated transmit power. Next, the SNR (at 3 m) will be evaluated for a transmit power of -41,3 dBm/MHz. This is necessary to show which peaks are measureable for e.i.r.p. = -41,3 dBm/MHz. Finally, a second position of the antenna is analysed, in which the antenna is placed on the roof above the rear seat.

### 5.2.1 Car shielding and fading analysis: TX antenna in the middle of the car

The measurement setup is shown in table 7. The sensor was placed close to the middle of the rotation axis.




(a) Measurement setup

(b) TX antenna (height 1 m)

(c) TX antenna

(d) RX antenna at 3 m and 1,45 m height (8,5°)

(e) RX antenna at 10 m and 1 m height (0°)

**Figure 7: Car Shielding and Fading Measurement Setup**

The measurement parameters are shown in table 5 and the settings of the spectrum analyzer are shown in table 1.

**Table 5: Shielding and Fading Analysis: Measurement Parameters**

| Measurement | e.i.r.p. | Distance | Elevation angle Θ | Frequency |
|---|---|---|---|---|
| 1 | 0 dBm | 3 m | 0°; 8,5°; 16,7° | 3; 3,5; 4; 4,5; 5; 6 |
| 2 | 0 dBm | 4,5 m | 0°; 8,5°; 16,7° | 3; 3,5; 4; 4,5; 5; 6 |
| 3 | 0 dBm | 7 m | 0°; 8,5°; 16,7° | 3; 3,5; 4; 4,5; 5; 6 |
| 4 | 0 dBm | 10 m | 0°; 8,5°; 16,7° | 3; 3,5; 4; 4,5; 5; 6 |

Figure 8 shows that for this car no shielding is given, because the signals can penetrate the windows with nearly no attenuation. This could be completely different if the car has metalized windows, where significant higher shielding can be expected [i.3] and [i.6]. Several peaks occur with gains of 0 dB meaning no shielding and maximum values of 3 dB occur. The horizontal polarization is significantly lower than the vertical polarization. Only a few peak values can be observed with maximum values of -3 dB.

The measurements of the fading analysis are shown in figure 9. Therefore the measurements where repeated for different distances. An angle of Θ = 8,5° was chosen because the previous measurements showed there the highest peaks. Obviously good correlation of the antenna pattern is given, but the peak values are slightly different in value and angle. Table 6 summarizes the peak values for analysis. The deviations $\Delta_{max}$(10 m) and $\Delta_{mean}$(10 m) are the maximum and the mean deviation with respect to 10 m for all frequencies. That assumes that 10 m leads to the most accurate measurements. We can see that the deviations at all distances are within 3 dB and are acceptable accurate. Furthermore we can see that always higher values of the mean and peak powers are observed at 3 m in comparison to 10 m. Thus a measurement at 3 m is on the safe side from the interference point of few.

**Table 6: Mean and peak e.i.r.p. with respect to distance**

| | **Mean e.i.r.p. [dBm]** | | | | **Angle max. e.i.r.p. [deg]** | | | | **Max. e.i.r.p. [dBm]** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **3 m** | **4,5 m** | **7 m** | **10 m** | **3 m** | **4,5 m** | **7 m** | **10 m** | **3 m** | **4,5 m** | **7 m** | **10 m** |
| 3 GHz | -6,3 | -7,3 | -7,1 | -7,6 | -176 | -12 | -24 | -25 | 1,2 | -1,8 | -0,5 | -1,6 |
| 3,5GHz | -4,6 | -5,4 | -5,4 | -5,8 | 1 | -69 | -66 | -71 | 1,8 | 1,2 | 1,1 | 0,1 |
| 4 GHz | -4,5 | -4,9 | -4,8 | -5,0 | 25 | 28 | 23 | 23 | 2,5 | 2,2 | 2,3 | 2,8 |
| 4,5GHz | -4,6 | -5,9 | -5,8 | -5,4 | 0 | -24 | 0 | -31 | 3,2 | 1,9 | 1,8 | 1,6 |
| 5 GHz | -5,0 | -5,4 | -5,1 | -5,1 | -8 | -5 | -3 | 0 | 5,0 | 5,1 | 5,4 | 3,4 |
| 6 GHz | -7,0 | -6,9 | -7,1 | -7,3 | -17 | -3 | -2 | -6 | 2,7 | 0,9 | 2,8 | 1,6 |
| $\Delta_{max}$(10 m) | 1,3 | 0,5 | 0,5 | -- | -- | -- | -- | -- | 2,8 | 1,7 | 2 | -- |
| $\Delta_{mean}$(10 m) | 0,7 | 0,33 | 0,28 | -- | -- | -- | -- | -- | 1,5 | 0,76 | 1 | -- |

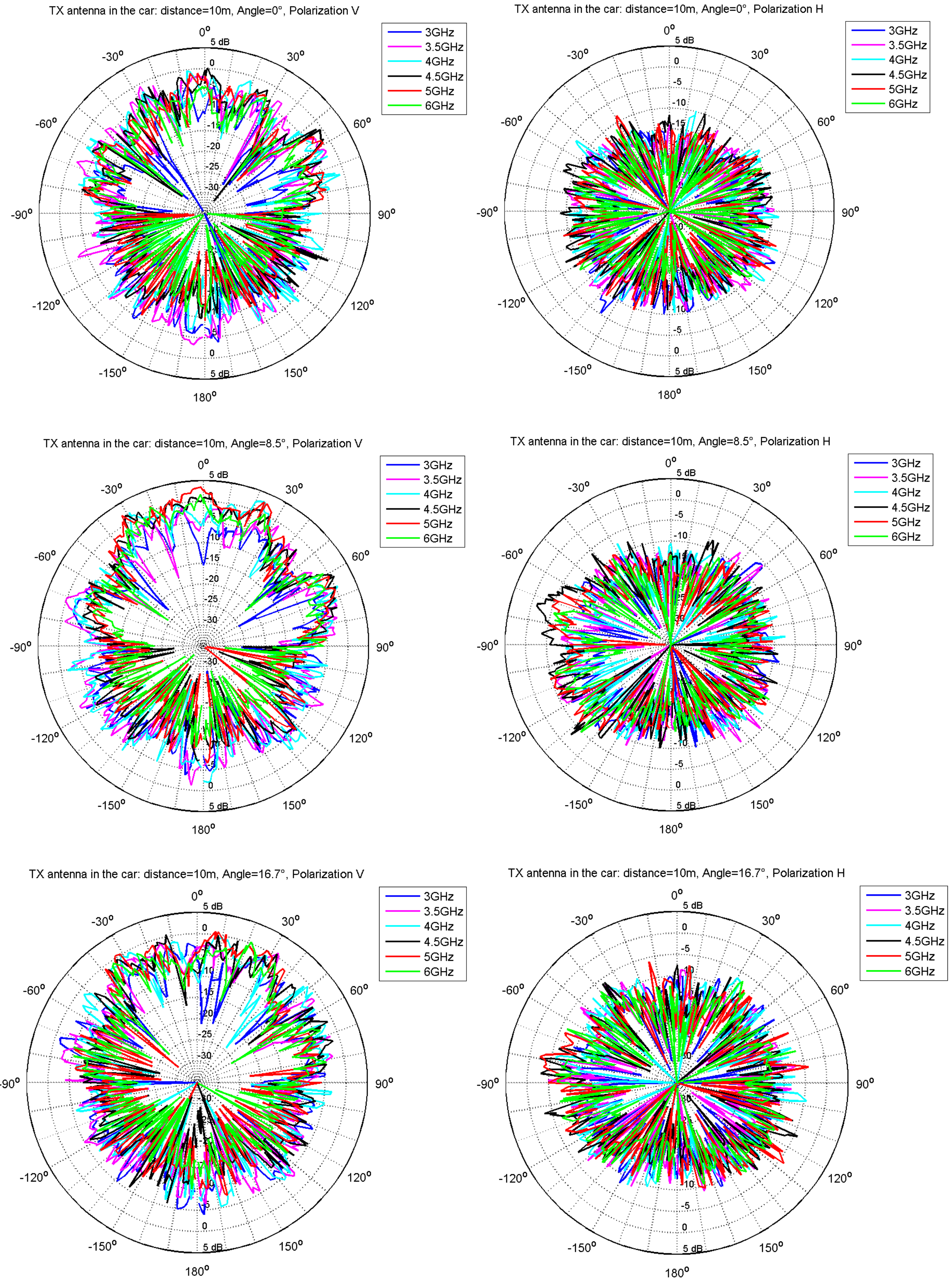



**Figure 8: TX antenna in the middle of the car: Measured e.i.r.p. (dBm/MHz)**

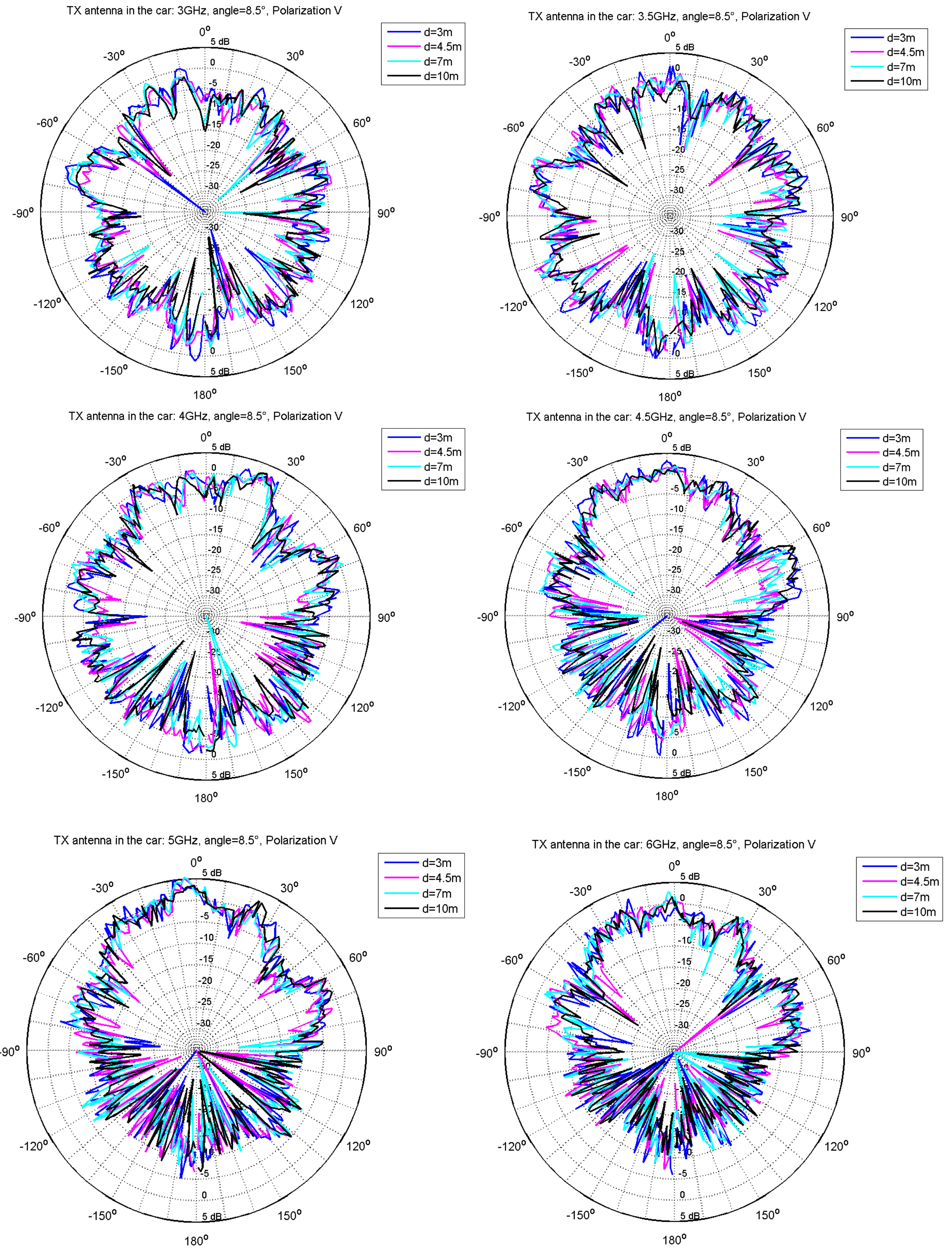



**Figure 9: TX antenna in the middle of the car: Measured e.i.r.p., distance dependency of measurements**

**Conclusions:**

- No shielding can be expected from the inside to the outside for this car. A different situation can be expected for e.g. metalized windows.
- The transmission patterns do not significantly vary for the different distances.
- A measurement at 3m is accurate enough and stronger peaks and more average power is measured in comparison to the other distances. Thus a measurement at 3m is safe from interference point of view.
- If it is not possible to place the TX antenna close to the center of the rotating plate, the measurements have to be corrected by a measurement correction procedure. (see EN 302 065-3 [i.8]).
- If a semi anechoic chamber is used, the ground between TX and RX antenna should be covered by absorber material. This should be done at least for the area of the direct ground reflection (see figure 9).

## 5.2.2 Measurements at 3 m using UWB transmission power (-41,3 dBm)

The measurement parameters can be found in table 7. The angle of 8,5° was chosen, because the highest peaks were observed at these heights in the previous clause.

**Table 7: Shielding and Fading Measurements Parameters**

| Measurement | e.i.r.p. | Distance | Angle | Frequency |
|---|---|---|---|---|
| 5 | -41,3 dBm | 3 m | 8,5° | 3; 4,5; 6; 7,5; 9 |

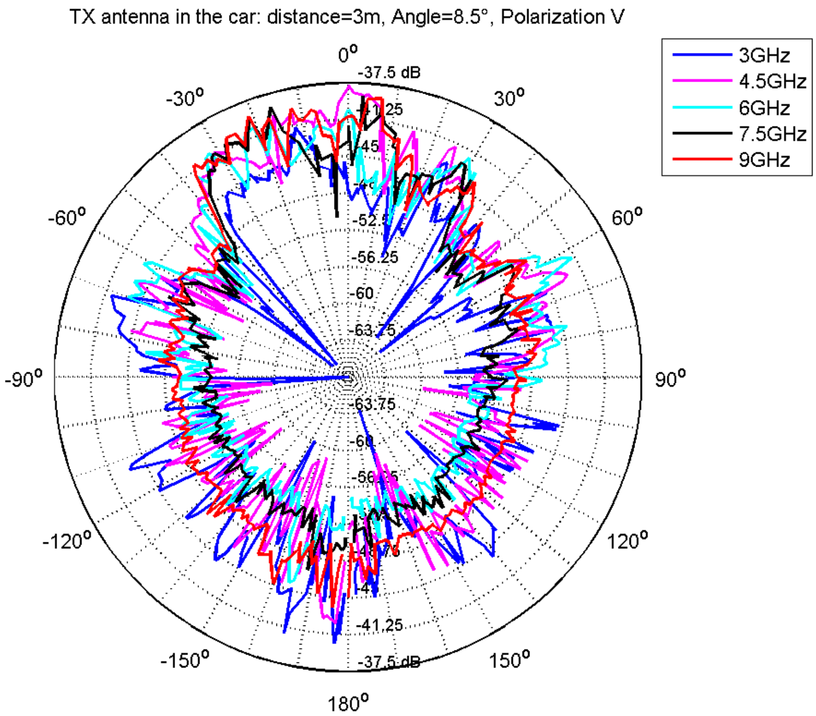



**Figure 10: Measurement at 3 m with e.i.r.p. -41,3 dBm: Measured e.i.r.p.**

We can see that the peaks are well measureable at e.i.r.p. = -41,3 dBm. The peak values of all frequencies occur in the main transmission direction. Only at 3 GHz many peak values are observable at other angels, because the therefore the antenna pattern is oval and has higher gain to the side (see figure 5).

## 5.2.3 In-Car measurements position on the roof of the car

In these measurements the TX antenna was mounted above the right rear seat under the roof (see figure 11). Again the car was rotated by 360° and the settings of the spectrum analyzer were the same as in table 1.

(a) TX antenna under the roof (b) RX antenna at 3m and 4m height (42°)

**Figure 11: In-Car measurements RX antenna under the roof**

**Table 8: In-Car under the roof measurements parameters**

| Measurement | e.i.r.p. | Distance | Angle | Frequency |
|---|---|---|---|---|
| 6 | 0 dBm | 3 m | [0°; 8,5°; 16,7°; 42°] | 3; 3,5; 4; 4,5; 5; 6 |

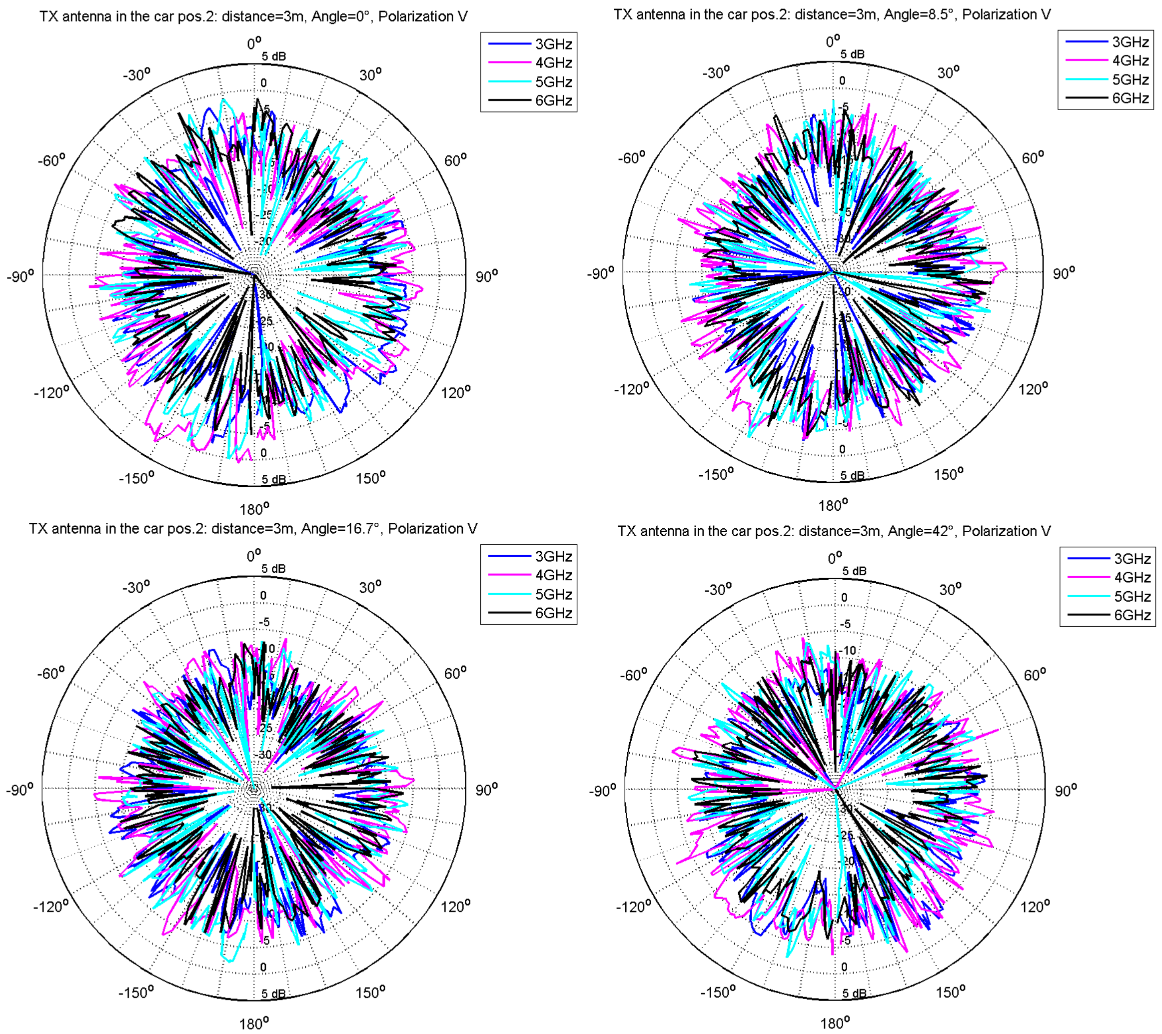



**Figure 12: TX antenna inside the car under the roof: Measured e.i.r.p.**

Figure 12 shows the measurement results. The shape of the antenna pattern is not observable, thus only reflections are detectable. A comparison to the other scenario (see figure 8) shows that the roof has a shielding between 5 dB and 10 dB. Only the signals, which could directly penetrate the window (see -90° to -180°), show low attenuation. Thus a smart placement of the TX antenna could lead to significant shielding by the roof.

## 5.3 Surface and Application Specific Location Measurements

These measurements were done according to specific application relevant locations. Three scenarios have been measured, where the TX antenna was mounted:

- Below the car on the exhaust pipe.
- On the surface of the car on the side mirror.
- On the wheel of the car in the fender.

The influence of the car has been studied.

### 5.3.1 TX antenna mounted below the car on the exhaust pipe

The TX antenna is mounted below the car on the exhaust pipe (see figure 11).

(a) Vertical polarized (b) Horizontal polarized (c) Horizontal polarized

**Figure 13: Mounting of the TX antenna below the car**

The measurement parameters are shown in table 9 and the settings of the spectrum analyzer can be found in table 1.

**Table 9: Measurement parameters for TX antenna below the car**

| Measurement | Polarization | e.i.r.p. | Distance | Height | Frequency |
|---|---|---|---|---|---|
| 7 | Vertical | 0 dBm | 10 m | [1 m, 2,5 m, 4 m] | 3, 4, 5, 6 |
| 8 | Horizontal | 0 dBm | 10 m | [1 m, 2,5 m, 4 m] | 3, 4, 5, 6 |

Figure 14 shows the measurement results for the vertical polarized antenna. Obviously no antenna pattern is observable, only strong reflections were measured due to the shielding of the car. As the ground plane was made of metal, no attenuation occurred and the ground with the basement of the car worked as a parallel-plate waveguide. Thus high gains of more than 5 dB can occur. On the other side, in a real scenario no metal ground plane occurs and thus lower gains should be expected (see clause C.3). It follows that the ground in the measurement chamber should be defined for such applications later in the harmonized standard. A comparison to the horizontal polarized antenna (see figure 15) shows no significant difference.

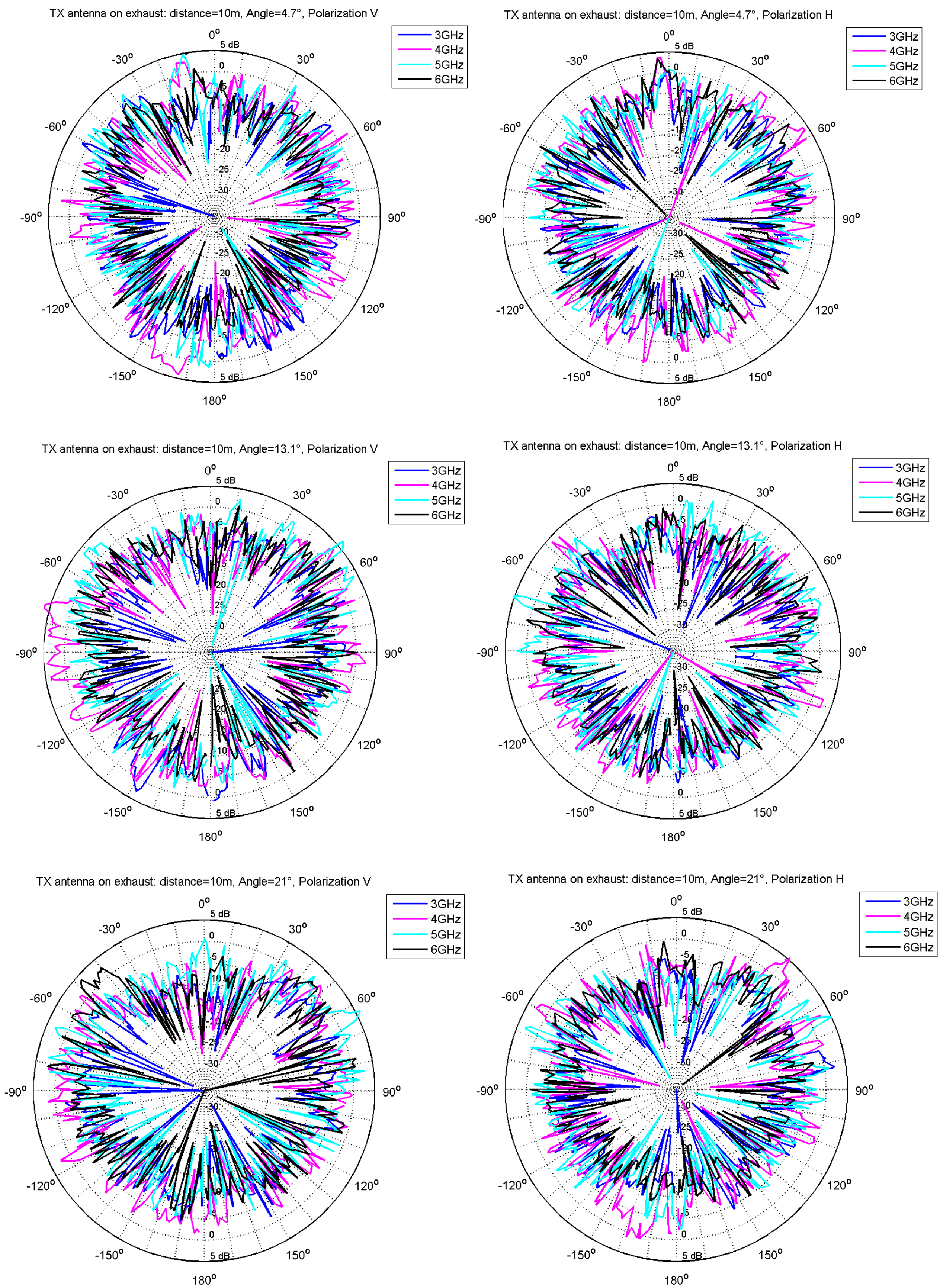



**Figure 14: Vertical polarized TX antenna below the exhaust at 10 m: Measured e.i.r.p.**

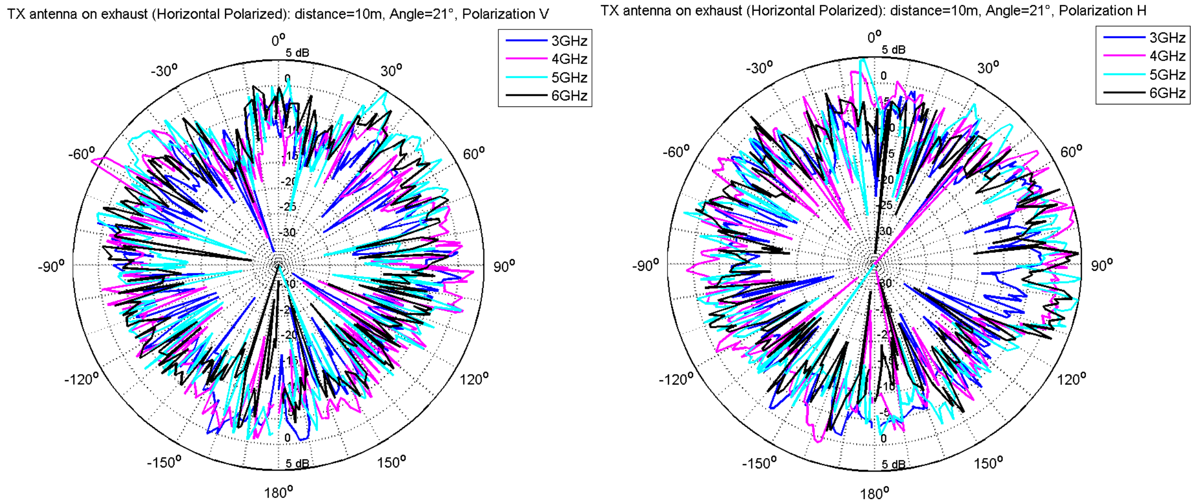



**Figure 15: Horizontal polarized TX antenna below the exhaust at d = 10 m: Measured e.i.r.p.**

## 5.3.2 TX antenna mounted on the side mirror

Next, the antenna was mounted on the side mirror. This analysis shows the influence of the car if the TX antenna is mounted on the surface of the car. The antenna mounting is shown in figure 16, in which the main transmission direction of the antenna is given by ⍰ = 90°.

**Figure 16: TX antenna on the side mirror**

The measurement parameters can be found in table 10 and the settings of the spectrum analyzer can be found in table 1.

**Table 10: Measurement Parameters: TX antenna on side mirror**

| Measurement | Polarization | e.i.r.p. | Distance | Height | Frequency |
|---|---|---|---|---|---|
| 9 | Vertical | 0 dBm | 10 m | [1 m, 2,5 m, 4 m] | 3, 4, 5, 6 |

Figure 16 shows the measurement results for vertical and horizontal polarized RX antenna. The transmission pattern is very well observable. We can see that the peaks occur in the main transmission direction. On the backside of the car no relevant peaks are observable due to shielding.

All measurements show good correlation with the real antenna pattern (compare to figures 2 and 3) except the measurement at 5 GHz where an untypical gain of +5 dB occurs. This can be explained by the measurement uncertainty discussed in Section Measurements at 3 m using UWB transmission power (-41,3 dBm), because an average additional gain of approx. +2,5 dB (main transmission direction) was measured in comparison to the real antenna pattern.

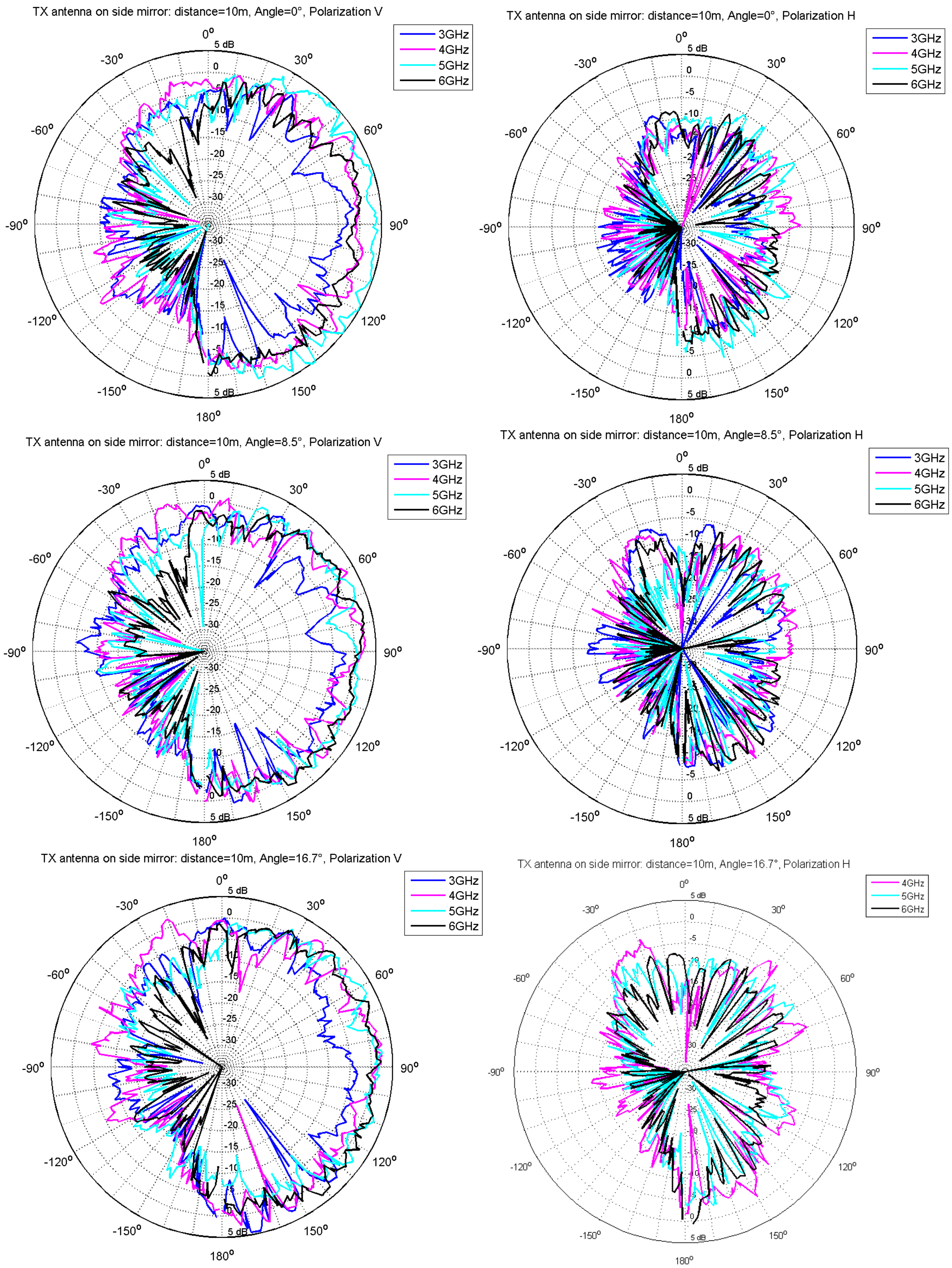



**Figure 17: TX antenna mounted on the mirror at d = 10 m: Measured e.i.r.p.**

NOTE: At Θ = 16,7° the 3 GHz measurement is missing, because the RX antenna did not switch correctly to horizontal polarization.

## 5.3.3 TX Antenna on the wheel in the fender

In this scenario the antenna was mounted inside the fender. The interaction of the antenna, the fender and the wheel needs to be studied. The antenna setup is shown in figure 18, in which the main transmission direction of the antenna is given at ⍰ = 90°.

**Figure 18: Car setup with antenna in the fender**

The measurement parameters can be found in table 11 and the settings of the spectrum analyzer can be found in table 1.

**Table 11: Measurement Parameters: TX antenna in the fender**

| Measurement | Polarization | e.i.r.p. | Distance | Height | Frequency |
|---|---|---|---|---|---|
| 10 | Vertical | 0 dBm | 10 m | [1 m, 2,5 m, 4 m] | 3, 4, 5, 6 |

Figure 19 shows the measured e.i.r.p. values with vertical and horizontal orientated RX antenna. It is clearly to see that the maximum peaks occur if the RX antenna is orientated directly to the wheel (⍰ = 90°). Thus the measurement area can be reduced to the area in front of the wheel instead of measuring the whole car.

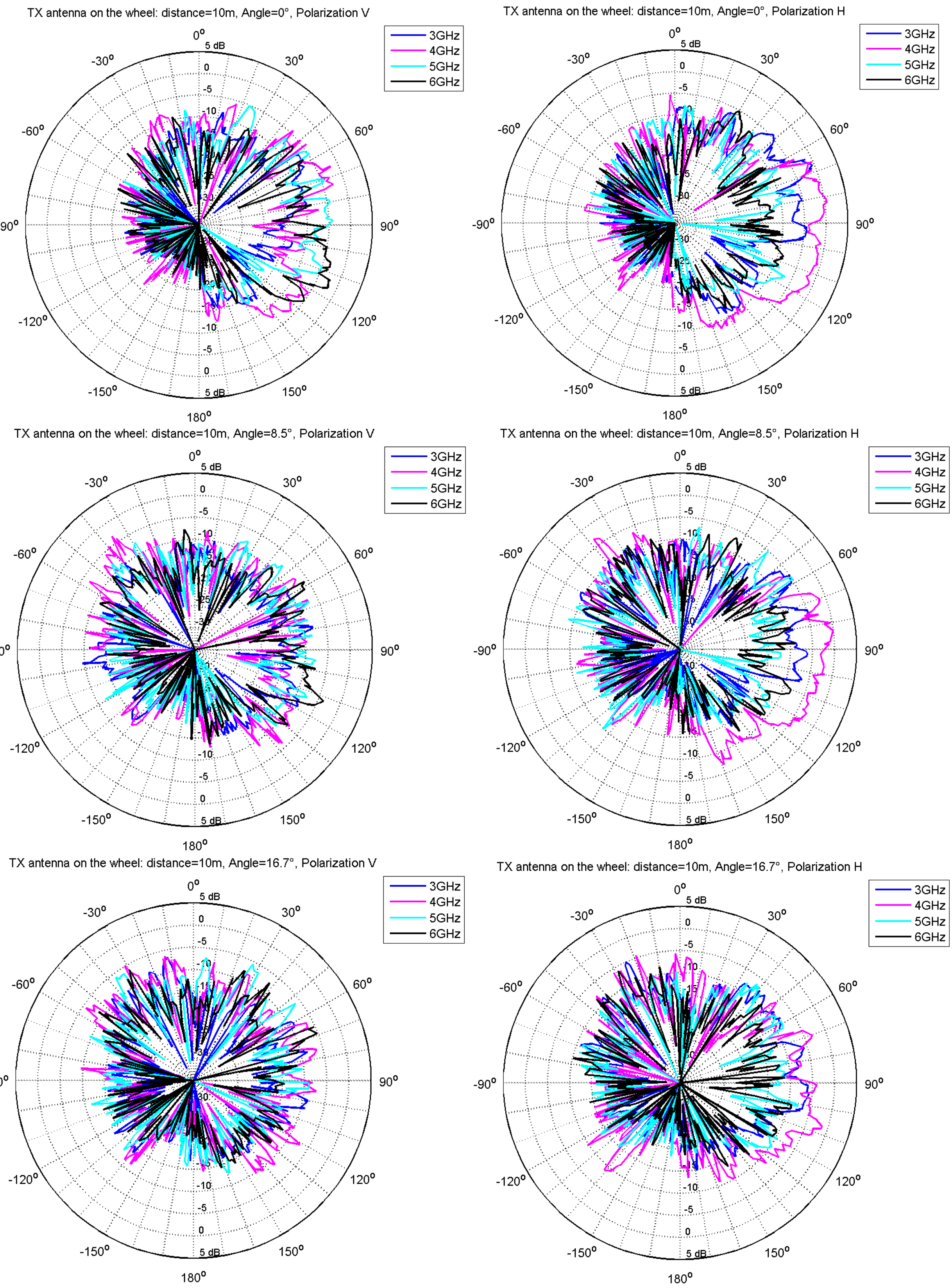



**Figure 19: TX antenna mounted on the wheel at d = 10m: Measured e.i.r.p.**

## 5.3.4 Conclusions

- We can observe that for applications where the TX antenna is mounted below the car the measurements should not be done with a metallic ground plane, because due to wave guiding effects high gains could occur. These gains do not occur in reality as the ground is usually not a perfect conductor.

- If the antenna is mounted on the surface of the car, all peaks occur in the line of sight (LOS) direction of the device. Furthermore the antenna pattern is very well observable in this area.
- If the antenna is mounted on the wheel and the fender, all peaks occur in the LOS direction to the wheel. Thus this area is sufficient to measure, because the rest of the car does not have significant impact on the measurement. It follows that a combination of the fender and the wheel is sufficient to measure.
- No specific gain was measured for the tire, thus it is sufficient only to measure the tire if the exterior limit is transmitted.

# 6 Conclusions and Recommendations from the Measurements

Kolberg Measurement

- No shielding of the car could be observed from the inside to the outside for this car in the Kolberg measurements. If a manufacturer wants to transmit more than -53,3 dBm/MHz inside the car he has to ensure that the shielding of the car is higher. Higher shielding is expected e.g. for metalized windows. The manufacturer has to determine the parts with the lowest shielding (e.g. the windows) and has to adopt the transmission power to it.
- The maximum measureable distance according to TS 102 883 [i.5] with sufficient SNR is 3m using high performance measurement equipment. The measured transmission pattern correlates very well for distances between 3 m and 10 m and the measurement tolerance is within ±6 dB. A recommendation for the requirements of the measurement equipment is given in clause 5.1.4.
- At the usage of a semi-anechoic chamber the ground should be covered by absorbing material. This is necessary to reduce the effect of reflections and increase the measurement accuracy.
- If the UWB device is mounted below the car, a ground plane made of metal will lead to wave guiding effects with unrealistic high gains. This should be taken into account for the further measurement procedure in the harmonized standard EN 302 065-3 [i.8].
- For devices mounted on the surface of the car the maximum values occur in the LOS area, where the antenna pattern is very well observable. Therefore a complete spherical measurement around the device is not necessary. This car shielding effect should be taken into account for further measurement procedures in EN 302 065-3 [i.8].
- For devices mounted on the wheel or in the fender, it is observable that only parts of the car, e.g. wheel and fender are relevant for the maximum values and so the measurement of the whole car can be reduced to a combination it (see clause C.3).
- As no gain was measured for the tire scenario, it is sufficient to measure only the tire if only the exterior limit is transmitted. Otherwise a combination with the tire and the significant parts (see clause C.3) has to be measured.

# 7 Test Procedure

Based on the previous results the concept for the measurements of the exterior limit for EN 302 065-3 [i.8] is developed. The structure of the measurement is shown in figure 20.

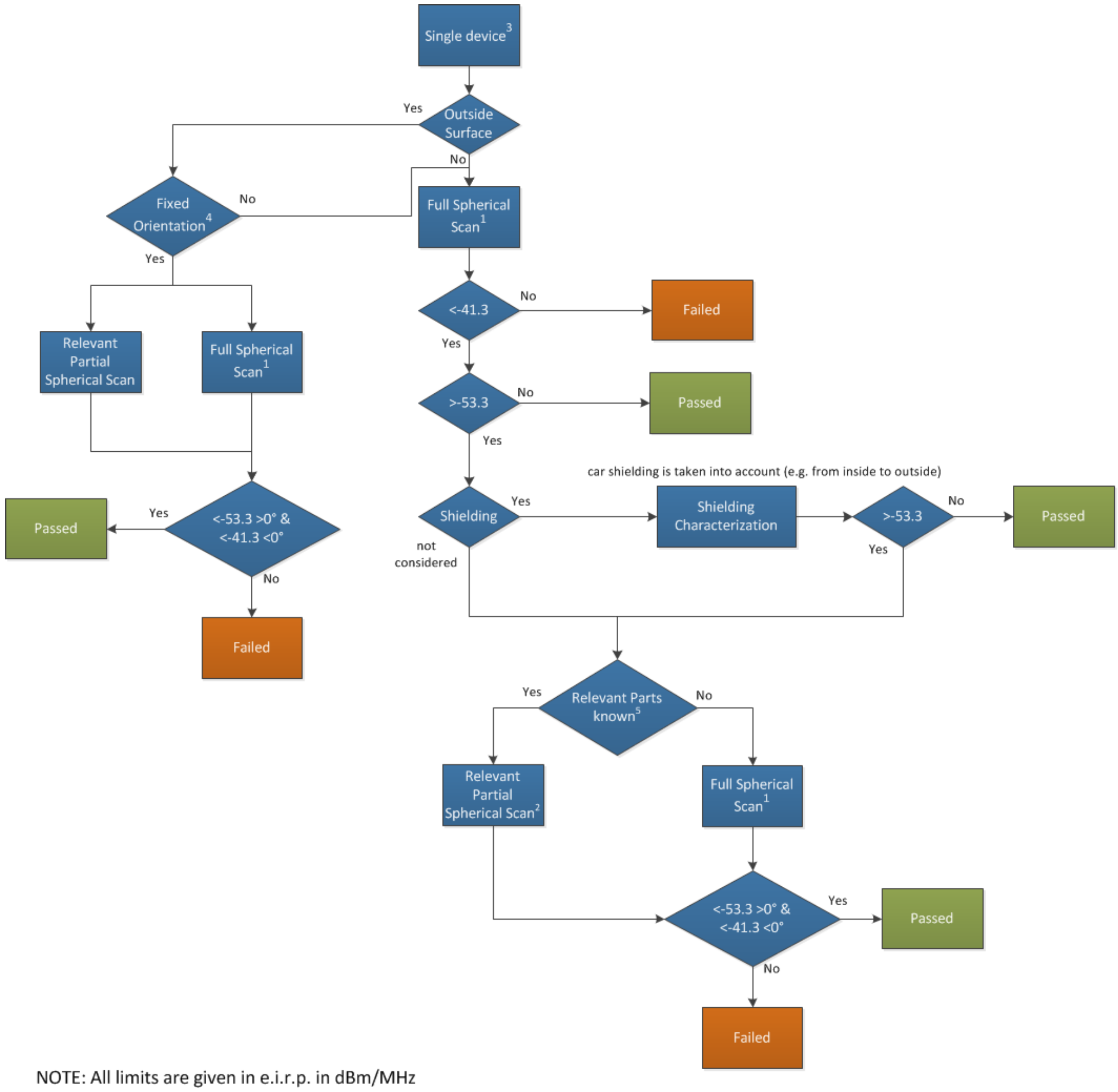



**Figure 20: Concept for the measurement procedure of the exterior limit of EN 302 065-3 [i.8]**

1) Full spherical scan to obtain transmission pattern or common measurement method according to TS 102 883 [i.5].

2) The horizontal reference plane is the height of the sensor and all measurements have to be performed above 0° elevation to this plane.

3) If the part of mounting has influence on the transmission pattern, then the manufacturer can declare the whole part as a device, e.g. door, mirror, bonnet, light, etc.

4) If the fixed orientation of the surface and therefore the main transmission direction can be declared by the manufacturer.

5) Are the relevant parts of the vehicle, which are expected to influence the transmission to the outside. The measurement setup can be reduced to the known relevant parts.

The device under test (DUT) is specifically measured for different applications and mounting locations.

If a device has a maximum mean power of less or equal than -53,3 dBm/MHz (e.i.r.p.) including the transmission pattern, then it is only necessary to measure the device by itself. This can be done radiated or conducted according to TS 102 883 [i.5]. If the transmission pattern of the device is not known a full spherical scan according to annex B should be performed.

If the maximum mean power is greater than -53,3 dBm/MHz (e.i.r.p.) and no shielding to the outside of the car occurs or the shielding is not considered, then the device has to be measured with the relevant parts of the car, which influence the transmission pattern. When the relevant parts are known, then the device can be measured with these only and if applicable for a relevant area, e.g. see tire applications in annex C. These parts and the relevant area have to be declared by the manufacturer and should be included in the measurement report.

If shielding from the inside to the outside of the car occurs, it can be taken into account if the manufacturer can characterized the lowest shielding in all direction to the outside. An example for a measurement procedure for the shielding characterization can be found in clause C.1 or [i.6]. If the transmit power minus the shielding is less than -53,3 dBm/MHz the device passes, otherwise the device has to be measured with the relevant parts of the car.

If the device is mounted outside on the surface of the car and the mounting orientation is known the spherical scan may be reduced to the relevant area, e.g. if the device is mounted on a door the spherical scan can be limited to the area in front of the door.

If a shielding to the outside of the car is given, the manufacturer has to ensure that the part with the lowest shielding is taken into account. Therefore the shielding value should be provided by the manufacturer or it should be measured. If the lowest shielding is known, then two scenarios can be distinguished:

# 8 Conclusions

Extensive measurement campaigns have been performed to develop a measurement procedure to verify the exterior car limit according to ECC/DEC/(06)04 [i.2].

A measurement procedure is presented, which is based on state of the art measurement equipment and delivers sufficient measurement accuracy. This measurement procedure will be included in EN 302 065-3 [i.8].

# Annex A: Measurement Hardware

## A.1 Measurement Hardware

The list of the measurement equipment from Kolberg is shown in table A.1.

**Table A.1: Measurement Equipment Kolberg**

| Parameter | Device name | Specification | Reference |
|---|---|---|---|
| Signal Generator | Anritsu™ MG3694B | 2 GHz to 40 GHz, 20 dBm | |
| Spectrum Analyzer | R&S® ESIB40 | EMI Test receiver | |
| Car | Mercedes C-Class® | | [i.4] |
| Transmit UWB Antenna | Vivaldi Antenna | | [i.4] |
| Receive UWB Horn Antenna | R&S® HL024S2 | Cross Log-Periodic antenna, Gain = 7,1 GHz to 18 GHz | |
| LNA | Miteq® AMF-4D-001120-42-20P | Gain 28 dB, 0,1 GHz to 12 GHz | |

## A.2 Link Budget

The link budget is calculated according to the measurement equipment of the ML Kolberg. As for reliable measurement an SNR of 6 dB to 10 dB is required, we can see that the higher frequencies are not measureable for a transmit power of e.i.r.p. = -41,3 dBm. Especially the signal corresponding to the exterior limit with e.i.r.p.=-53,3 dBm is not measureable at all. Better measurement equipment is needed and the minimum requirements should be defined in EN 302 065-3 [i.8].

**Table A.2: Example Link Budget for the Measurements**

| Parameter | Device name | Fc = 2 GHz | Fc = 10 GHz | Fc = 2 GHz | Fc = 10 GHz | Fc = 2 GHz | Fc = 10 GHz |
|---|---|---|---|---|---|---|---|
| e.i.r.p. [dBm] | Anritsu™ MG3694 B | 20 | | -41,3 | | -53,3 | |
| Free Space Loss 10m [dB] | | 58,5 | 72,4 | 58,5 | 72,4 | 58,5 | 72,4 |
| RX Power [dBm] | | -38,5 | -52,4 | -99,8 | -113,7 | -111,8 | -125,7 |
| Receiver antenna [dBi] | R&S® HL024 | 7 | | | | | |
| Low noise amplifier [dB] | Miteq® | 28 | | | | | |
| Cable losses [dB] | | 0,6 | 1,3 | 0,6 | 1,3 | 0,6 | 7,9 |
| Measurement Power [dBm] | | -3,1 | -20,7 | -67,4 | -82,0 | -79,4 | -94,6 |
| Noise Power [dBm/MHz] | | -114 | | | | | |
| LNA Gain [dB] | Miteq® | 28 | | | | | |
| LNA NF [dB] (Assumption) | | 0,6 | 1,3 | 0,6 | 1,3 | 0,6 | 1,3 |
| Cable NF [dB] | | 3,6 | 7,9 | 3,6 | 7,9 | 3,6 | 7,9 |
| Noise Figure Spectrum Analyzer | R&S® ESIB40 | 10 | | | | | |
| Total Cascaded NF [dB] | | 2,7 | 3,1 | 2,7 | 3,1 | 2,7 | 3,1 |
| **SNR [dB]** | | **77,2** | **62,2** | **15,9** | **0,9** | **3,9** | **-11,1** |

# Annex B: Spherical Scan

The spherical scan can be realized in two ways:

- An automatic arm can be rotated on a sphere around the Device Under Test (DUT).
- The DUT can be rotated and the RX antenna is fixed.

# B.1 Spherical scan with automatic test antenna placement

Figure B.1 shows the spherical measurement method using automatic test antenna placement. The RX antenna moveable and it is mounted for example on an automatic arm, which moves the antenna stepwise on a sphere around the DUT.

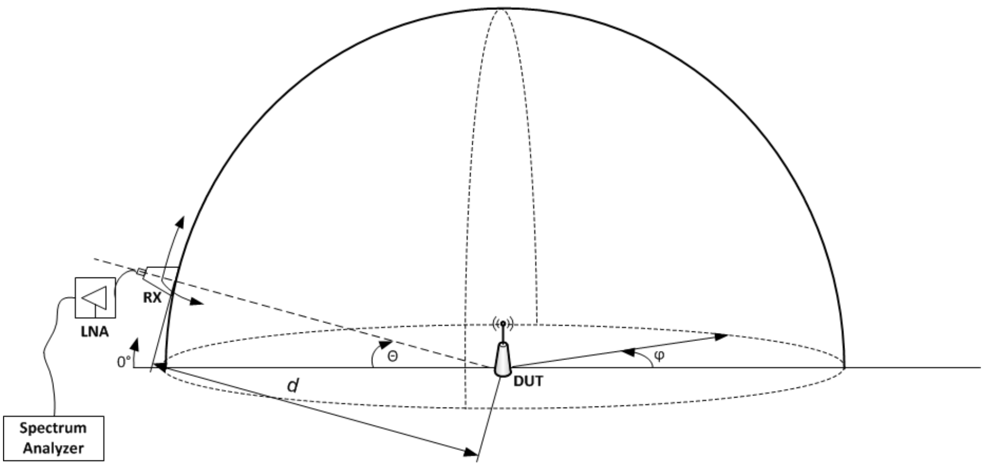



**Figure B.1: Spherical scan setup using automatic test antenna placement**

The maximum measurement step size for the azimuth angle  and for the elevation angle Θ is smaller or equal to 5°. In a half sphere scan  is varied from 0° to 360° and Θ is changed from 0° to 90°. Therefore the DUT has to be mounted according to the typical usage in the application. If a full sphere scan is performed, then the device can be tilted by 180° and the half sphere should be measured again. The scan should be performed at a distance given by

$$\frac{2(d_1 + d_2)^2}{\lambda}$$

Where:

$d_1$ is the largest dimension of the EUT/dipole after substitution (m);

$d_2$ is the largest dimension of the test antenna (m);

$\lambda$ is the test frequency wavelength (m).

It is not necessary to measure the exterior limit at ranges larger than 3 m, because sufficient accuracy is achieved even for a whole car see clause 5.2.1.

NOTE: Another relation of the angles is possible, but the coverage of the whole spheres should be ensured.

## B.1.1 Calibrated setup

The measurement receiver, test antenna and all associated equipment (e.g. cables, filters, amplifiers, etc.) should have been recently calibrated against known standards at all the frequencies on which measurements of the equipment are to be made. A suggested calibration method is given in TS 102 883 [i.5] and a specification of the measurement equipment is recommended in clause 5.1.4.

If an anechoic chamber with conductive ground plane is used, the ground should be covered by absorbing material in the area of the direct ground reflection from the DUT to the test antenna. If the device is mounted below the car, the measurements should be done on a non-metalized ground, therefore e.g. absorbing or realistic ground material should cover the area of the sensor and direct reflections.

The equipment should be placed in an anechoic chamber, which allows the spherical scan. The DUT should be placed closest to the orientation of normal operation.

The test antenna should be oriented initially for vertical polarization and should be chosen to correspond to the frequency of the transmitter.

The output of the test antenna should be connected to the spectrum analyser via whatever (fully characterized) equipment is required to render the signal measurable (e.g. amplifiers).

The transmitter should be switched on, if possible without modulation, and the spectrum analyser should be tuned to the frequency of the transmitter under test.

The RX antenna should be moved stepwise on the sphere and in each location the signal level should be noted.

After all locations have been reached, the measurement procedure should be repeated for horizontal polarized test antenna orientation.

The maximum signal level, measured by horizontal and vertical orientated antenna, detected by the spectrum analyser should be noted and converted into the radiated power by application of the pre-determined calibration coefficients for the equipment configuration used.

## B.1.2 Substitution method

The equipment should be placed in an anechoic chamber, which allows the spherical scan. The DUT should be placed closest to the orientation of normal operation.

If an anechoic chamber with conductive ground plane is used, the ground should be covered by absorbing material in the area of the direct ground reflection from the DUT to the test antenna. If the device is mounted below the car, the measurements should be done on a non-metalized ground, therefore e.g. absorbing or realistic ground material should cover the area of the sensor and direct reflections.

The test antenna should be oriented initially for vertical polarization and should be chosen to correspond to the frequency of the transmitter.

The output of the test antenna should be connected to the spectrum analyser.

The transmitter should be switched on, if possible without modulation, and the measuring receiver should be tuned to the frequency of the transmitter under test.

The RX antenna should be moved stepwise on the sphere and in each location the signal level and its coordinates should be noted.

After all locations have been reached, the maximum signal level and its coordinates should be determined.

The transmitter should be replaced by a substitution antenna.

The substitution antenna should be orientated for vertical polarization.

The substitution antenna should be connected to a calibrated signal generator.

If necessary, the input attenuator setting of the spectrum analyser should be adjusted in order to increase the sensitivity of the spectrum analyser.

If an anechoic chamber with a conductive ground plane is used, then the substitution antenna should be moved to the position of the previous maximum. The test antenna should be moved around this position within a radius of at least five times the wavelength of the center frequency on the sphere to find the local maximum.

The input signal to the substitution antenna should be adjusted to the level that produces a level detected by the spectrum analyser, that is equal to the level noted while the transmitter radiated power was measured, corrected for the change of input attenuator setting of the spectrum analyser.

The input level to the substitution antenna should be recorded as power level, corrected for any change of input attenuator setting of the spectrum analyser.

The measurement should be repeated with the test antenna and the substitution antenna orientated for horizontal polarization.

The measure of the radiated power of the radio device is the larger of the two levels recorded at the input to the substitution antenna, corrected for the gain of the substitution antenna if necessary.

# B.2 Spherical scan with rotating device

Instead of using an automatic arm, it is also possible to rotate and tilt the DUT (see figure B.2). Thus, the same sphere can be measured as with the automatic arm. In contrast to the previous method Θ is changed from 0 to -90° for the half sphere measurement. The distance d defined as in clause B.1.

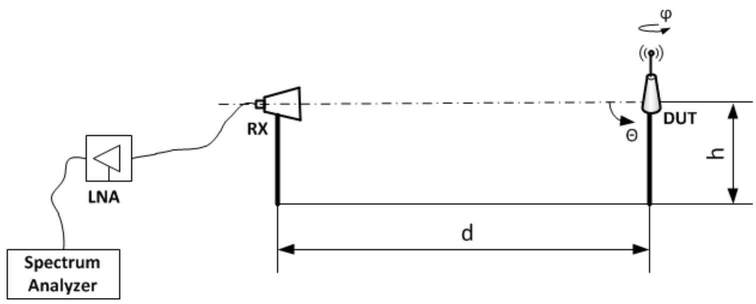



**Figure B.2: Spherical scan setup with rotation and tilt of the DUT**

## B.2.1 Calibrated setup

The measurement receiver, test antenna and all associated equipment (e.g. cables, filters, amplifiers, etc.) should have been recently calibrated against known standards at all the frequencies on which measurements of the equipment are to be made. A suggested calibration method is given in TS 102 883 [i.5] and a specification of the measurement equipment is recommended in clause 5.1.4.

If an anechoic chamber with conductive ground plane is used, the ground should be covered by absorbing material in the area of the direct ground reflection from the DUT to the test antenna.

The equipment should be placed in an anechoic chamber, which allows the rotation and tilt of the DUT. The DUT should be placed closest to the orientation of normal operation.

The test antenna should be oriented initially for vertical polarization and should be chosen to correspond to the frequency of the transmitter.

The output of the test antenna should be connected to the spectrum analyser via whatever (fully characterized) equipment is required to render the signal measurable (e.g. amplifiers).

The transmitter should be switched on, if possible without modulation, and the spectrum analyser should be tuned to the frequency of the transmitter under test.

The TX antenna should be stepwise rotated and tilted that the sphere of interest is covered. The signal level should be noted in each location.

After all locations have been reached, the measurement procedure should be repeated for horizontal polarized test antenna orientation.

The maximum signal level detected by the spectrum analyser should be determined and converted into the radiated power by application of the pre-determined calibration coefficients for the equipment configuration used.

## B.2.2 Substitution method

The equipment should be placed in an anechoic chamber, which allows the rotation and tilt of the DUT. The DUT should be placed closest to the orientation of normal operation.

The test antenna should be oriented initially for vertical polarization and should be chosen to correspond to the frequency of the transmitter.

The output of the test antenna should be connected to the spectrum analyser.

The transmitter should be switched on, if possible without modulation, and the measuring receiver should be tuned to the frequency of the transmitter under test.

The TX antenna should be stepwise rotated and tilted that the sphere of interest is covered. The signal level should be noted in each orientation.

After all locations have been reached, the maximum signal level and the orientation of the DUT should be noted.

The transmitter should be replaced by a substitution antenna.

The substitution antenna should be orientated for vertical polarization and the length of the substitution antenna should be adjusted to correspond to the frequency of the transmitter.

The substitution antenna should be connected to a calibrated signal generator.

If necessary, the input attenuator setting of the spectrum analyser should be adjusted in order to increase the sensitivity of the spectrum analyser.

If an anechoic chamber with a conductive ground plane is used, then the test antenna should be raised and lowered through the specified range of height that the maximum signal level is received.

The input signal to the substitution antenna should be adjusted to the level that produces a level detected by the spectrum analyser, that is equal to the level noted while the transmitter radiated power was measured, corrected for the change of input attenuator setting of the spectrum analyser.

The input level to the substitution antenna should be recorded as power level, corrected for any change of input attenuator setting of the spectrum analyser.

The measurement should be repeated with the test antenna and the substitution antenna orientated for horizontal polarization.

The measure of the radiated power of the radio device is the larger of the two levels recorded at the input to the substitution antenna, corrected for gain of the substitution antenna if necessary.

# Annex C: Tire Related Applications

## C.1 Introduction

The main goal of the present document is to present a procedure for characterizing the electromagnetic shielding of certain elements of the road vehicles, in particular, when the UWB devices are positioned inside the tire.

Another purpose is to define, for this location of the UWB Device Inside the Tire (DIT), which part of the vehicle are influential for the measurement of the maximum mean e.i.r.p. spectral density. A DIT case is useful example at a particular mounting location, and this is taken in account in the concept for the measurement procedure of the exterior limit of EN 302 065-3 [i.8].

Finally, this annex establishes what is the relevant area necessary and sufficient to guarantee the measurement of the maximum peak in the mentioned case (DIT) and shows, as an example, a measurement setup using a planar scanner.

## C.2 Procedure to establish the shielding characterization of the tire

In the first part of the document, we show an example of an exhaustive procedure to establish what is the minimum level of the attenuation or shielding of the maximum mean e.i.r.p. spectral density through a tire in a DIT case. This shielding characterization can be used in the test procedure descripted in clause 7.

This procedure is based on the principle of the substitution: the main idea is to show this shielding effect comparing two measurements of the maximum of the radiation power pattern of a UWB antenna in free space, and that of the same antenna mounted inside the tire, mounted on its turn on a rim.

The antenna, in both configurations, is fed with the same power with a CW signal, for different values of the carrier frequency (from 4 GHz to 5,5 GHz with 500 MHz step). In this procedure, we have limited the frequency band from 4 GHz to 5,5 GHz, to use the same RX probe. However, it is possible to characterize the whole UWB frequency range from 3,1 GHz to 10,6 GHz with the same procedure using an adequate probe(s).

Using the same cables, the same generator with same configuration and the same receiving antenna, we can use the substitution principle in order to characterize the shielding effect of the tire.

As reference UWB antenna we used an antenna sufficiently small to be inserted inside the small space between the tire and the rim. A commercial antenna that allows an easy and efficient integration into space-limited areas with minimum antenna clearance is a UWB Fractus chip antenna. Figures C.1 shows in detail how the UWB antenna is mounted inside the tire. This tire has then been fitted on the rim, as in a standard set up, so it was necessary to avoid the outflow of air through the hole made on the tread for the coaxial cable connection of the antenna.

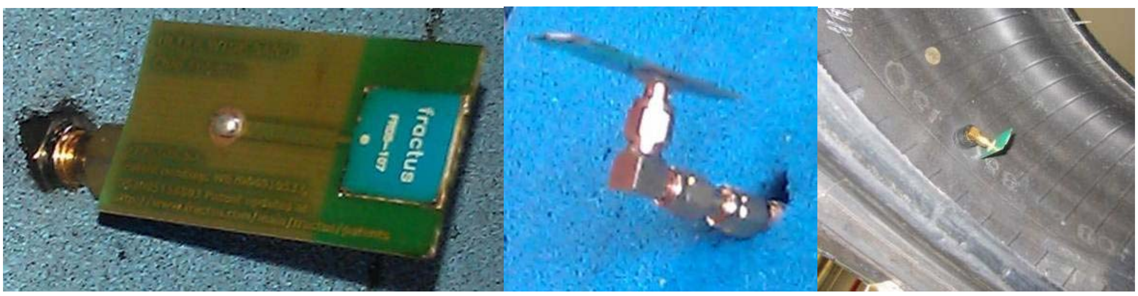



**Figure C.1: UWB antenna used for the test and antenna mounted inside the tire**

All the details of the antenna are given by the manufacturer. Table C.1 shows only the main characteristics of gain and efficiency of this antenna acknowledged by the manufacturer.

**Table C.1: Antenna Gain and Efficiency within the 3,1 GHz to 5 GHz bandwidth. Measures made in the evaluation board and in an unechoic chamber**

| | | |
|---|---|---|
| Gain | Peak Gain | 3,5 dB |
| | Average Gain across the band | 2,6 dB |
| | Gain Flatness (horizontal plane) | < 2 dB |
| Efficiency | Peak Efficiency | 92 % |
| | Average Efficiency across the band | 84 % |
| | Efficiency Range across the band | 77 % - 92 % |

When the antenna is inserted inside the tire, the magnitude of its reflection coefficient changes but still keeping low values below -10 dB, as shown in figure C.2.

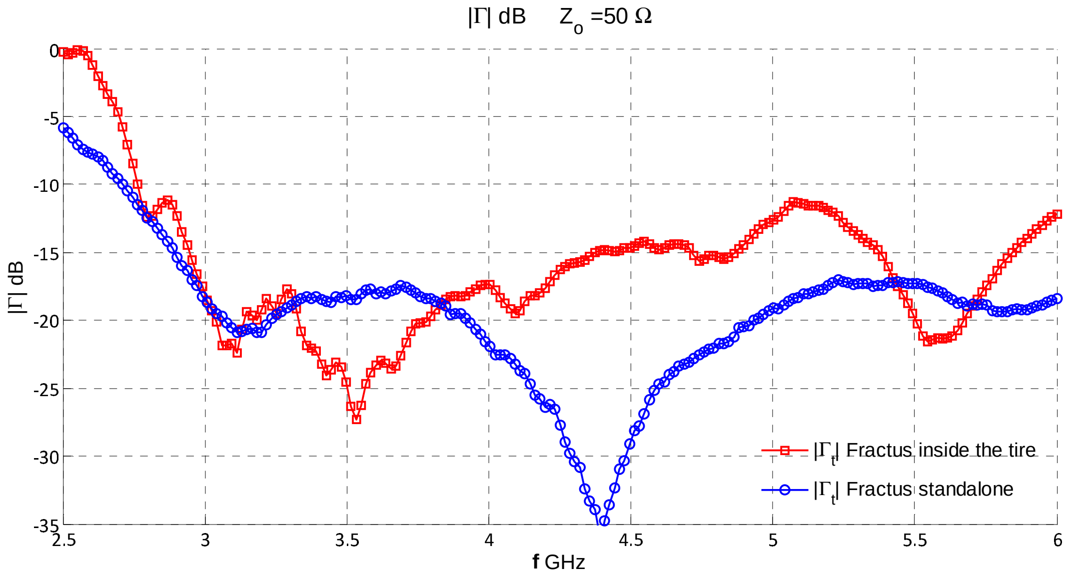



**Figure C.2: Reflection coefficient magnitude for the antenna standalone and inside the tire**

$$\frac{P_{RX}(f,d)}{P_{TX}} = (1-|\Gamma_{RX}(f)|^2)(1-|\Gamma_{TX}(f)|^2)\left(\frac{1}{L_{TX,cable}(f)L_{RX,cable}(f)}\right)\left(\frac{\lambda}{4\pi d}\right)^2 G_{TX}(\theta,\phi,f)\,G_{RX}(\theta,\phi,f)\left|\hat{\rho}_{TX}\cdot\hat{\rho}_{RX}^{*}\right|^2$$

In the Friis transmission equation, the first two factors in brackets represent the reflection losses in receiving and in the transmitter (impedance mismatch); the following factors are the TX and RX cable losses, the free space losses, the gain of each antenna, and finally the mismatch due to different polarizations of the RX and TX antenna. In this generic equation without LNA, we can substitute the values of the reflection coefficient magnitude with the values of represented in the figure above. In particular, the mismatch of the transmitting antenna is calculated with: $1-|\Gamma_{TX}(f)|^2$ and consequently the transmission losses are:

**Table C.2: Reflection losses in TX-antenna (impedance mismatch)**

| Frequency [GHz] | \|Γ\| dB | | $1-\|\Gamma\|^2$ dB | |
|---|---|---|---|---|
| | Antenna Stand Alone | Antenna Inside the tire | Antenna Stand Alone | Antenna Inside the tire |
| 3 | -18,55 | -18,64 | -0,06 | -0,06 |
| 3,5 | -24,56 | -18,21 | -0,01 | -0,06 |
| 4 | -17,36 | -21,88 | -0,08 | -0,02 |
| 4,5 | -14,63 | -29,12 | -0,15 | -0,005 |
| 5 | -12,61 | -19,06 | -0,24 | -0,05 |
| 5,5 | -19,52 | -17,28 | -0,04 | -0,08 |

Clearly these very small differences, due to different mismatch of the antenna inside and outside of the tire, can be neglected because its influence is irrelevant in order to establish the spatial maximum of the radiation pattern at each frequency in both positions of the antenna. In other words, the values of the reflection coefficient are maintained below a level that allows ensuring a minimum power loss for mismatching. **Therefore we can consider that all terms in the equation are constant in both configurations (antenna in free space and antenna inside the tire) except the terms providing the characteristic of the attenuation for the UWB device placed inside the tire, i.e. the received power maximum for the same transmitted power level at each frequency.**

To carry out this measurement we used a fully anechoic chamber with an indoor spherical near field/far field system at the Laboratory of Antennas and Electromagnetic Compatibility (LACE) of the Politecnico di Torino. This chamber has 18" absorbers and a minimum operating frequency of 750 MHz. In the frequency range 3 GHz to 10 GHz the uncertainty is ±2 dB. This system allows transform the near field values of the measurement (amplitude and phase) in Far Field results with a mathematical transformation.

Figure C.3 shows the main characteristics of this system.

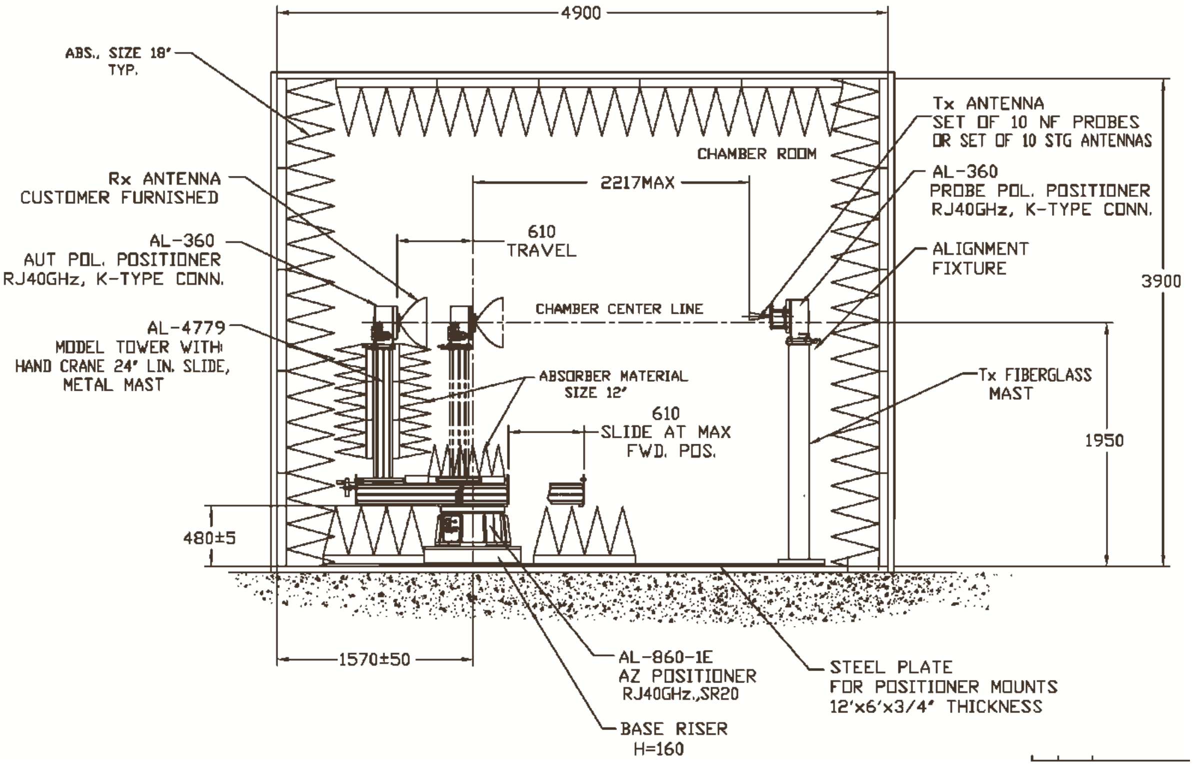



**Figure C.3: Indoor FF/NF system Politecnico di Torino**

The goal of these measurements is to study the impact of the tire and rim on the measured/calculated transmit power (e.i.r.p.) from a UWB device mounted inside the tire. The RX antenna is mounted in a quasi EM transparent but robust support structure that maintains it at the same radial distance from the center of rotation, and orientation, as when the antenna is mounted on the tire. In other words, the radial distance of the support structure is coincident with the radius of the belt of the tire, where the antenna is fixed. For both configurations, with and without tire, the positioner makes an azimuthal scan (φ) by 360°, and an elevation scan (θ) by 180°, both with step of 2°, thus covering the whole sphere. The two polarization components are measured rotating 90° the TX probe. After the measurement, the results are transformed to obtain the far field. The difference between the maximum of these pattern, using the same excitation power at each frequency, is used to establish the minimum level of attenuation of the tire. Figures C.4 to C.6 show both measurement arrangements.

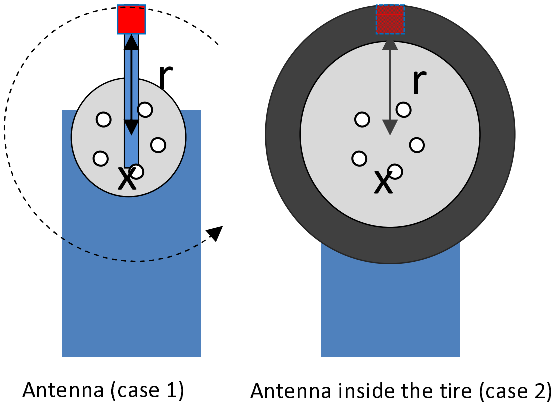



**Figure C.4: Detail of two cases**


**Figure C.5: Antenna (case 1) and the reference system**

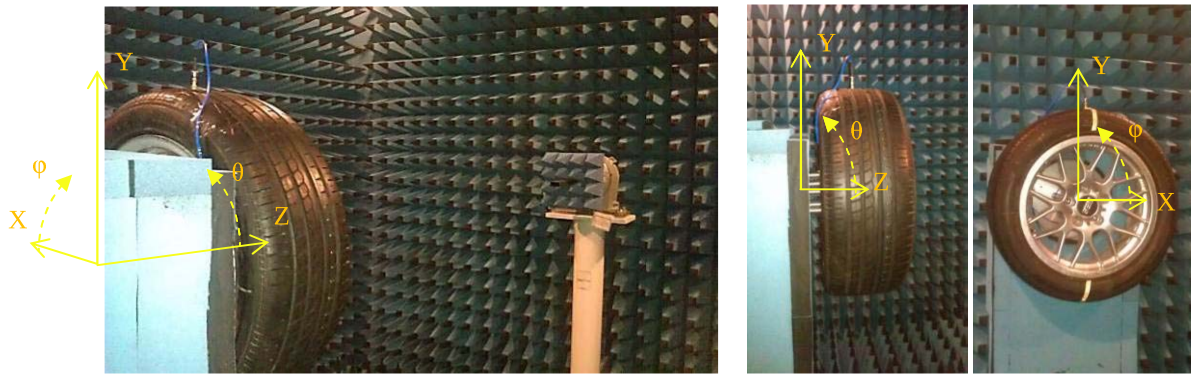


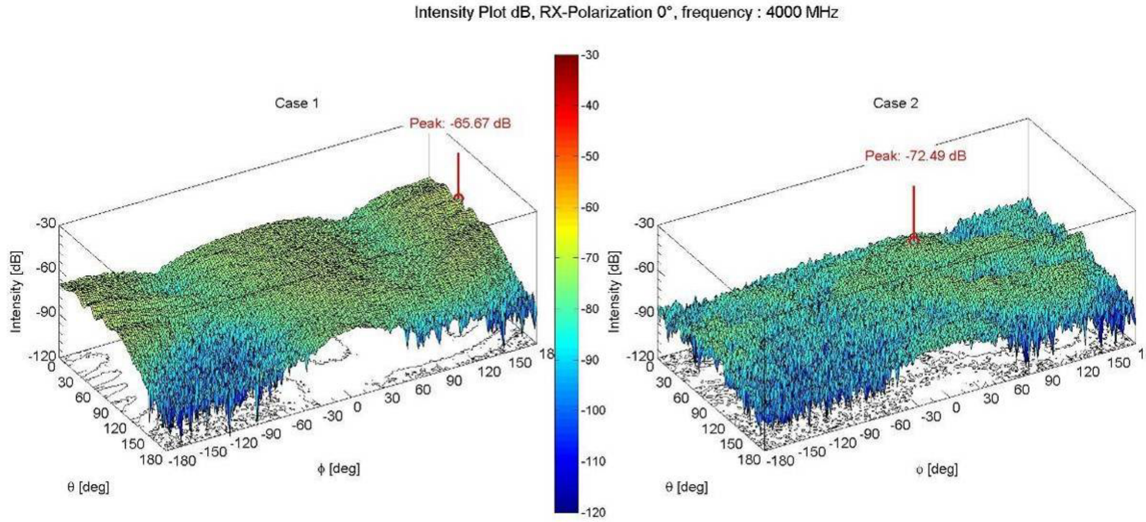

**Figure C.6: Antenna inside the tire (case 2) and the reference system**

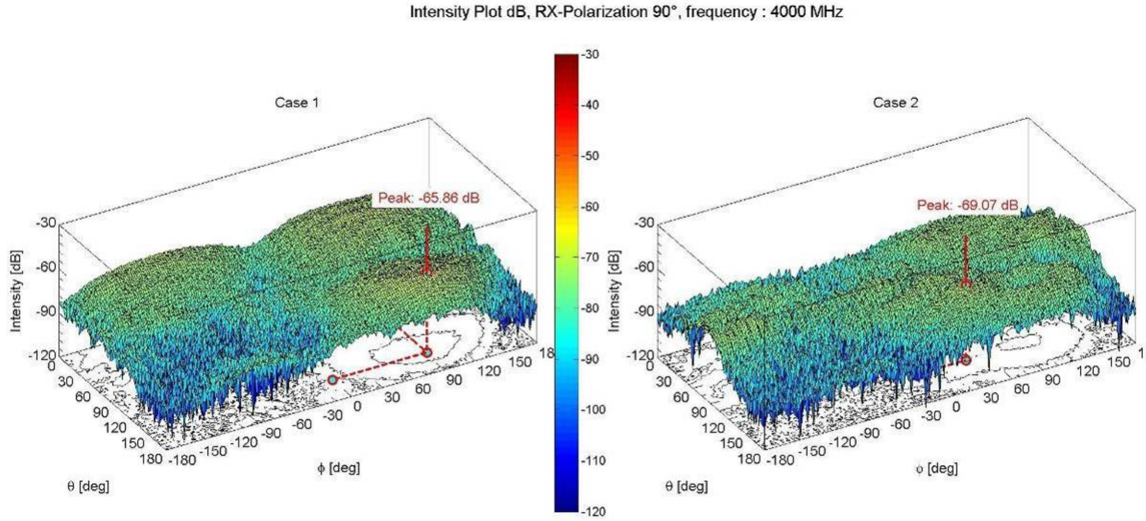
As an example for the measurement procedure a Pirelli tire 225/55 R17 is used.

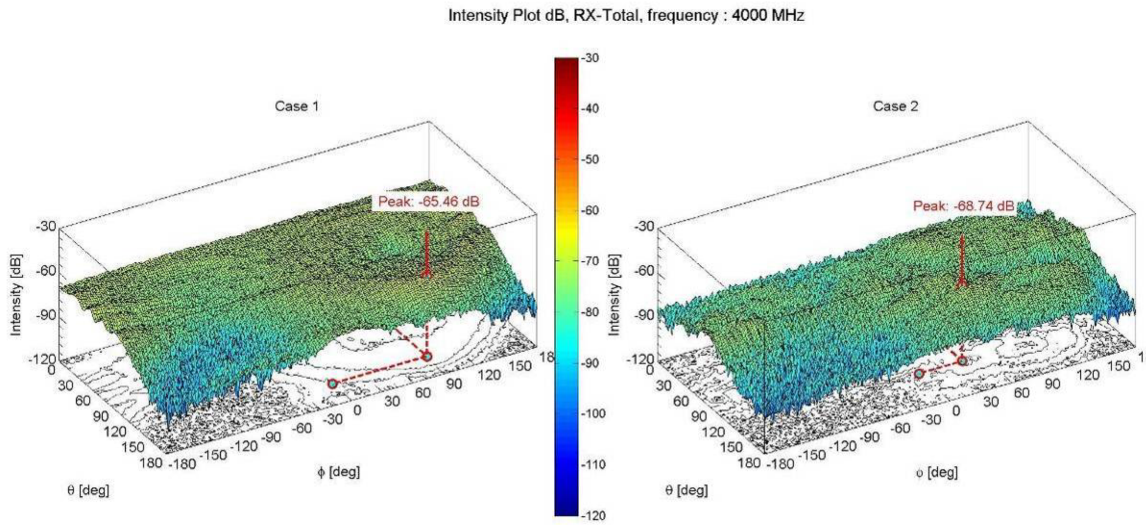
Figures C.7 shows the measured values of the attenuation, in dB, of the complete transmission chain, including all the elements (cables, attenuators, amplifiers, etc.) for the same excitation power at 4,0, 4,50, 5,0, and 5,5 GHz, in both cases:

- Case 1: Antenna standalone
- Case 2: Antenna inside the tire

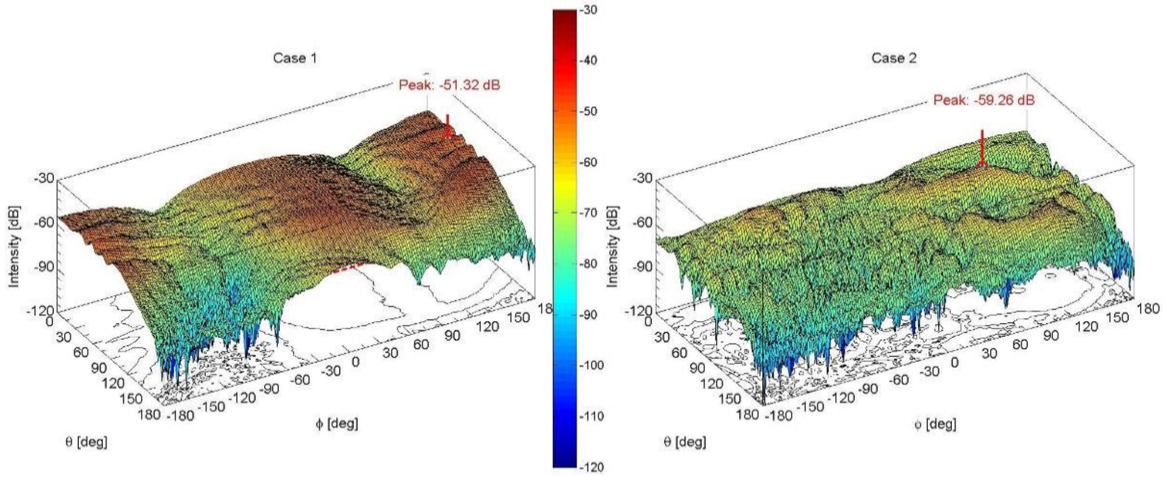
with vertical and horizontal orientated RX antenna (and the total component like a vector sum of its components).


Intensity Plot dB, RX-Polarization 0°, frequency : 4000 MHz
Case 1
Peak: -65.67 dB
Case 2
Peak: -72.49 dB
Intensity [dB]
θ [deg]
ϕ [deg]

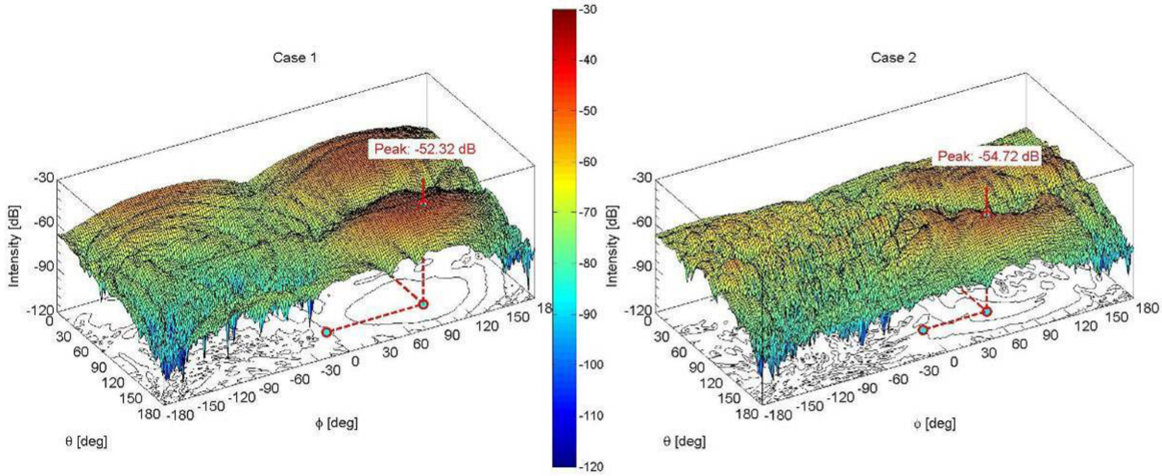

Intensity Plot dB, RX-Polarization 90°, frequency : 4000 MHz
Case 1
Peak: -65.86 dB
Case 2
Peak: -69.07 dB
Intensity [dB]
θ [deg]
ϕ [deg]


Intensity Plot dB, RX-Total, frequency : 4000 MHz
Case 1
Peak: -65.46 dB
Case 2
Peak: -68.74 dB
Intensity [dB]
θ [deg]
ϕ [deg]

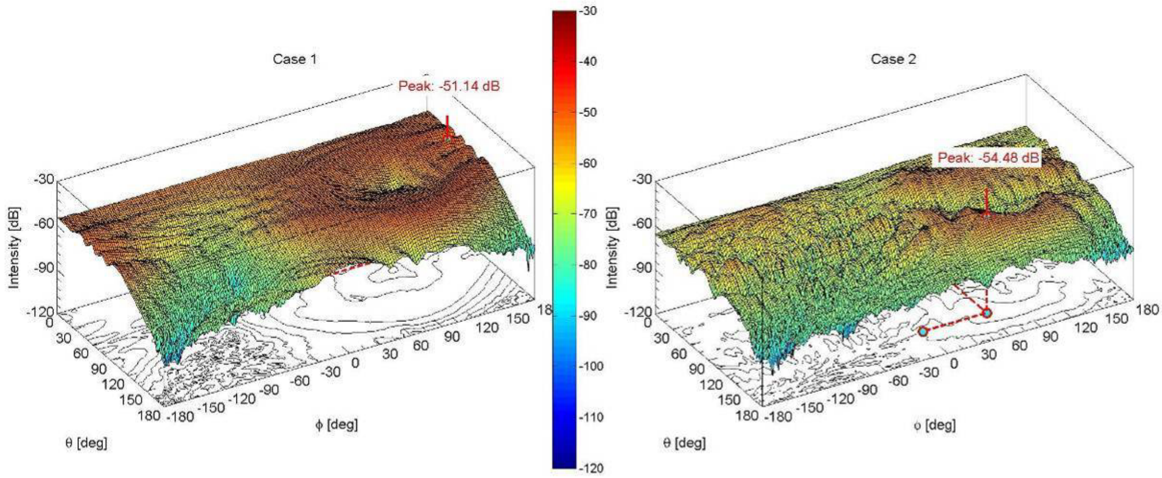
Intensity Plot dB, RX-Polarization 0°, frequency : 4500 MHz

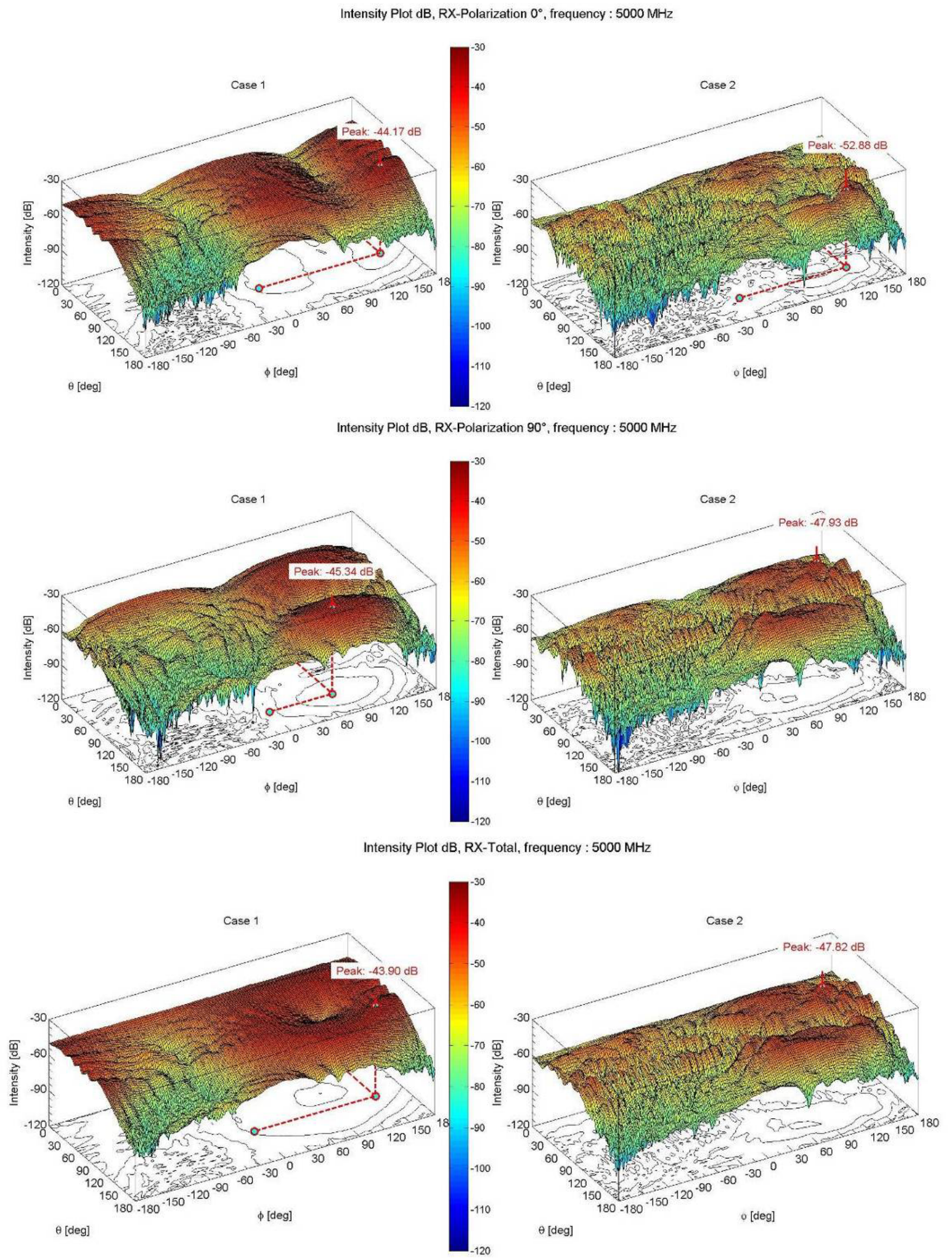



Intensity Plot dB, RX-Polarization 90°, frequency : 4500 MHz




Intensity Plot dB, RX-Total, frequency : 4500 MHz




Intensity Plot dB, RX-Polarization 0°, frequency : 5000 MHz
Case 1
Peak: -44.17 dB
Case 2
Peak: -52.88 dB
Intensity Plot dB, RX-Polarization 90°, frequency : 5000 MHz
Case 1
Peak: -45.34 dB
Case 2
Peak: -47.93 dB
Intensity Plot dB, RX-Total, frequency : 5000 MHz
Case 1
Peak: -43.90 dB
Case 2
Peak: -47.82 dB
Intensity [dB]
θ [deg]
ϕ [deg]

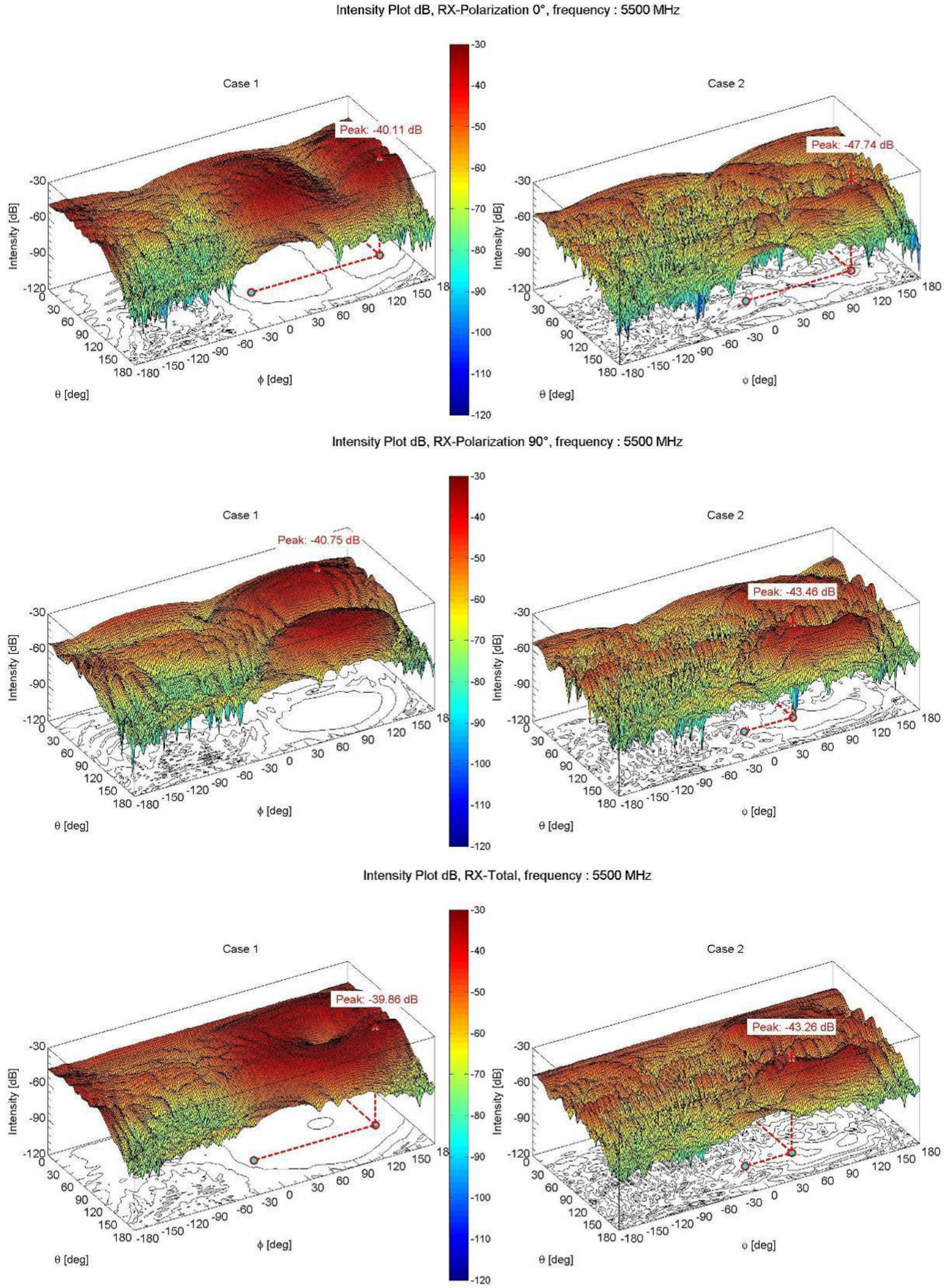



**Figure C.7: Intensity Plots (dB) frequencies from 4,0 GHz to 5,5 GHz with a step of 500 MHz**

Table C.3 summarizes the peak power of the patterns and presents the minimum attenuation with and without the tire.

**Table C.3: Peaks of the radiation pattern for the same excitation power, and differences**

| Frequency [GHz] | Antenna whithout tire. Pol: 0° | Antenna whithout tire. Pol: 90° | Antenna whithout tire. Total | Antenna whith tire & rim. Pol: 0° | Antenna whith tire & rim. Pol: 90° | Antenna whith tire & rim. Total | Difference Pol: 0° | Difference Pol: 90° | Difference (Total) |
|---|---|---|---|---|---|---|---|---|---|
| 4,00 | -65,67 | -65,86 | -65,46 | -72,49 | -69,07 | -68,74 | 6,82 | 3,20 | 3,28 |
| 4,50 | -51,32 | -52,32 | -51,14 | -59,26 | -54,72 | -54,48 | 7,94 | 2,40 | 3,33 |
| 5,00 | -44,17 | -45,34 | -43,90 | -52,89 | -47,93 | -47,82 | 8,72 | 2,60 | 3,91 |
| 5,50 | -40,11 | -40,75 | -39,86 | -47,74 | -43,46 | -43,26 | 7,63 | 2,71 | 3,40 |

Representing in a plot the values of the last column, as a function of frequency, **we can observe that with this type of tire the differences between peak e.i.r.p. values is at least 3,3 dB for the frequencies 4 GHz to 5,5 GHz.**

**However, it can be observed that, computing the total attenuation introduced by the tire, i.e. the ratio between the total power on the surface of the two cases, the value of attenuation is higher than 5,3 dB, as shown in the following table. The difference between the two results is due to the fact that the attenuation of the tire is partially compensated by the highest directivity due to the larger aperture (the tire) and the constructive interferences between direct signal and reflected-diffracted signals.**

**Table C.4: Total attenuation of the tire**

| Frequency (GHz) | Total attenuation (dB) |
|---|---|
| 4 | 5,3 |
| 4,5 | 5,7 |
| 5 | 6,4 |
| 5,5 | 6,4 |

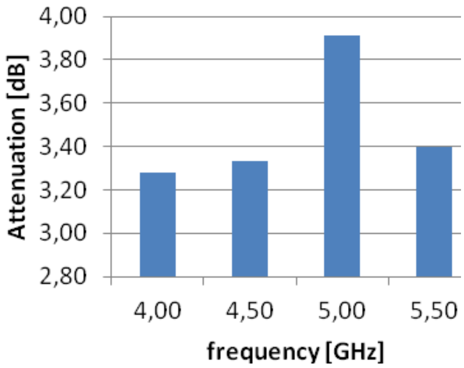



**Figure C.8: Minimum attenuation of the tire for each frequency**

These values are valid only for this type of tire; however, the procedure is applicable to determine the attenuation of any tire in the UWB frequencies.

**Conversely, in order to characterize more generally the attenuation of the tire, it is needed to measure a significant number of tires, the characteristics of which may contain all extremes of size and materials in the manufacturing process.** For example, in figure C.10 it is represented the set of the main car tires manufactured by Pirelli, depending on the sidewall height and the section width. Each coloured point represents a type of tyre. Taking the central and extreme cases of this diagram, we can define the shielding or minimum attenuation of the tire.

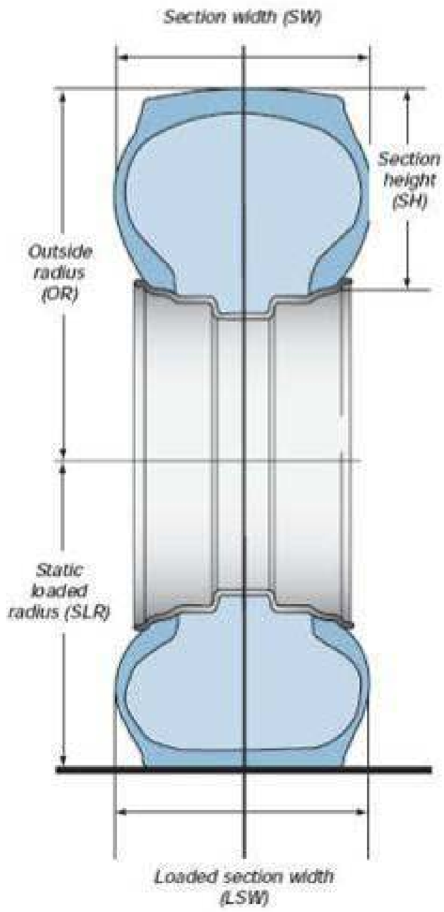



**Figure C.9: Cross section of the tire. Main dimensions**

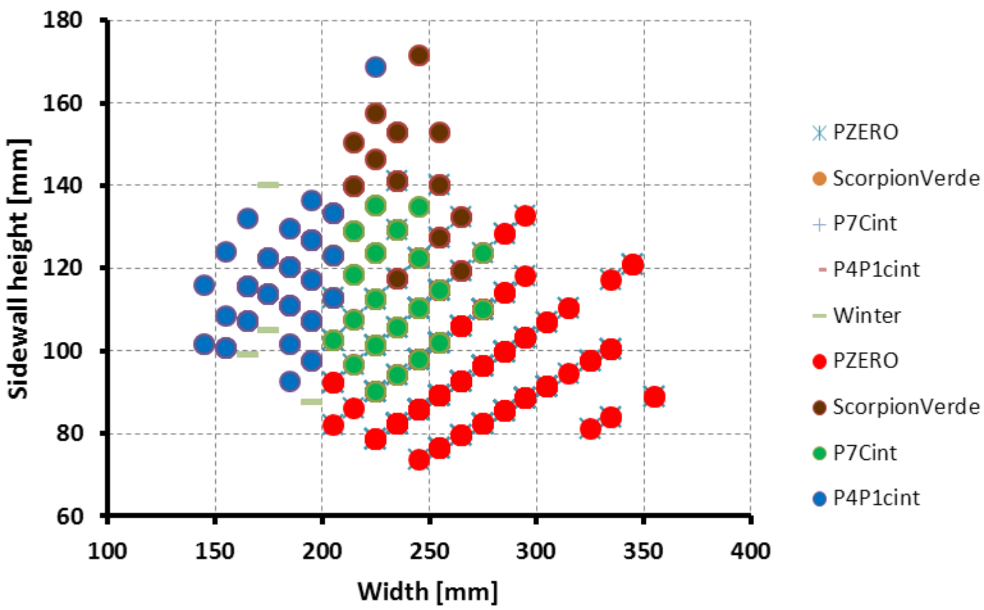



**Figure C.10: Main families of Pirelli tires as a function of cross section and materials (summer and winter)**

# C.3 Main influencing elements of a road vehicle

There are, in the literature, many papers discussing which elements affect significantly the field distribution of a radiofrequency source inside the tire at different frequencies. In [i.7], the authors describe in detail how is the field distribution of a radiofrequency source placed inside the tire a frequency of 433,92 MHz. They describe which elements influence significantly this field distribution, and obviously, for this, they take in account the rim design and material, the tire and the ground. These elements deform the original antenna radiation pattern and, as we have shown previously, change its impedance. Here, instead, the characterization is done for the UWB frequency band. The main goal of this part of the document is to establish which elements are significantly influent in order to establish the maximum of the e.i.r.p.

Each parameter constituting the "wheel unit" potentially affects the radiating pattern in near field and in far field conditions; however, comparing three different size of rim ( for example 16”, 17” and 19”) with at least three different type of tire (possibly taking at least one "border-line" case in the family of the different types of tire in figure C.10) it is sufficient to understand the quantitative differences between the measured power peaks and to be able, in this way, to establish a generic value of shielding or attenuation for a UWB device embedded inside the tire.

Obviously, one of these main elements is the tire where the lumped antenna is placed, because the radiation pattern is strongly modified.

The effect of the tire on the device is comparable to that of a dielectric-metallic waveguide, i.e. with horizontal metallic walls and the vertical walls consisting in a lossy dielectric slab (see figures C.11 and C.12 for more details). The propagation of a microwave signal, generated by a half-wave dipole, along this structure, at the frequency of 4,5 GHz, has been studied; the additional effect of a thin layer of mud on the tire was also considered.

In particular, we have studied 9 cases: 3 different orientations of dipole (along X, Y and Z direction) in three different situations (free space, dielectric/metallic waveguide and dielectric/metallic waveguide partially covered with mud) (2 mm thickness) at a central frequency of 4,5 GHz (see figures C.11 to C.13). We have calculated the electric field level difference (attenuation/gain) between collinear probes located along three axis.

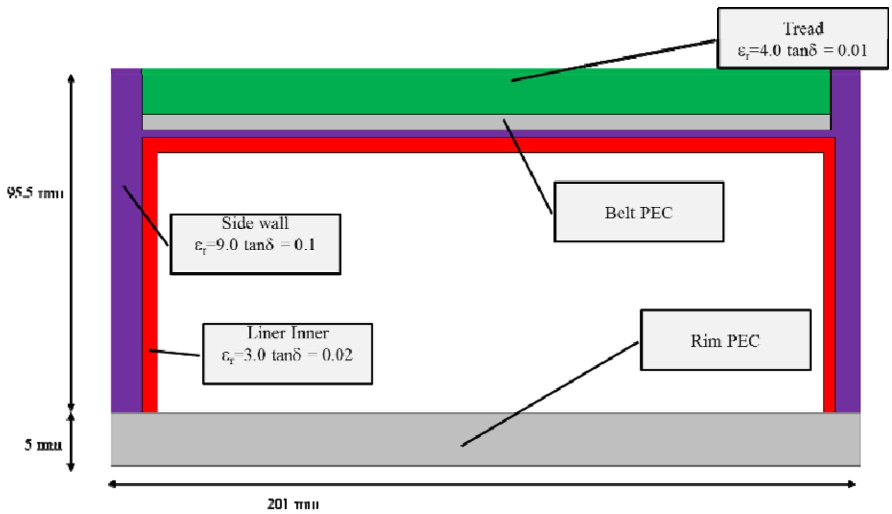



**Figure C.11: Details of the cross section of the waveguide equivalent to the tire**

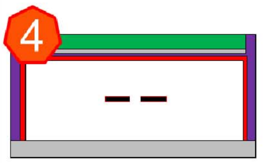
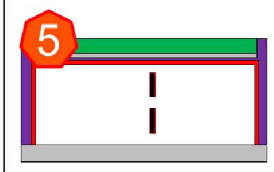
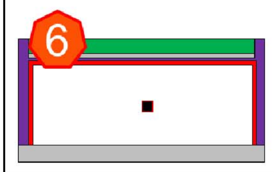
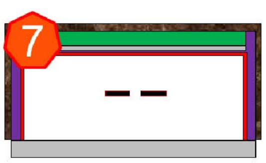
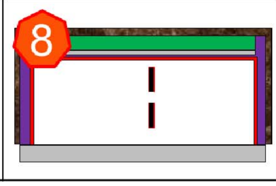
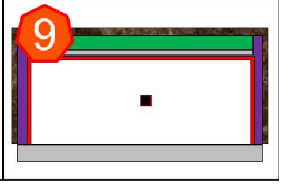
| 9 cases | Dipole orientation | | |
|---|---|---|---|
| | Along X direction | Along Y direction | Along Z direction |
| Free space |   |   |   |
| Inside of waveguide (Tire) |   |   |   |
| Inside of waveguide with mud (Tire with mud) (5 mm thickness, εr=15 S= 0.1 S/m) |   |   |   |

**Figure C.12: 9 cases**

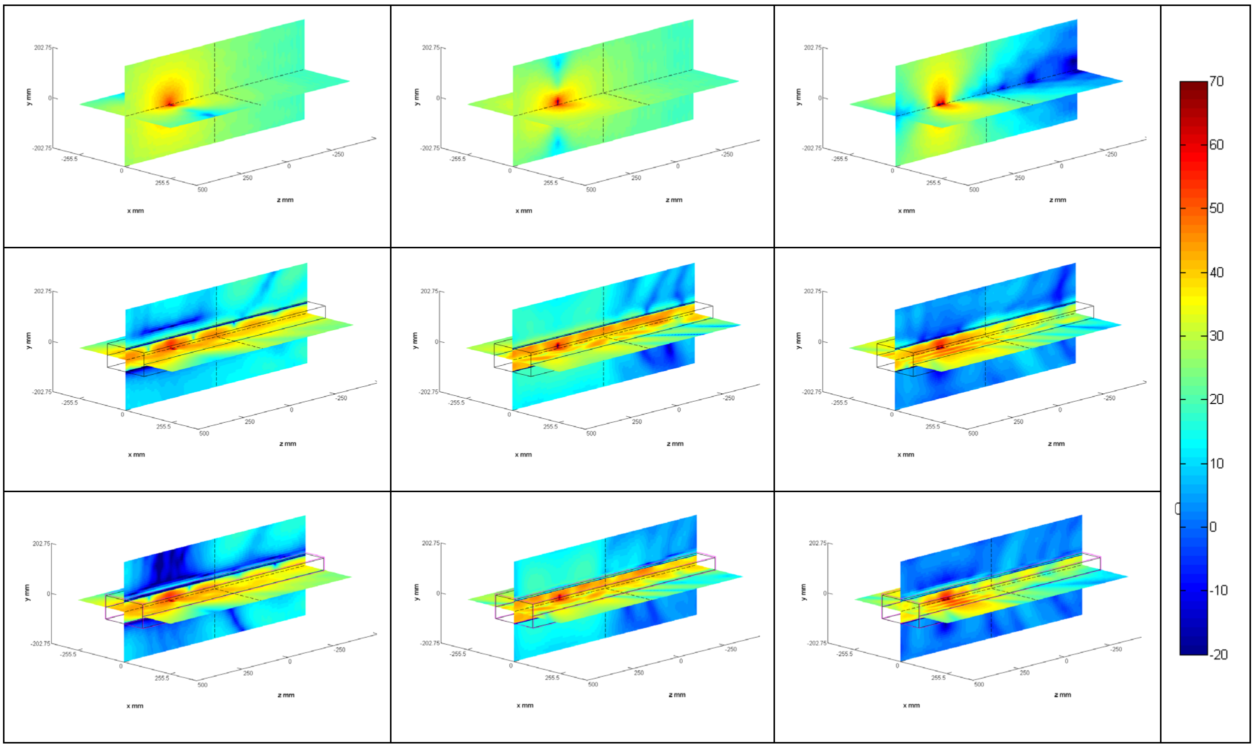



**Figure C.13: Electric field Magnitude (dBV/m) at 4,5 GHz for each case**

The conclusions of this study (developed using a full wave simulation of the structure) on dispersive modal propagation of the waveguide (with the same cross section of the tire) at 4,5 GHz are:

- The waveguide-effect creates other field components inside the tire but the field transmission through the side wall tends to maintain the same polarization.
- The best orientations of the antenna in order to increase the transmission through the tire is along x (axial) and z direction. With these dimensions of the waveguide (tire), an antenna positioned along y direction (radial) transmits less power outside than the other polarizations.
- The average influence of the uniform thickness of mud (5 mm thickness) around "the entire" surface of tire is a reduction of the transmitted power of about 3 dB to 4 dB.

**It is quite easy to verify that this wave guiding effect of the tire still occurs even if the 3D simulation is complicated by adding the main elements of the surroundings, such as fender, suspension and chassis**. The next figure shows the E-field magnitude in a V/m scale at 4,5 GHz, for 1 W of TX power, for three different positions of the UWB source. The E-field magnitude range was clamped from 0 to 200 V/m in order to highlight the lower levels of the field.

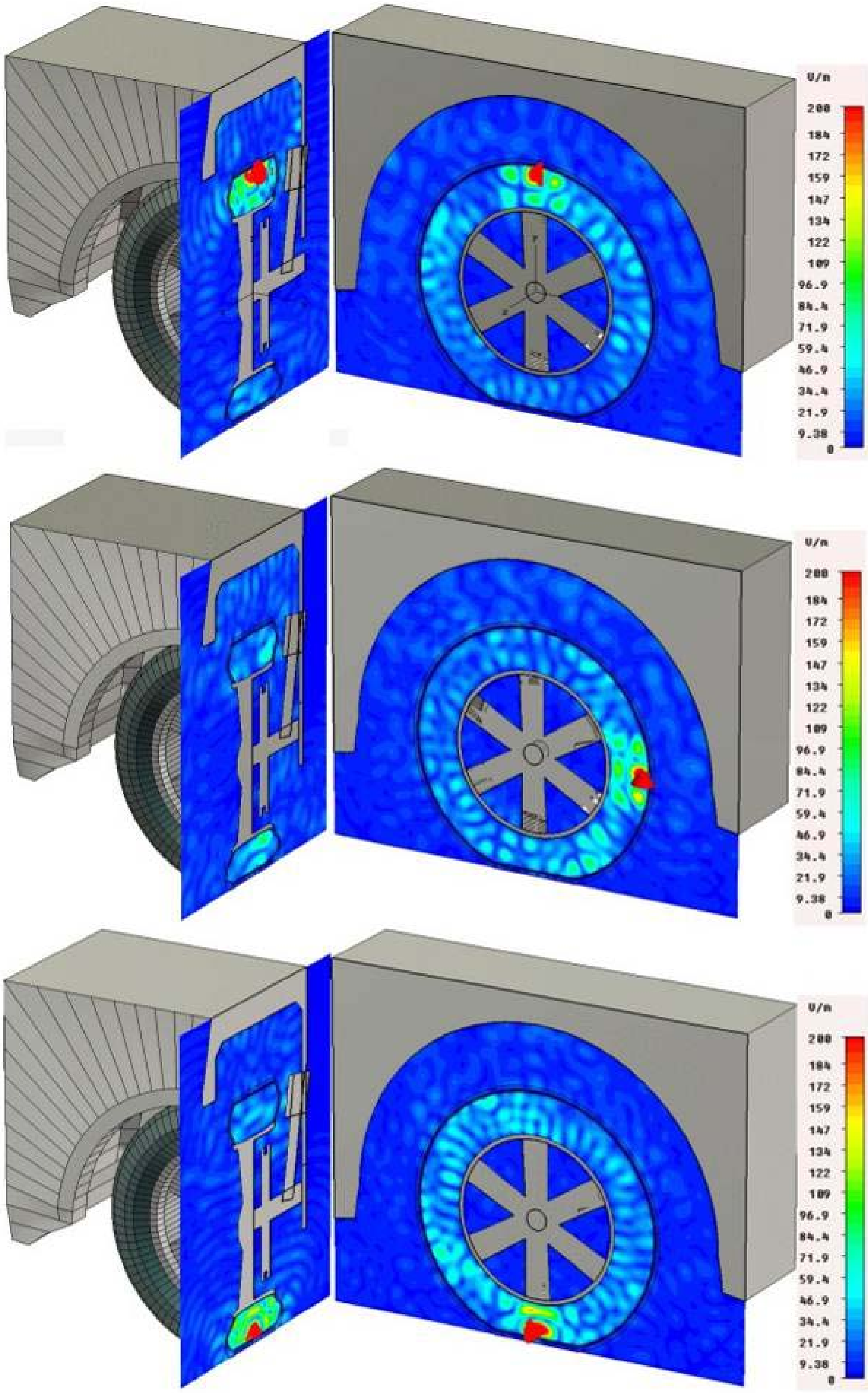


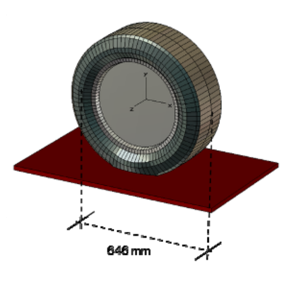
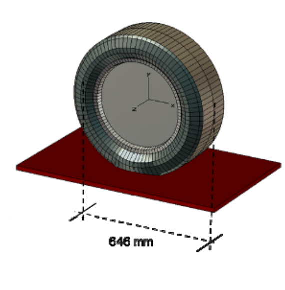
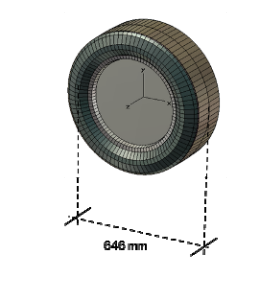

**Figure C.14: Electric field magnitude at 4,5 GHz in two main cuts for 3 different positions of the antenna (simplified model of a vehicle part)**

Another very important element is the rim. The 3D metallic frame of the rim interacts with the wave, in particular, the shape of the section of the rim in the tire is the most influent characteristic, in addition to the material, because, in fact, still considering the radial section of the tire as a waveguide, we know that it is the shape of the contour to establish the field distribution inside and outside. However, it is much less influential the shape and the number of arms that constitute the rim.

## Influence of the Ground

Next, once the UWB device is embedded in the tire, the influence of the ground is estimated by the comparison between three representative boundary conditions:

- Ground material: a dielectric with losses that simulates a realistic floor.
- Ground material: a PEC (Perfect Electric Conductor) plane that represents the highest level of the reflection that may have a ground.
- The tire in free space, this is a situation analogous to that which would occur by adding an ideal absorbent material under the tire.

| **Complex EM model of Loaded Tire on a dielectric ground** | **Complex EM model of Loaded Tire on a PEC ground** | **Complex EM model of Tire in the free space** |
|---|---|---|
|   |   |   |
| Ground material<br>$\varepsilon_r = 4$ , $\sigma = 0.001$ S/m | Ground material<br>$\sigma \to \infty$ | Background space<br>$\varepsilon_r = 1$ , $\sigma = 0$ S/m |

The followings figures show the near field distribution of the magnitude of the E-field (dBV/m scale for 1 W of TX power) at 4,5 GHz in main cuts for the three mentioned cases (PEC ground, realistic dielectric ground, and free space, in the order). The ground in these geometries is perpendicular to the y axis, at its minimum shown value, and its thickness is assumed infinite. In fact, observing figures C.15 for the PEC ground plane case, there is a very clear cut in the E-field pattern, while in the cases of figures C.16 and C.17 there is a non-zero value of the E-field under this edge.

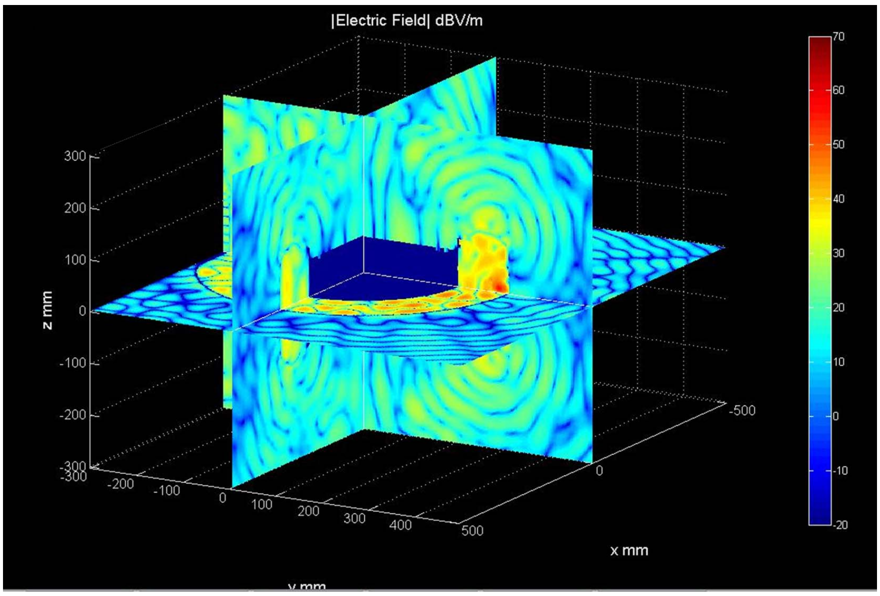



**Figure C.15: E-field magnitude (dBV/m) in three main orthogonal cuts @ 4,5 GHz, PEC ground**

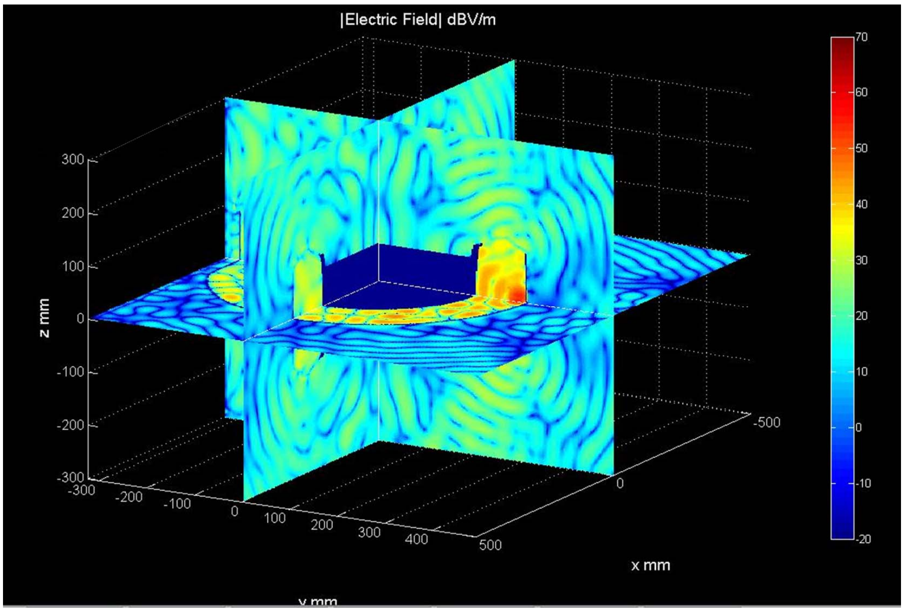



**Figure C.16: E-field magnitude (dBV/m) in three main orthogonal cuts @ 4,5 GHz, realistic ground**

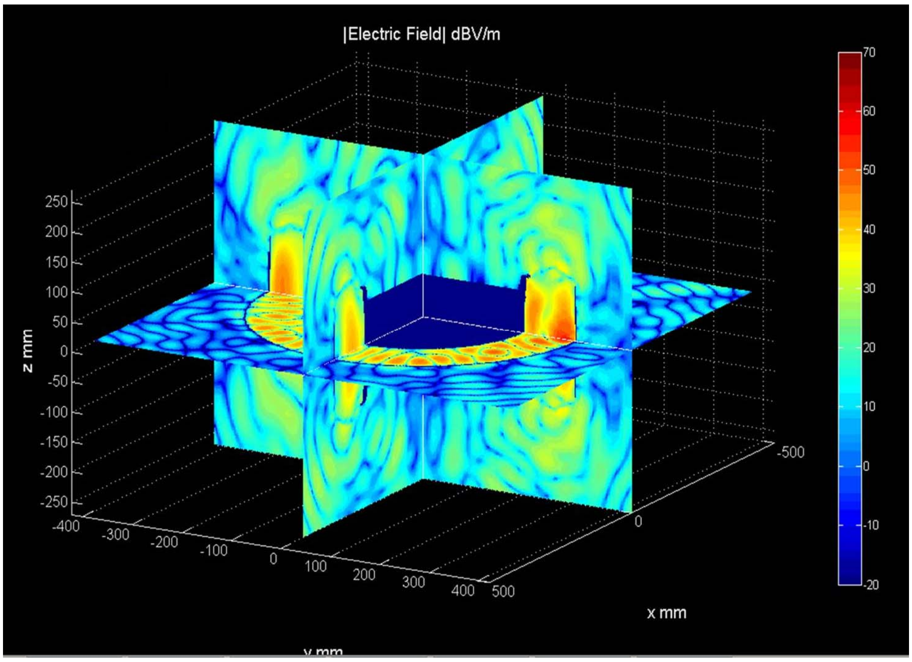



**Figure C.17: E-field magnitude (dBV/m) in three main orthogonal cuts @ 4,5 GHz, tire in free space**

In particular, if we keep in mind only the first two cases, i.e. the PEC ground and a realistic ground plane ($\varepsilon_r$ = 4,0 and *tan* $\delta$ = 0,001), and we add the main elements around the wheel in the full wave simulation, like shown in figure C.18.

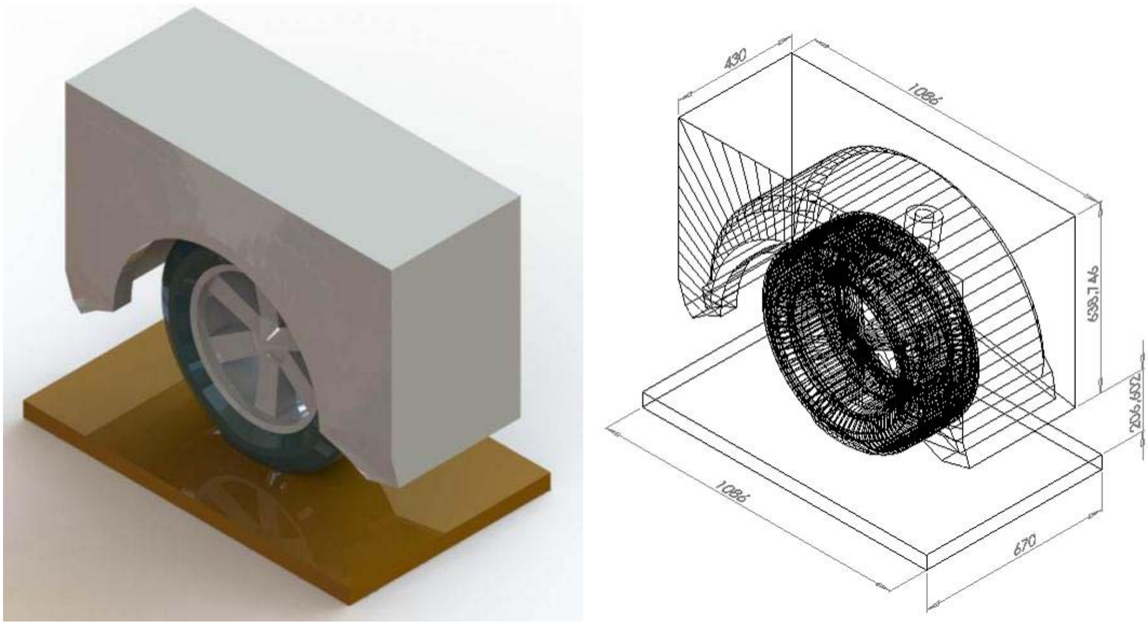



**Figure C.18: Geometry and main dimensions of a simplified EM 3D model of part of the road vehicle**

Then we can show the directivity pattern of these cases, when the UWB device is placed inside the tire, in the opposite side of the ground. The next figure shows the main cuts of the directivity patterns for main views with □ = 90° and θ = 90° respectively at 4,5 GHz. The values shown in this figure represent the directivity values, however, these do not take in account the losses in the all elements.

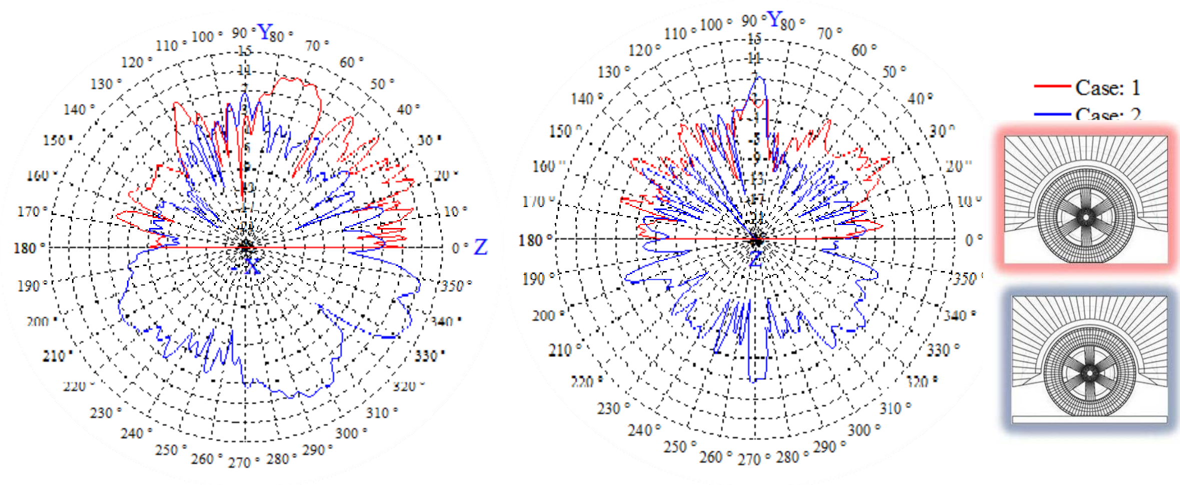



**Figure C.19: Cut planes phi= 90° (left) and theta = 90° (right)**

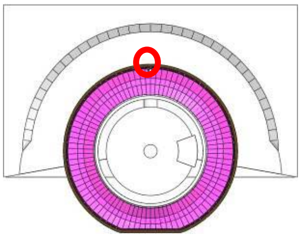
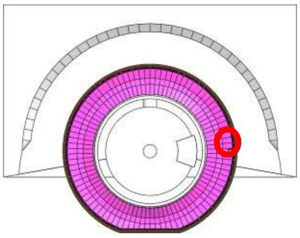
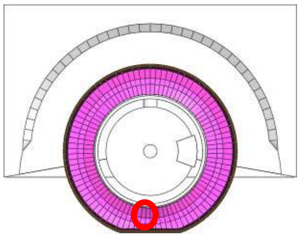
The following table shows the peak of the directivity of this radiating system in the 4,2 GHz to 4,5 GHz frequency band, for two cases: PEC ground (red colour) and a realistic ground (blue colour). **Therefore, we can conclude that the metallic ground compared to a realistic ground, such as asphalt, sedimentary rock, etc., adds an increase in the peak of the radiated power equal to about 2,6 dB in this frequency band, but this increase could be larger for higher frequencies in the UWB range.**

**Table C.5: Comparison between the gain peaks of the two ground models: PEC and dielectric (realistic)**

| Ground | PEC | | | | Realistic Ground | | | |
|---|---|---|---|---|---|---|---|---|
| Frequency (GHz) | 4,2 | 4,3 | 4,4 | 4,5 | 4,2 | 4,3 | 4,4 | 4,5 |
| Gain peak (dBi) | 8 | 6 | 8,7 | 6,9 | 6,63 | 6,62 | 6,1 | 6,72 |

We can repeat the same simulations for the PEC ground, but this time the wheel is rotated with the embedded UWB device by 90 ° counter clockwise, in order to establish the position of the wheel (assuming the device fixed to it), or of the device inside the tire (assuming a floating device inside the tire), that generates in the external region the highest peak of the radiated power in the same range of frequency (from 4,2 GHz to 4,5 GHz). The following table and figures show the results.

**Table C.6: Gain peak for different angular position of the tire (f = 4,2, 4,3, 4,4 and 4,5 GHz)**

| Cases | 1 | | | | 2 | | | | 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency [GHz] | 4,2 | 4,3 | 4,4 | 4,5 | 4,2 | 4,3 | 4,4 | 4,5 | 4,2 | 4,3 | 4,4 | 4,5 |
| Gain peak[dBi] | 7 | 6 | 8,7 | 6,9 | 9,4 | 7 | 6,8 | 9,5 | 5,8 | 5,7 | 5,4 | 5,4 |
| Geometry |  | | | |  | | | |  | | | |

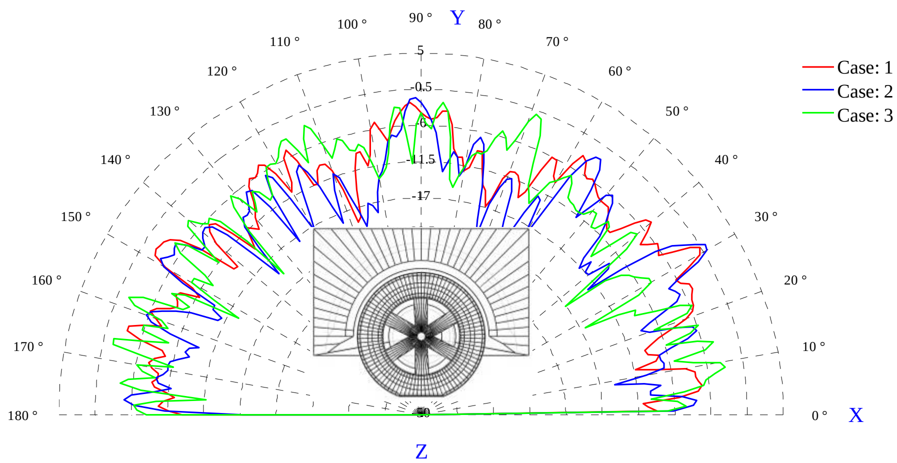



**Figure C.20: Polar plot of the gain at 4.5 GHz. Theta = 90°. PEC ground**

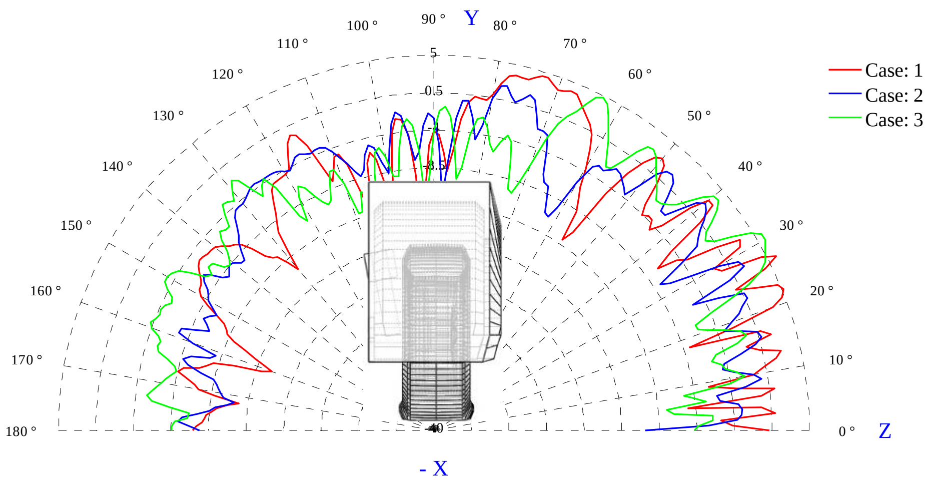



**Figure C.21: Polar plot of the gain at 4,5 GHz. Phi = 90°. PEC ground**

From table C.6, and other measurements carried out, we can conclude that the worst case corresponds to the position rotated 90° from the floor, i.e. to the left or right side of the wheel axis.

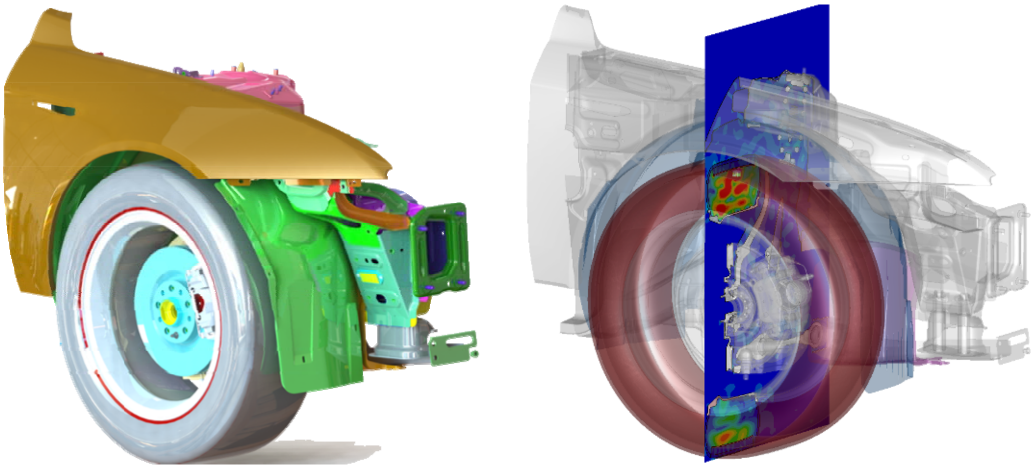


**Figure C.22: Detail of all elements around the wheel and a cut of E-field peak magnitude at 4,5 GHz when a UWB device is placed inside, on the top of the tire (Clamp range 0 – 100 V/m, 1 W radiated power)**

In conclusion, after having made a large number of EM simulations and measurements with the UWB DIT, we conclude that the parts or the elements of the car that most influence the radiation are those bordering or closer to the space around the wheel, only if not transparent to the microwaves. In addition to all the elements which constitute the wheel, such as tire and rim or hub cap, we recommend still to consider the suspension on the same side of the wheel with the UWB device, the fender, the brake system (disk brake), the part of the lower control arm of this wheel, the part of the bumper close to the wheel, the ground and finally all the elements close to the wheel with dissipative characteristics or that are opaque to microwaves.

**In any case, in the test setup all the elements (metallic and non-metallic) with significant parasitic surface currents in the usual configuration of DIT, or that create a strong shielding effect or reflection, need to be included. However, all the elements in which, for the great distance from the source, only negligible surface currents are excited, or which do not reflect or scatter significant parts of the radiated power, can be excluded. And so, in order to measure the maximum of radiation of a DIT, it is enough, for example, to take the part of a whole vehicle around the wheel equipped with the UWB device.**

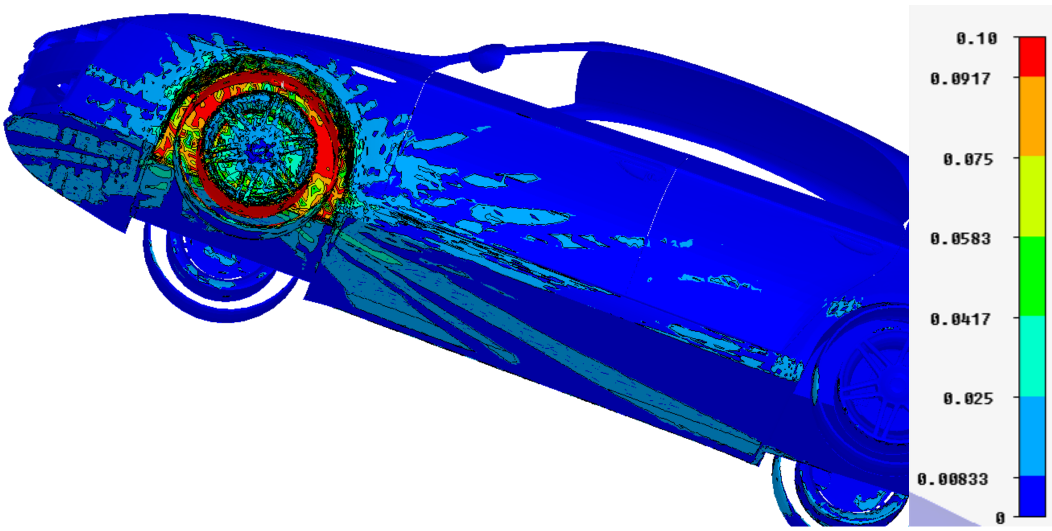



**Figure C.23: Parasitic surface current magnitude [A/m] at 4,5 GHz when a UWB device is placed inside, on the top of the tire (Clamp range 0 A/m to 0,1 A/m, 1 W radiated power)**

# C.4 Relevant area for the case of the UWB device inside tire

For a scenario where the antenna was mounted inside the fender space or inside the tire and in agreement with the results of clause 5.3, **the measurement area can be reduced to the area in front of the wheel instead of measuring the whole space around the car**. This can be proven computing the distribution of the electric field on the surface of an ideal boundary box at 1 m distance from the car. This was calculated accurately with a 3D full wave commercial software (CST Suite Studio® 2012) for a 3D EM model of a quarter of a vehicle (Alfa Romeo® 159) at different frequencies: 4,25 GHz, 4,5 GHz, 4,75 GHz; in this example, the device is located in the top part of the wheel, inside the tire. It is possible to compare these near field patterns with the equivalent field patterns of the same antenna placed in the same position but without the car and without tire (see figures C.24 and C.25, only at 4,50 GHz); it is easy to see as the car (or a part of it) has a shielding effect on the field distribution in the opposite direction to the fender aperture.

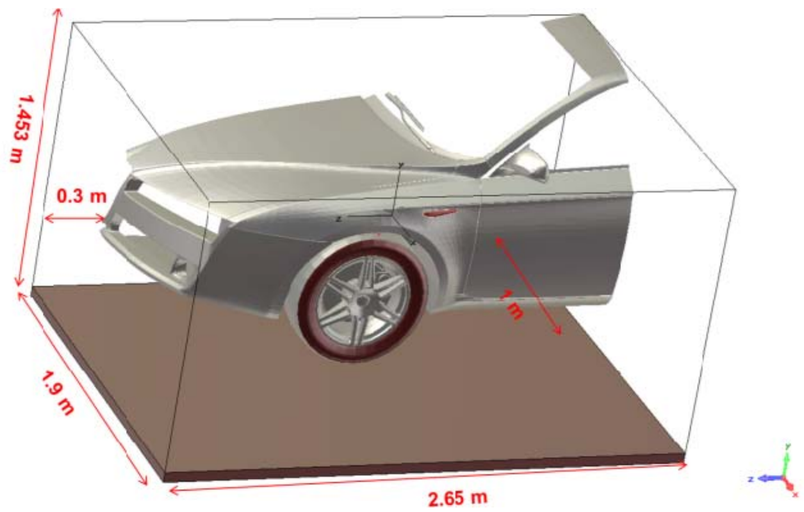



**Figure C.24: Main dimensions (mm) of the boundary box**

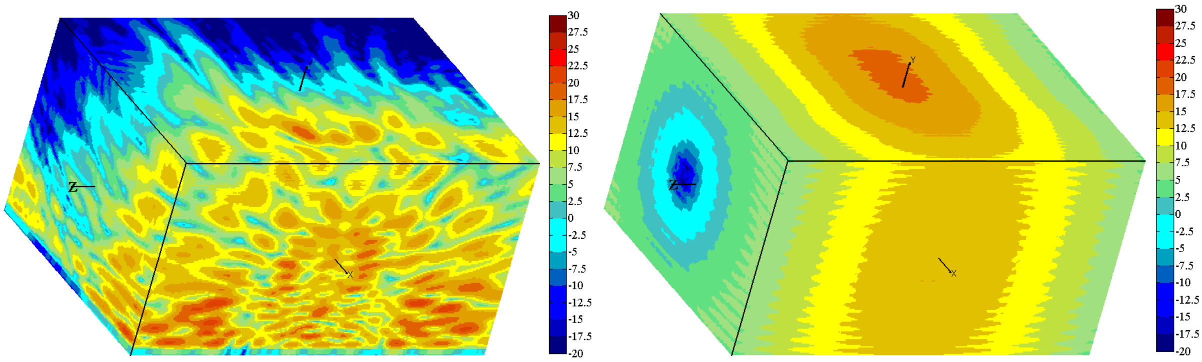



**Figure C.25: Electric field magnitude [dBV/m] on three sides of the boundary box at 4,50 GHz (with -left- and without car -right-)**

Figure C.26 shows the corresponding far field pattern, with realistic ground (concrete). This is another proof of that, in order to find the maximum of the radiated field, it sufficient to scan an angular area limited by the aperture of the fender surrounding the wheel with the device.

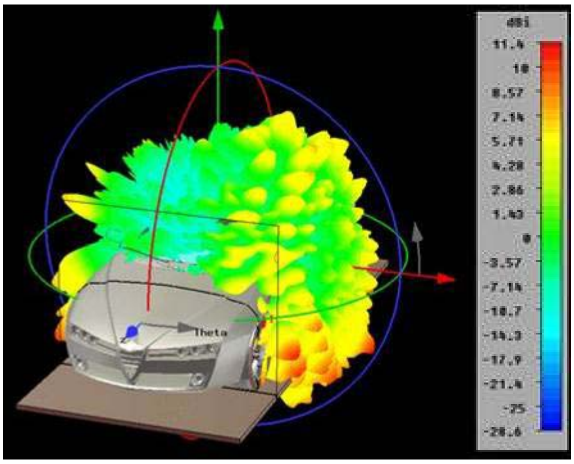


**Figure C.26: Directivity 3D magnitude pattern at 4,5 GHz**

Now we describe a measurement system dedicated to find the maximum of the transmission power for a UWB device embedded inside the tire in a road vehicle.

# C.5 Measurement in a relevant area for the case of the UWB device inside tire or inside the fender space.

In this clause we describe a Planar Scanner measurement system for UWB frequencies. It is divided in two parts; one presenting all the instrumentation used in the measurement, with a brief description, the other illustrating the procedure and the setup.

### Instrumentation

A Planar Scanner provides a cost-effective solution for precise positioning, with good speed and accuracy. It moves the probe on a planar surface to take samples of the near- or far-field over a regular grid. The probe is a small antenna (often taking the form of an open-ended waveguide or a small horn antenna), that is kept as small as possible to minimize reflections between the UWB device and probe.

Absolute position accuracy is critical to most measurement applications. The Planar Scanners are designed to make repeated measurements at critically accurate positions.

In a system like this, is necessary to know completely the gain pattern of the probe, because for each position, the direction between the probe and the UWB device under test is different, so that it is necessary to correct the gain of the probe antenna for each point of the grid. Another characteristic of a planar scanning system with constant step is that the angular interval of the scan changes slightly from the edge of the scanner to the centre. It could be possible to change the scanner step in order to have a constant angular increment, but it is preferable to maintain the same planar step for an enhanced control of the motor stepper. In the following there will be an analysis of the consequences of changing the resolution of the scan in order to determine the peak radiated.

In order to measure the two main components of the E-field, the probe antenna is rotated for each complete scan by 90°.

Figure C.27 shows the block diagram of the scanner setup.

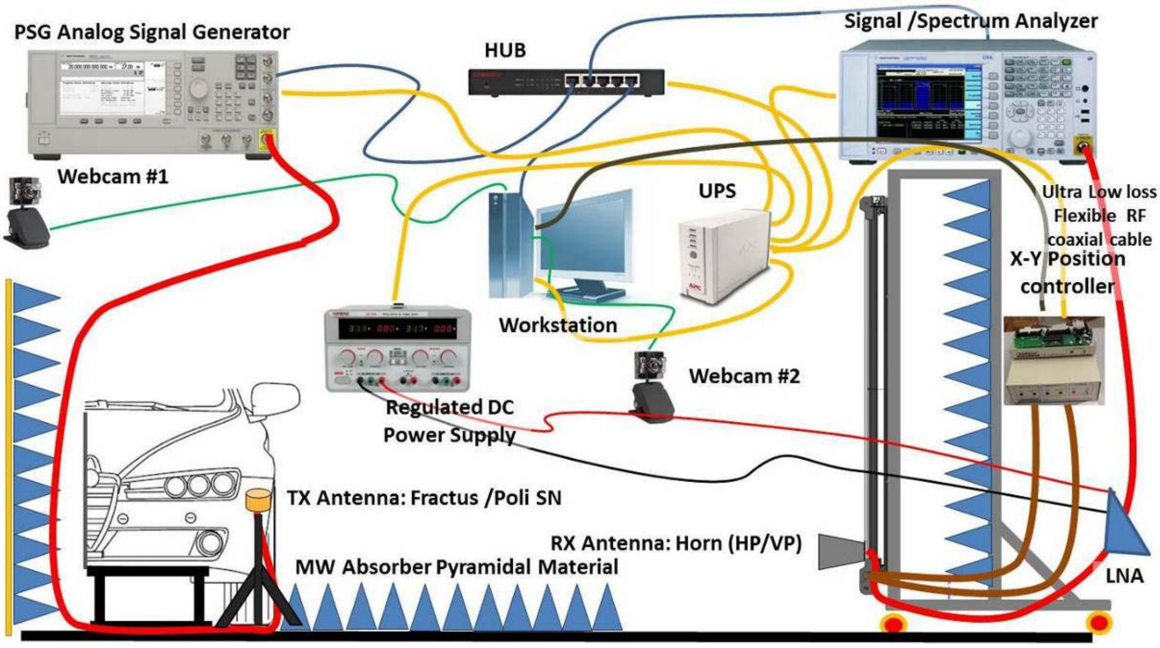



**Figure C.27: Block diagram of near field Scanner**

The complete scanner system consists of:

Hardware:

- Tire and a quarter of the whole car
- UWB device positioned inside this tire.
- Planar scanner with two high precision step by step motors. Main features:
    - Simple, reliable, cost-effective
    - X single-axis or XY dual-axis
    - Travel distances: 1" (25 mm) to 168" (4 267 mm)
    - 25 lb (11 kg) payload capacity
    - 0.01" (0.25 mm) repeatability
    - Max. Scan Are 3 x 2 m
    - Precision timing belt with nylon bearings
    - Integral cable carrier
- Field probe (Horn antenna designed to cover the entire UWB frequency band).
- Radar-absorbent material (RAM).
- RF source (signal generator).
- Spectrum analyzer
- Powerful data acquisition and controller workstation with many serial and LAN available ports and MatLab implemented.
- RF flexible low-losses coaxial cables with SMA and BNC 50 Ω threaded connectors.

Software:

- A set of programs and functions in MatLab, that controls the scanner movement via one serial port, the spectrum analyzer acquisition and the pulse generator excitation via LAN ports and show in real time (using two HD webcams) the mechanical progress of the scan.

Tire:

Typical approximate dimensions for a tire, that have been assumed in the test, are the following: overall diameter 600 mm; inner liner thickness 4 mm; metal belt thickness 5 mm; sidewall thickness 10 mm; thread thickness 15 mm; width 200 mm; rim diameter 400 mm; section height 100 mm, etc. However for different types of tire such values may vary (in particular width and height), as shown in figure 12.

UWB antenna: Fractus Media+ UWB Chip Antenna (both inside and outside the tire).

**Figure C.28: UWB Antenna inside the tire (left) and standalone (right)**

Scanner probe (Horn antenna):

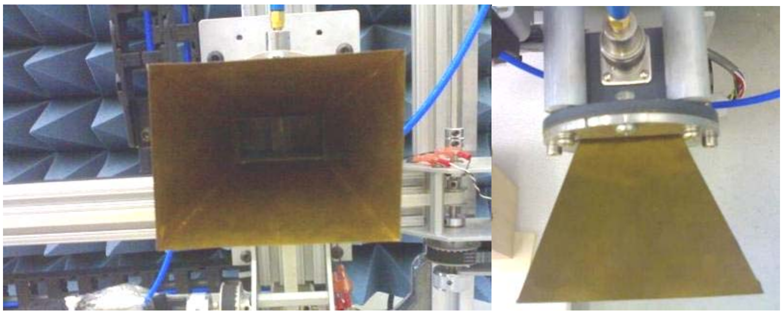


**Figure C.29: Front and top view of the horn antenna used like a probe in the planar scanner**

**RF source (signal generator):**

The power amplitude of the signal generator is fixed at 17 dBm, in CW mode; this power level ensures a large signal/noise ratio. In particular in this setup, we have used an E8267D Vector Signal Generator.

**Spectrum analyser:**

A spectrum analyser is the receiver of the measurement system. The correct selection of a receiver can greatly enhance the accuracy of the test system and satisfying the requirements of the EN 302 065-3 [i.8]. As: good linearity, high speed operation, high sensitivity, range gating and so on. In our system an 'Agilent N9000A' spectrum analyzer is used as a receiver. The receiver is connected (LAN cable) to a data acquisition computer.

**Microwave Absorbent Material:**

Panels with microwave absorbent material are positioned behind the scanner and behind the quarter of the vehicle, and sometimes also on the ground between them. This material, of pyramidal shape, is the same material used for lining anechoic chambers. This material typically consists of fire proofed urethane foam loaded with carbon black, and cut into long pyramids. The length from base to tip of the pyramid structure is chosen based on the lowest expected frequency and the amount of absorption required. For low frequency damping, this distance is often 24 inches, while high frequency panels are as short as 3 to 4 inches. Pyramidal absorbers attenuate signal by two effects: scattering and absorption. As illustrated in figure C.30, in our open area test space we used two types of these panels, the largest ones in the lateral sides of our transmitter and the medium ones in the front to avoid the ground reflections.

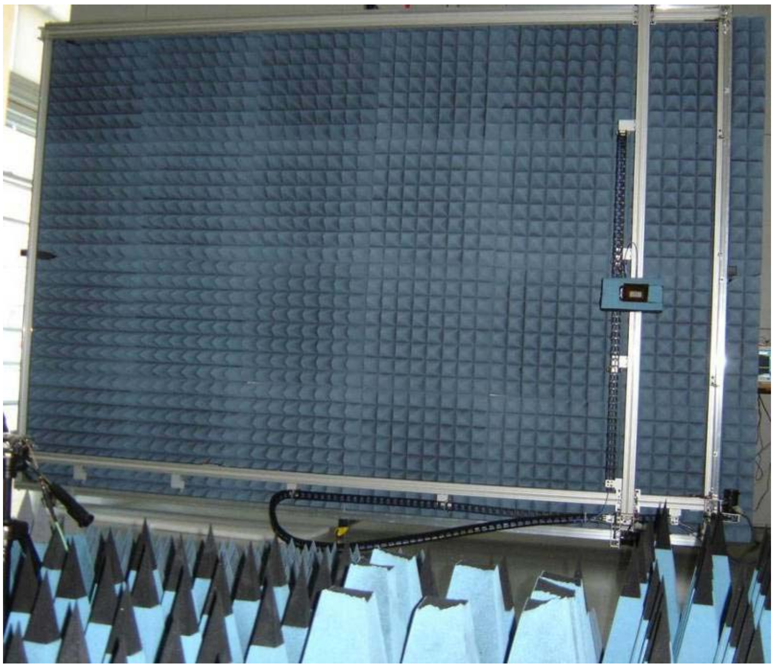


**Figure C.30: Planar scanner (LACE Lab - Politecnico di Torino, Vercelli, Italy)**

**Figure C.31: Open area test space**

**Measurement setup:**

To carry out the measurements, a laboratory has been set up, with a part of a real vehicle (the left front quarter of a car; the fender and all elements inside, including the suspension, were preserved) equipped with the tire, a sensor and an electromechanical system to move the tires in a controlled way. The UWB antenna is placed inside, on the top of the tire, on the inner liner. To generate the transmit signal, a signal generator is used to simulate the signal generated by the sensor. The receiving antenna is the horn shown before as a probe for the planar scanner, and is connected to a spectrum analyser through an ultra-low losses flexible coaxial cable. Then this probe is controlled by a dual motor stepper to move the scanner in the (x, y) plane. The spectrum analyser, the signal generator and the dual motor controller are connected to a control pc using a LAN switch creating a small LAN network giving each one of these devices a network address that allowed us to control them remotely.

The control of this instrument was achieved implementing MatLab as a software controller. Moreover, source code was made up to open the connections to the dual motor stepper, to the spectrum analyser and to the signal generator.

Each complete scan is performed for 8 positions around the rotation of the tire every 45°, the scanning in each position has been made at three different frequencies.

All values of the measurements are properly corrected by the gain values of the probe (horn antenna) and by the attenuation of the free space for each position.

**Correct sampling resolution:**

In order to understand the influence of change the sampling step, we repeated measurements with the same configuration or scheme of the elements, same polarization of the RX antenna, same power level at the TX-antenna, but by changing the step of sampling in both directions, and verifying the variation of the peak of the received power. A table follows that shows the maximum raw values of the received power for the UWB antenna alone (without vehicle) with the ground with absorbent material, for a vertical polarization of the receiving antenna and for the same level of power transmitted at different frequencies (here the UWB antenna is placed in the top of tire).

**Table C.7: Sampling resolution comparison without car**

| Position # | Polarization | Absor. material | Steps in mm | ANTENNA Tx | CAR | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Vertical | with | 200-200 | Fractus-2 | Without | -39,21 | -31,50 | -31,99 | -32,18 | -34,63 | -42,24 |
| 1 | Vertical | with | 100-100 | Fractus-2 | Without | -40,10 | -31,08 | -31,38 | -31,39 | -33,98 | -40,78 |
| 1 | Vertical | with | 50-50 | Fractus-2 | Without | -39,10 | -30,72 | -31,31 | -31,31 | -34,12 | -41,06 |
| 1 | Vertical | with | 30-30 | Fractus-2 | Without | -38,70 | -30,79 | -31,40 | -31,06 | -33,97 | -40,84 |

We can observe that by increasing the number of samples and the reducing step from 200 mm to 30 mm in each direction, the peak value changes at most of 1,3 dB. **For a good compromise between scanning time and precision, a 100 mm step has been chosen.**

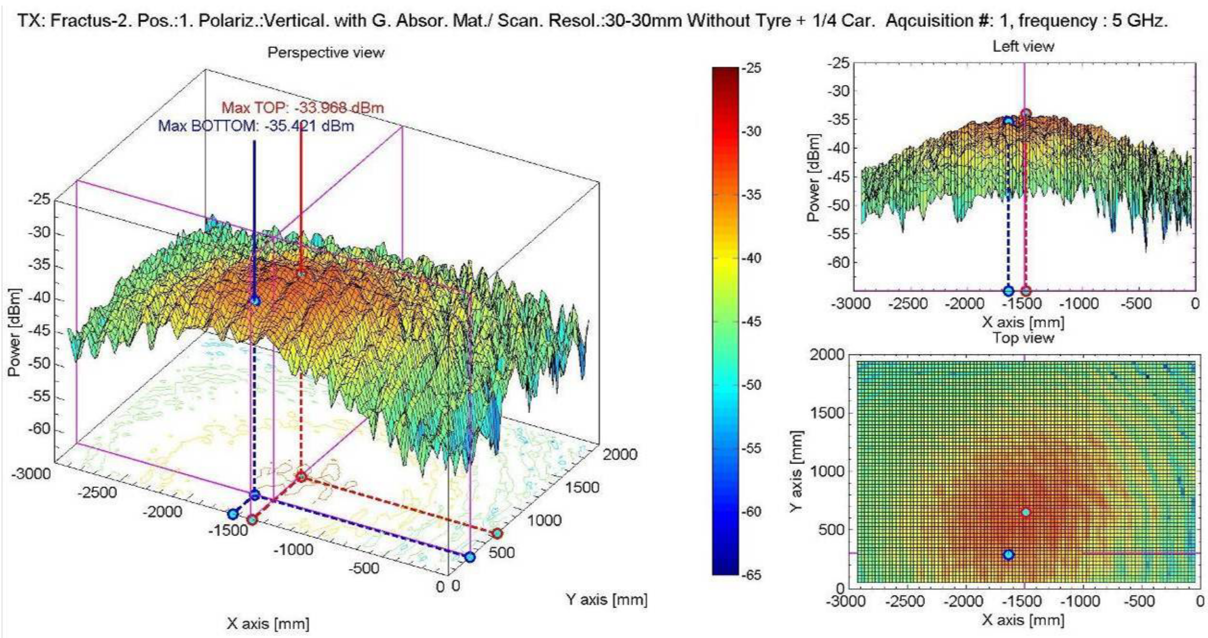



Figure C.32: Resolution: 3 x 3 cm

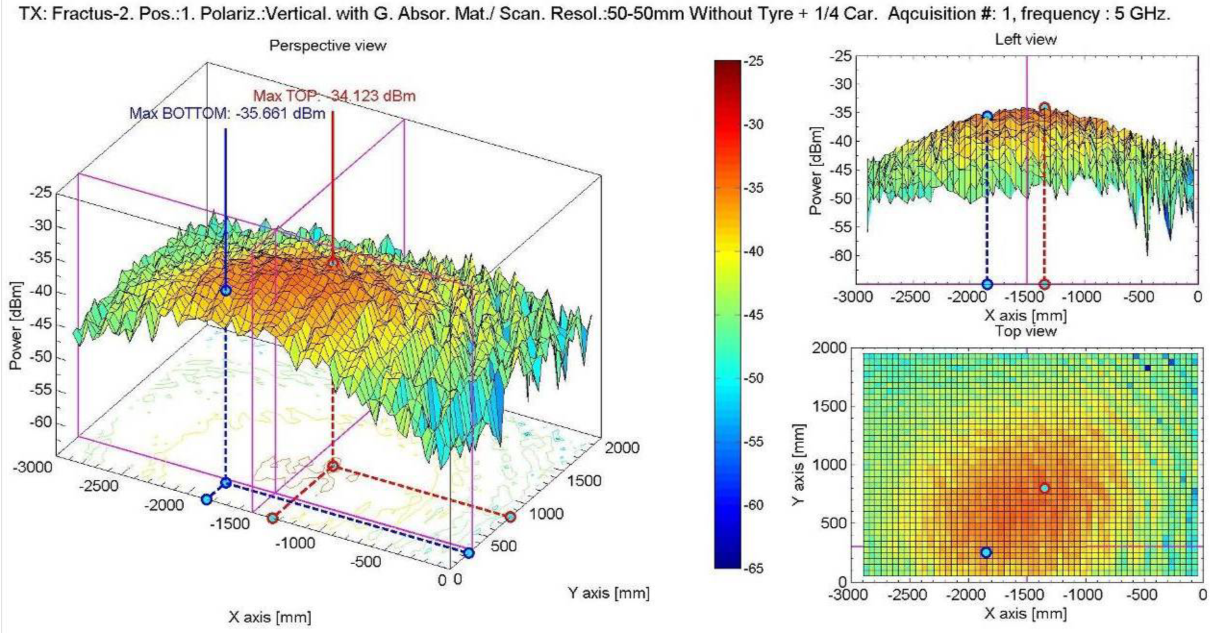



**Figure C.33: Resolution 5 x 5 cm**

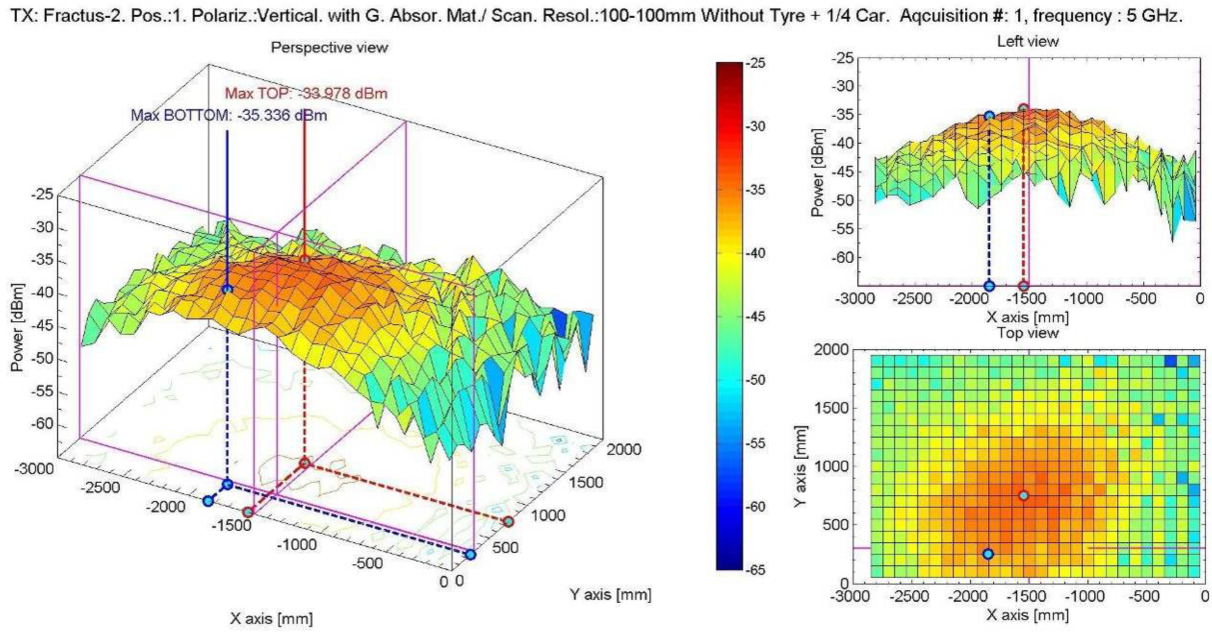



**Figure C.34: Resolution 10 x 10 cm**

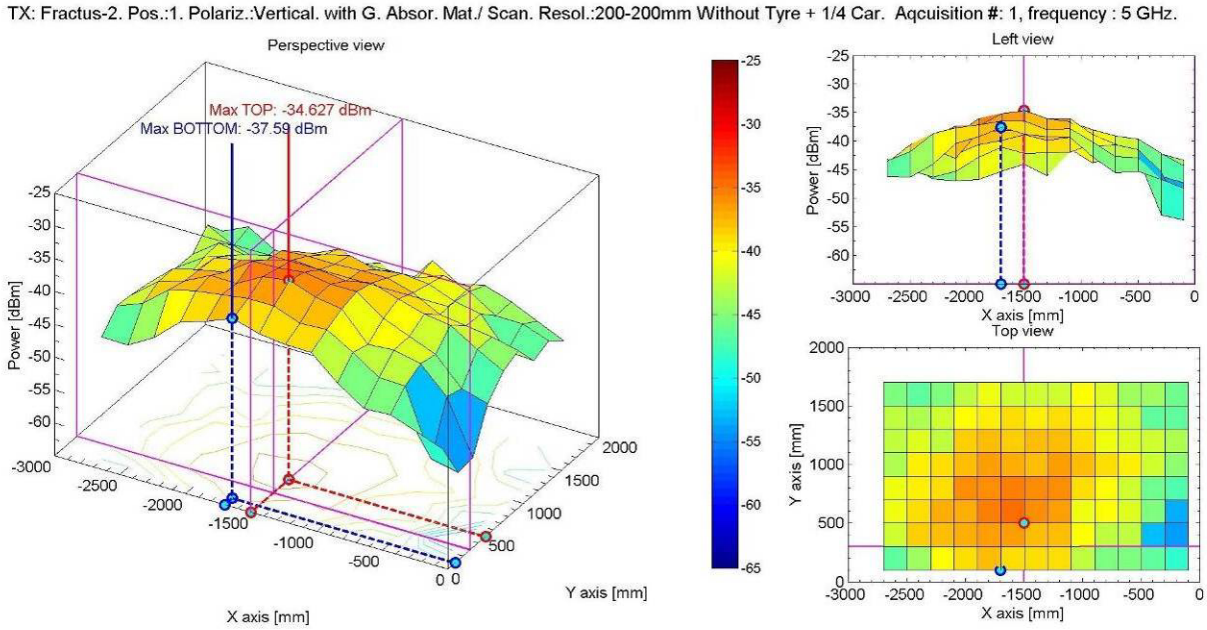



**Figure C.35: Resolution 20 x 20 cm**

In a similar way, we can repeat the test but by taking the raw measurements in presence of the vehicle, and considering both polarizations (vertical and horizontal polarization), it still occurs that 100 mm is an appropriate step. From table 8 it can be seen that the maximum difference is ≤ 0,54 dB.

**Table C.8: Sampling resolution for both polarizations and in presence of the car**

| Position # | Polarization | Absor. material | Steps in mm | ANTENNA Tx | CAR | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Vertical | With | 100-100 | Fractus 1 | With | -39,79 | -35,13 | -34,46 | -37,70 | -40,14 | -42,91 |
| 1 | Vertical | With | 50-50 | Fractus 1 | With | -40,02 | -34,95 | -34,44 | -37,36 | -39,68 | -42,97 |
| Difference | | | | | | 0,23 | -0,19 | -0,02 | -0,34 | -0,46 | 0,05 |
| 1 | Horizontal | With | 100-100 | Fractus 1 | With | -43,50 | -38,72 | -36,63 | -38,61 | -43,76 | -45,39 |
| 1 | Horizontal | With | 50-50 | Fractus 1 | With | -43,59 | -38,70 | -36,09 | -38,20 | -43,97 | -45,51 |
| Difference | | | | | | 0,09 | -0,02 | -0,54 | -0,41 | 0,21 | 0,12 |

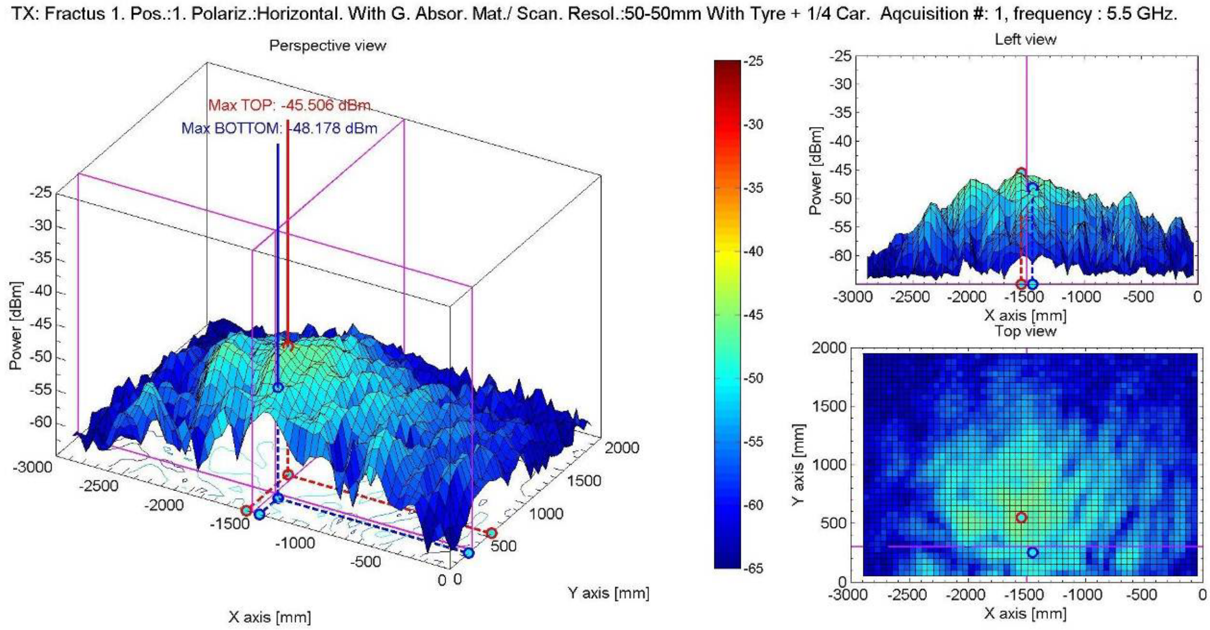



**Figure C.36: Resolution 5 x 5 cm. UWB Antenna inside the tire, in the top position, with the presence of the car, Horizontal component of the field**

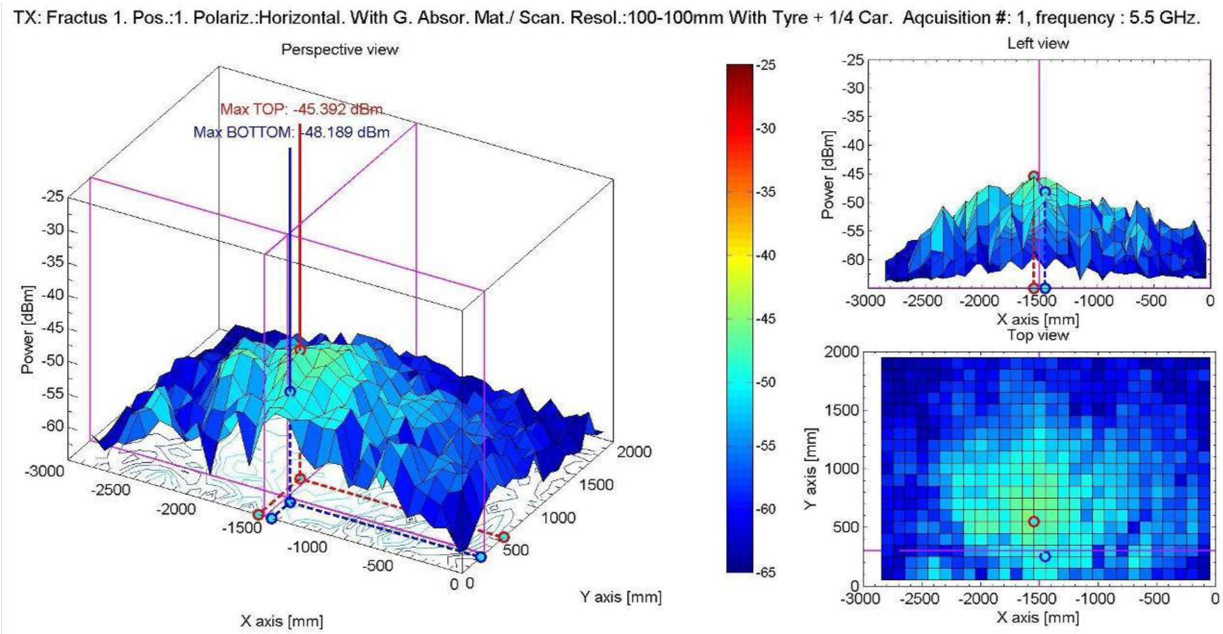



**Figure C.37: Resolution 10 x 10 cm. UWB Antenna inside the tire, in the top position, with the presence of the car, Horizontal component of the field**

**Effect of the ground absorbing material positioned between the RX and TX devices.**

In order to understand the effect of an absorbing material on the ground, we can compare two measurements where this is the only change.

**Table C.9: Difference in peak power (dB) with or without ground absorbing material (f = 3,0 GHz to 5,5 GHz)**

| | Without car | Frequency | | | | | |
|---|---|---|---|---|---|---|---|
| Rx Polarization | Ground absorbing material | 3,0 | 3.5 | 4,0 | 4.5 | 5,0 | 5,5 |
| Vertical | With | -40,1 | -31,1 | -31,4 | -31,4 | -34,0 | -40,8 |
| Vertical | Without | -40,3 | -30,4 | -32,1 | -31,5 | -33,7 | -40,5 |
| | Difference | 0,2 | -0,7 | 0,7 | 0,1 | -0,3 | -0,3 |
| Horizontal | With | -45,3 | -40,0 | -40,5 | -41,7 | -44,9 | -50,1 |
| Horizontal | Without | -45,1 | -39,1 | -39,5 | -40,8 | -45,4 | -50,0 |
| | Difference | -0,2 | -0,9 | -1,0 | -0,9 | 0,5 | -0,2 |
| | | | | | | | |
| | With car | Frequency | | | | | |
| Rx Polarization | Ground absorbing material | 3,0 | 3.5 | 4,0 | 4.5 | 5,0 | 5,5 |
| Vertical | With | -39,8 | -35,1 | -34,5 | -37,7 | -40,1 | -42,9 |
| Vertical | Without | -39,4 | -34,4 | -34,2 | -37,8 | -41,4 | -42,7 |
| | Difference | -0,3 | -0,7 | -0,2 | 0,1 | 1,2 | -0,2 |
| Horizontal | With | -43,5 | -38,7 | -36,6 | -38,6 | -43,8 | -45,4 |
| Horizontal | Without | -45,0 | -37,3 | -36,9 | -38,3 | -44,7 | -46,0 |
| | Difference | 1,5 | -1,4 | 0,3 | -0,3 | 0,9 | 0,6 |

It can be easily seen that the effect of the absorbers is not much significant: the maximum difference is 1,5 dB.

# C.6 Summary

1) A procedure to measure the shielding of the tire in a full anechoic chamber is presented

   - It is shown that a tire has a significant shielding effect. For the specific measured tire a shielding of at least 3,2 dB could be observed. The most important parameters for the shielding are the size of the cross section, the thickness of the sidewall, and the losses in the rubber. Due to the strongly varying parameters of the tire family, it is expected that every tire has specific shielding. It is recommended to measure the extreme cases to verify the minimum shielding of the tire family.

   - It is recommended to measure the tire mounted on the rim, because the rim influences significantly the transmission pattern of the tire.

2) Simulations have shown that the ground has impact on the measured peak power. Three ground materials have been analyzed, first a perfect electric conductor, a realistic ground, and the tire in free space. It could be observed that for the perfect electric conductor with respect to the realistic ground a gain of 2,6 dB occurs which depends on the operating frequency. Thus, it is recommended that the measurements should be performed with a realistic ground.

3) For the device inside the tire and inside the fender space, it is shown by simulation that only a part of the car around the wheel is necessary for accurate measurements. A combination of the tire, rim, fender, and not microwave transparent elements is needed for the verification of the exterior limit.

4) For a planer scanner a good compromise between scanning effort and precision is a step size of 10 cm. The relevant area is the area in front of the wheel.

# History

| Document history | | |
|---|---|---|
| V1.1.1 | March 2013 | Publication |
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