TEM Waveguides
- Principles, Evaluation Criterions and Examples -

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0 Introduction

The testing of electromagnetic interference presents, in general, enormous problems due to the very high costs involved in constructing and preparing test equipment. Over the past years, investigations have been carried out as to how these very complex field tests could be carried out using simpler, less expensive equipment.

Various new test installations have been proposed based upon far field measurements of an antenna. The aim of these installations was to test the emission or interference resistance of a device under far field conditions as realistic as possible. TEM cells and other TEM wave guide constructions have already become part of today's standards. Well-enclosed housings no longer require expensive, shielded rooms. Therefore, a large requirement has evolved for this type of inexpensive test equipment. Recently, a lot of test facilities have been offered on the market as further possibilities for field measurements. They all claim to fulfil the function of TEM wave guides.

The intention of this presentation is to investigate how it could be determined whether they fulfil TEM wave conditions. This leads to definitions as presented in IEC 1000-4-3. This standard should appear as EN 61 000-4-3. The general definitions from the standard will be clarified to allow a comparison between the test devices. The proposed limits for field homogeneity and depolarisation angle are justified.

Under these assumption TEM-, GTEM-, G-Strip and MAC-cells are tested. As a result the applicable frequency range for each test facility could be clearly identified.

1 Antenna far field = TEM wave propagation

As shown in [1] each given electromagnetic field can be described as a superposition of well known wave types called field modes:

$$\vec{E} = \vec{E}_{TEM} + \vec{E}_{TE_{10}} + \vec{E}_{TM_{10}} + \cdots$$
$$\vec{H} = \vec{H}_{TEM} + \vec{H}_{TE_{10}} + \vec{H}_{TM_{10}} + \cdots$$

The term *Txy* stands for *"There is* ***no*** *component of the* ***x-*** *and* ***y-field*** *in longitudinal direction (=direction of wave propagation). There are* ***only transverse*** *components of x- and y-field"*.

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From this we can see that the TEM-wave doesn't have to have a longitudinal component.

The ratio of $\left|\vec{E}_{TEM}\right|$ and $\left|\vec{H}_{TEM}\right|$ is given by

$$\Gamma_{TEM} = \frac{\left|\vec{E}_{TEM}\right|}{\left|\vec{H}_{TEM}\right|} = \sqrt{\frac{m_0}{e_0}} = 120p\ \Omega$$

for propagation in air.

The propagation velocity of the TEM-mode is given by the material constant likewise:

$$c_{TEM} = \frac{1}{\sqrt{m_0 \cdot e_0}} = c_0$$

This is the well known speed of light.

Identifying TEM-fields we have to look for the following criterions:

1. Only field components in the transverse plane
2. Ratio of the absolute value is given by $120\pi\ \Omega$.
3. Propagation velocity is equal to c_0.

Another important aspect of the TEM mode is that it is independent of the radiator / antenna.

After this scientific considerations let's have a look to real applications of field measurements. As proposed by IEC 1000-4-3 a typical test set-up is shown in figure 1.

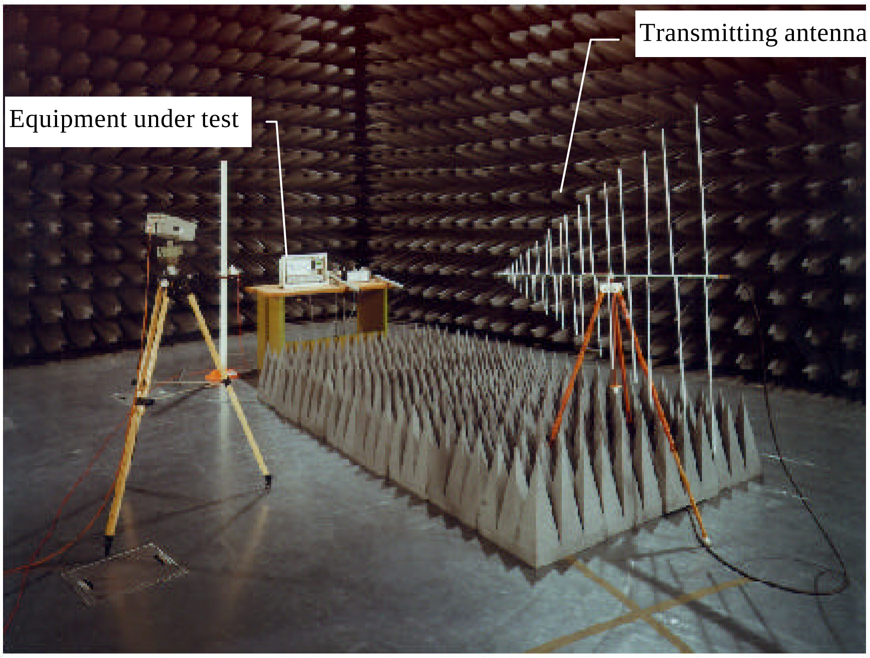


Fig. 1: Immunity measurement in an ALC (MAZ, Hamburg)

An antenna illuminates the EuT for the frequency range from 10 - 1000 MHz. The distance between EuT and transmitting antenna has to be 3 m.

It can be show that the radiated field far away from the antenna fulfils the TEM-mode criterions. the rule of thumb for the minimum distance is some what in the order of the used wavelength. For this case this isn't valid. The wavelength from 10 MHz requires a distance of 30 m. On the other hand a high field strength is needed at the EuT. So a compromise is found and the minimum distance is set to 3 m. Nevertheless TEM-mode conditions is assumed at the EuT.

Concluding this chapter we can say that we need a defined field mode (TEM mode) to ensure reproducible and well defined field measurements. If several test facilities have to be compared the main task is how the test site generates a pure TEM-field.

2 Evaluation Criterions

The calibration procedure for field immunity tests is shown in figure 2.

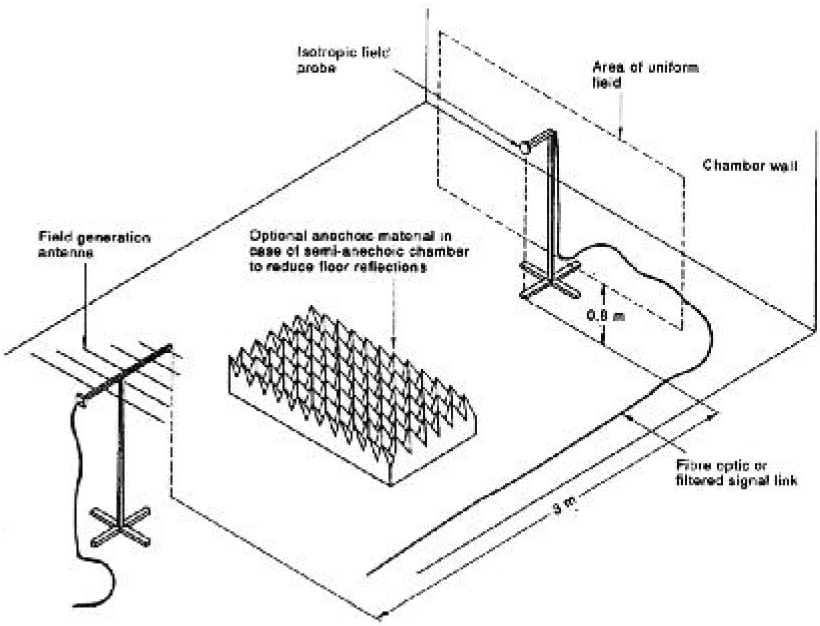


Fig. 2: Field calibration according to IEC 1000-4-3

Various criterions which alternative test equipment must fulfil, can be extracted from the IEC 1000-4-3 standard. They are presented briefly below:

Field Homogeneity

The IEC 1000-4-3 chap. 6.2 requires the field to be homogeneous over a surface in front of the test object.

A surface perpendicular to the direction of the field propagation is selected. This square surface must be at least as large as the irradiated surface of the device under test (DUT), but not more than 1.5m x 1.5m. The DUT is removed and the field strength measured at each of 16 equally distributed points. For at least 12 points, the difference between the minimum and maximum values must not exceed 6 dB.

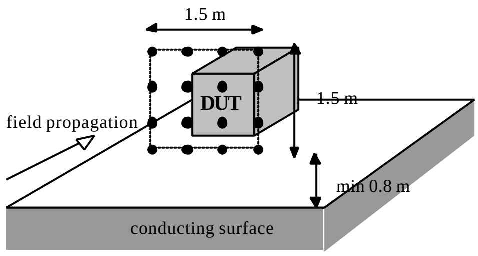


Fig. 3: Definition of field homogeneity for irradiation test according to IEC 1000-4-3

The surface in which the field point are located must be as large as the irradiated surface of the DUT. The test points may not be situated on the conducting surface or under the DUT.

A disadvantage of this procedure is that 25% of the measured values are not taken into account in any way. For this reason a new statistical approach was proposed in [4]. Assuming a statistical distribution of the measured values the 6 dB criterion can be written as

$$20 \cdot \log \frac{\bar{x}+1{,}15 \cdot s}{\bar{x}+1{,}15 \cdot s} \le 6\,dB$$

with: mean value $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

standard deviation $s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}$

probability $p\left(\bar{x} - k \cdot s \le x_i \le \bar{x} + k \cdot s\right) = 75\% \rightarrow k = 1{,}15$

To obtain the required homogeneity of the field strength at first the mean value and the standard deviation for the n=16 measured field values have to be calculated. If $20 \cdot \log \frac{\bar{x}+1{,}15 \cdot s}{\bar{x}+1{,}15 \cdot s}$ is smaller than 6 dB the criterion is fulfilled. Figure 4 shows an example for the field homogeneity of a GTEM cell at 100 MHz.

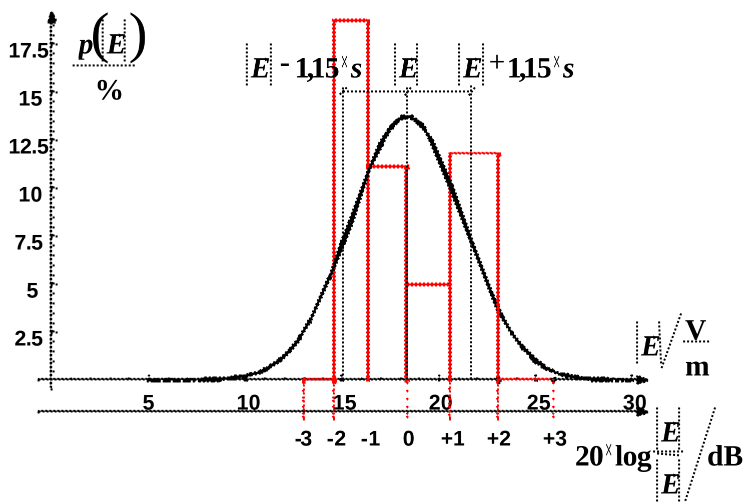


Fig. 4: Field homogeneity of a GTEM cell

Defined field polarisation / TEM wave propagation

”… This investigation shall be carried out separately for vertical and horizontal fields ….” (IEC 801-3/IEC 1000-4-3 chap. 7)

At this point the observed field strengths must be differentiated. The **total field strength** is often viewed as

$$E_{ges} = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

Polarisation direction

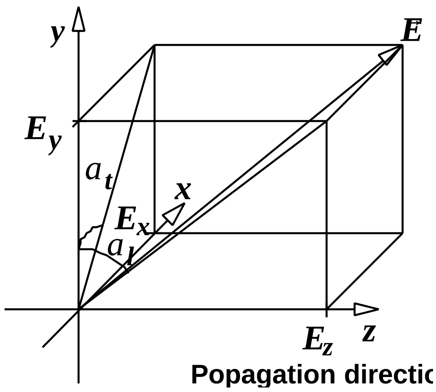


Fig. 5: Definition of the field components

On the other hand, the field strength component in the **polarisation direction** is often investigated. For wave guides with dominant higher order modes a consideration of the total field strength is better. Both values are investigated in the following comparison.

This requirement should clarify any possible radiation intrusion channels. The dependence of interference resistance on the polarisation direction allows deductions to be made concerning , e.g., intrusive radiation caused by slits or other apertures.

By determining the depolarisation between the theoretical and actual polarisation angles, information can also be gained on the existence of TEM-mode. The existence of a component in the direction of propagation gives information about the presence of a higher mode. The error angle can be deduced from the following equations:

$$a_{trans} = \arctan \frac{E_{xpol}}{E_y} \quad \text{and} \quad a_{long} = \arctan \frac{E_{long}}{E_y}$$

where:

E_{xpol} is the field strength component in the transverse direction perpendicular to the polarisation vector

E_{long} is the field strength component in the direction of propagation

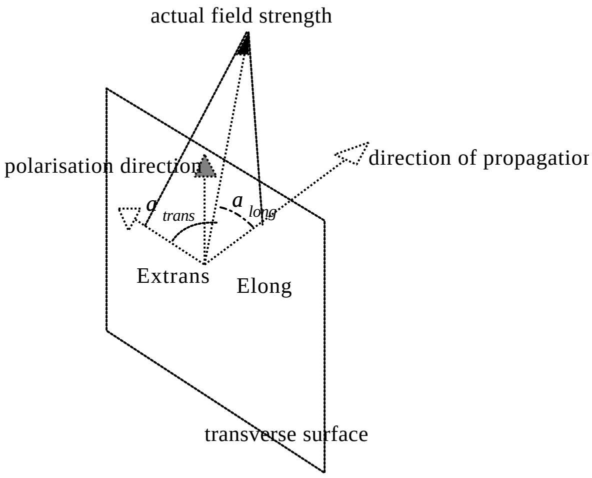
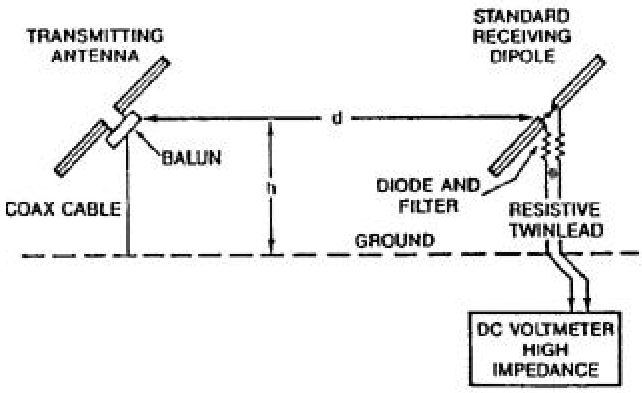


Fig. 6: Definition of depolarisation angle

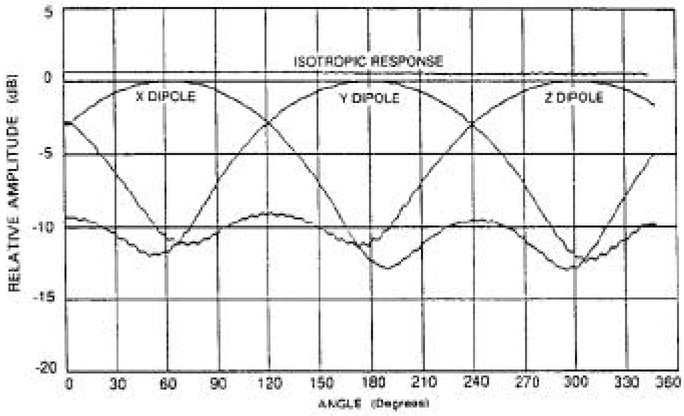
The ideal angle of 0° can never be achieved. Assuming a point source the propagation of the TEM wave is spherical. This introduce an angle of 14°. As already shown in [4], a value of 20° for both angles is realistic. This leads to the limit that 75% of the measured depolarisation angles have within $\pm 20°$.

3 Measuring the field components

Normally a high resistive dipole is used to measure the components of the E-field. The radiation pattern of such a dipole is shown in figure 6.



Dipole with diode to measure rms-values



Isotropic radiation pattern

Fig. 7: Radiation pattern of a high resistive dipole

It can be seen that through the diode the sign of the E-field components is missing. This leads to a misinterpretation of the direction of $\vec{E}$ as shown in figure 8.

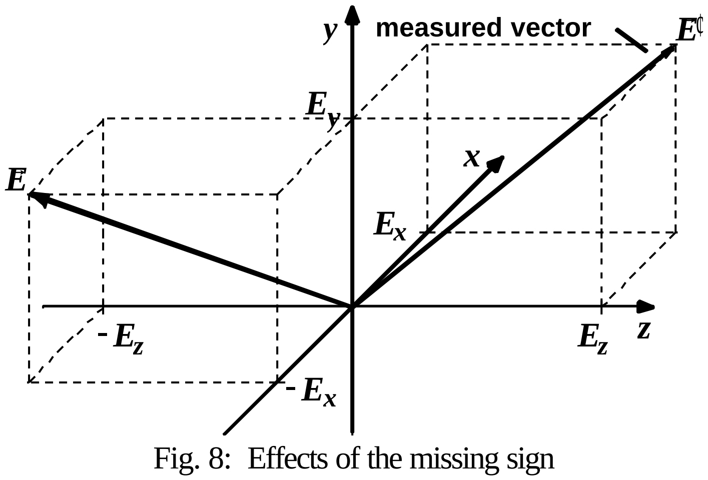


Fig. 8: Effects of the missing sign

To reconstruct the sign the measurement has to be done twice at each point. Figure 8 shows the procedure for a rotation of the coordinate system of 15°.

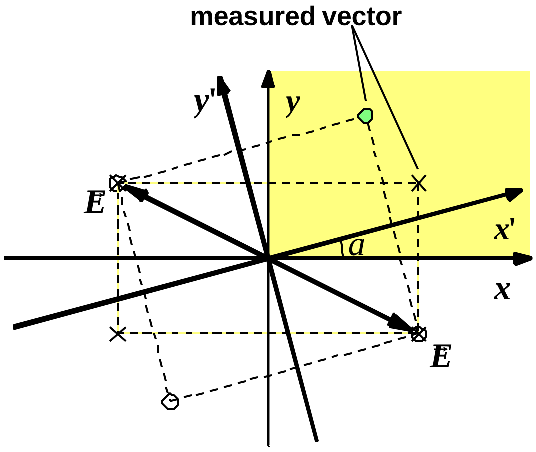


Fig. 8: Reconstruction of the missing sign

4 TEM wave guide examples

4.1 Measurement set-up

The following were investigated:

- TEM Cell (Crawford type)
- GTEM 500
- GTEM 1250
- G-Strip
- MAC

The positioning of the measurement points is shown in figure 9. Figure 10 displays the measurement equipment for the example of a GTEM-cell. For each field point the components of the electrical field strength are shown. The following nomenclature is used for the coordinate system:

- z coordinate
  coordinate in the propagation direction or longitudinal direction
- y coordinate
  polarisation direction
- x coordinate
  direction of transverse plane perpendicular to the direction of polarisation

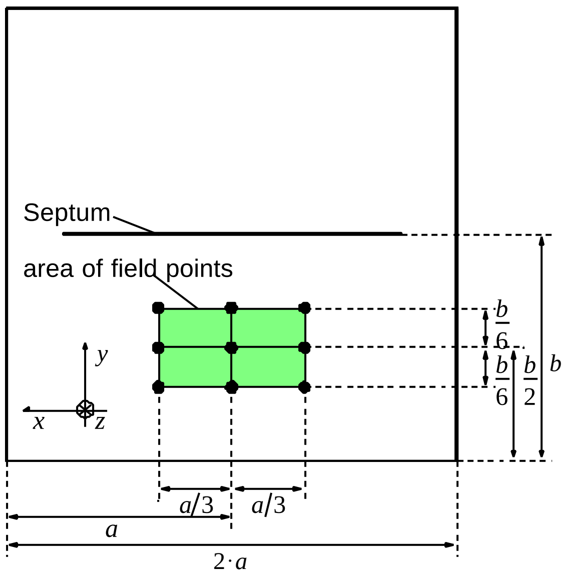


Fig. 9: Field points in the TEM Cell

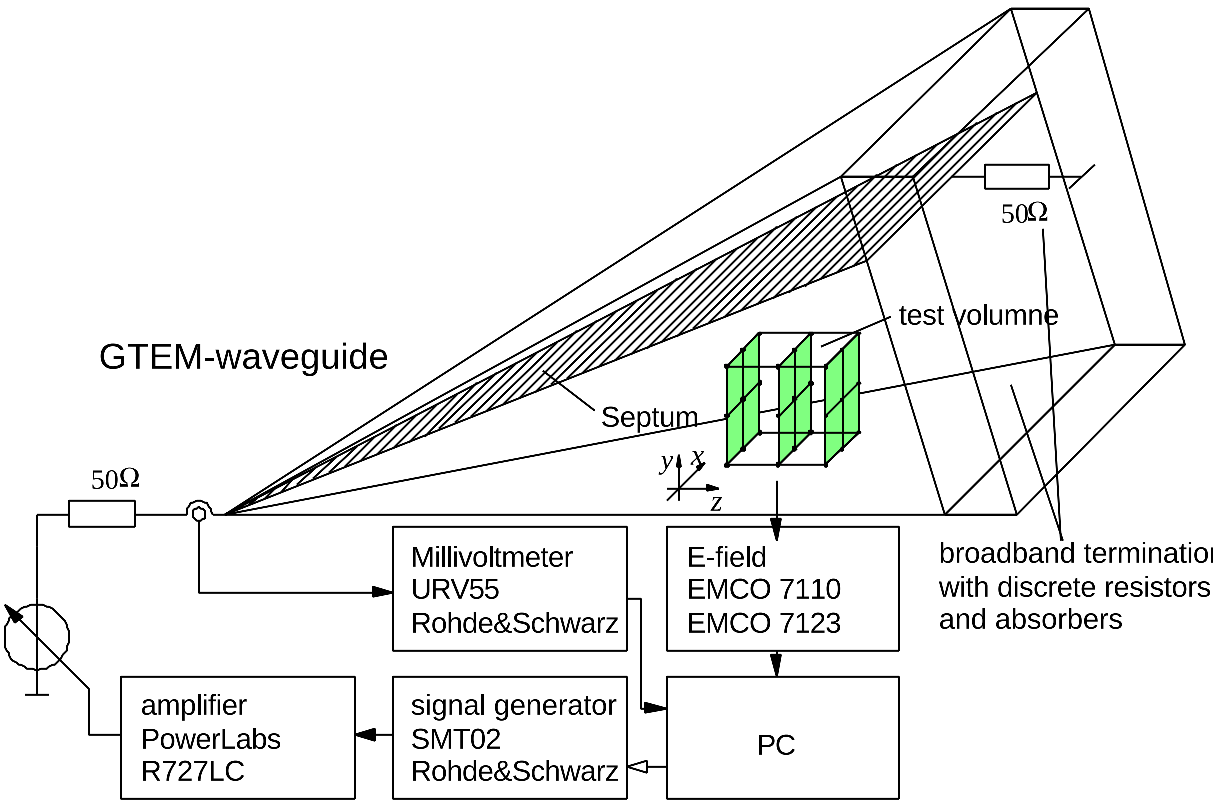


Fig. 10: Measurement equipment

Nine measurement points in one plane were chosen for each of the three arrangements and this plane was further considered. For the TEM cell, GTEM cell, G-Strip and MAC the frequency range 10 MHz to 1000 MHz was considered. The input voltage (fig. 10) was always set to 10 V.

	a / mm	b / mm
TEM	490	580
GTEM 500	450 +/- 40	460 +/- 50
GTEM 1250	1140 +/- 94	1160 +/- 94
G-Strip	350	660

MAC	225	450

Tab. 1: Dimensions of a and b

To judge the different TEM wave guide the results are displayed in the order as written in table 2.

Figure	Value	solid line	dashed line	Unit
a)	Measurement set-up			
b)	transversal depolarisation angle	a_t	$2 \cdot 1{,}15 \cdot s$	deg
c)	longitudinal depolarisation angle	a_l	$2 \cdot 1{,}15 \cdot s$	deg
d)	Field strength 75% interval	$\overline{E} + 1{,}15 \cdot s$	$\overline{E} - 1{,}15 \cdot s$	$dB \frac{mV}{m}$
e)	75% Interval in dB	$20 \log \frac{\overline{E} + 1{,}16s}{\overline{E} - 1{,}16s}$	6	dB

Tab. 2: Title of the measurement figures

The measurement results can be found in the annex of this paper.

5 Conclusion

Within this presentation it was is investigated how it could be determined whether a new proposed test site is equal to the old Open Area Test Site (OATS) or anechoic chamber (ALC). The general definitions from the standard will be clarified to allow a comparison between the test devices. This leads to the condition that a pure TEM wave must be generated on such a new test site. A new statistical approach characterising the field homogeneity was shown. The criterion "depolarisation angle" determines the dominant present of the TEM mode.

Under these assumptions TEM-, GTEM-, G-Strip and MAC-cells were tested. As a result the applicable frequency range for each test facility could be clearly identified.

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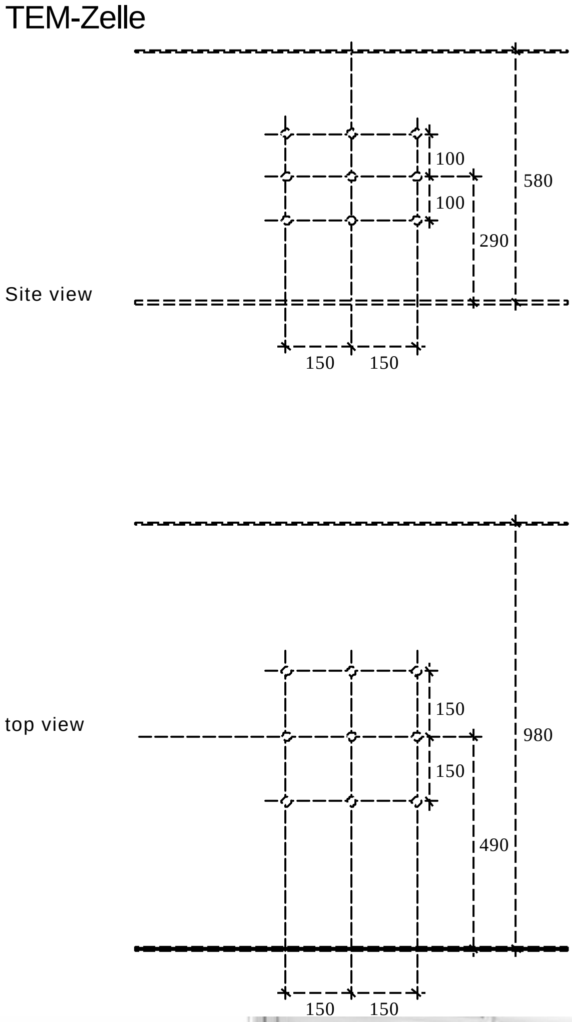
Annex

A TEM cell (Crawford type)



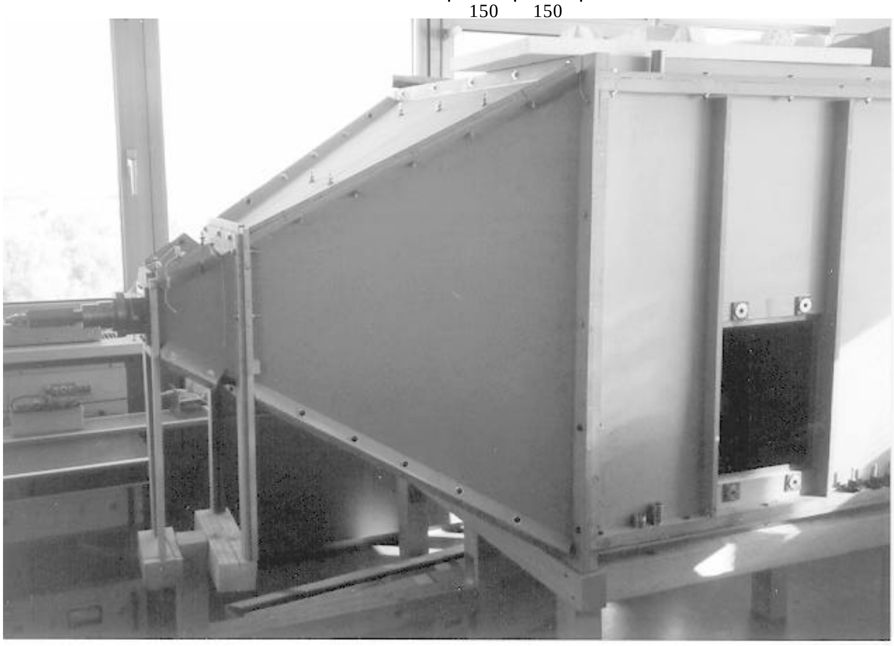


Fig. a: Measurement set-up

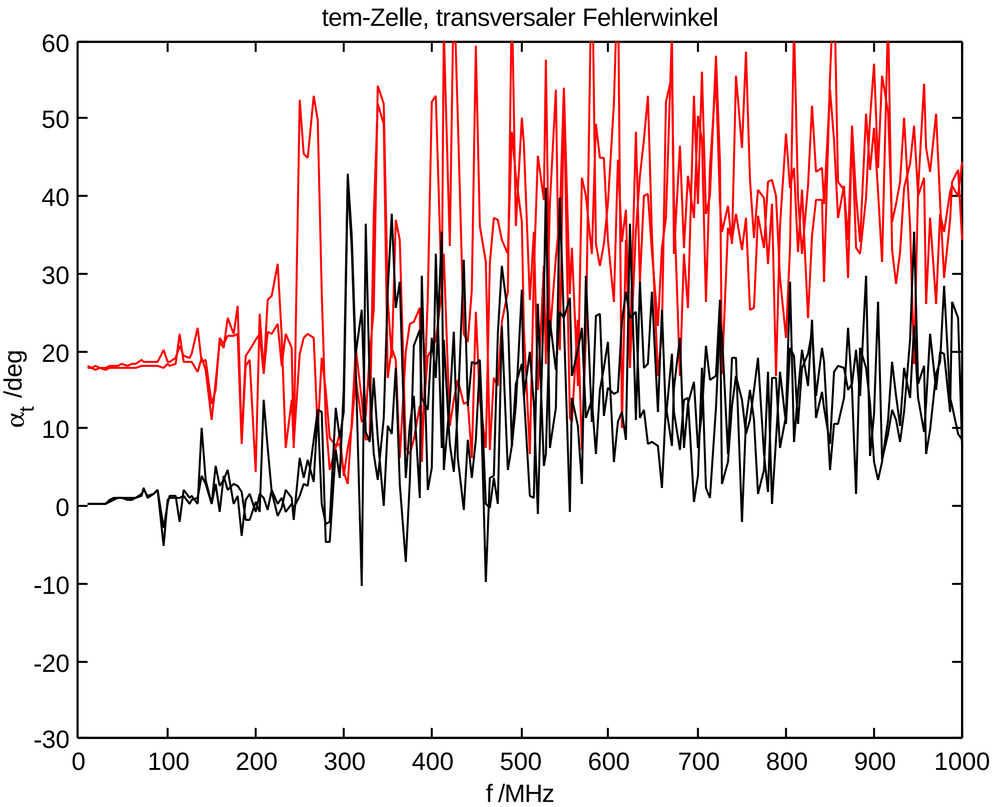


Fig. b: Transversal depolarisation angle

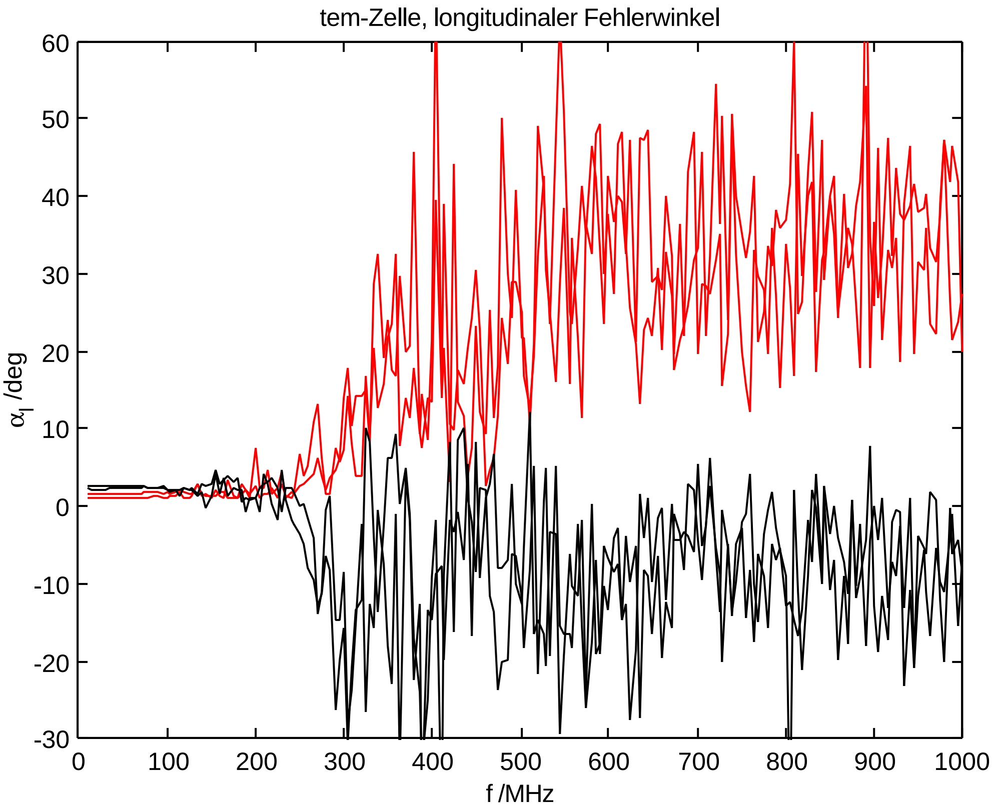


Fig. c: Longitudinal depolarisation angle

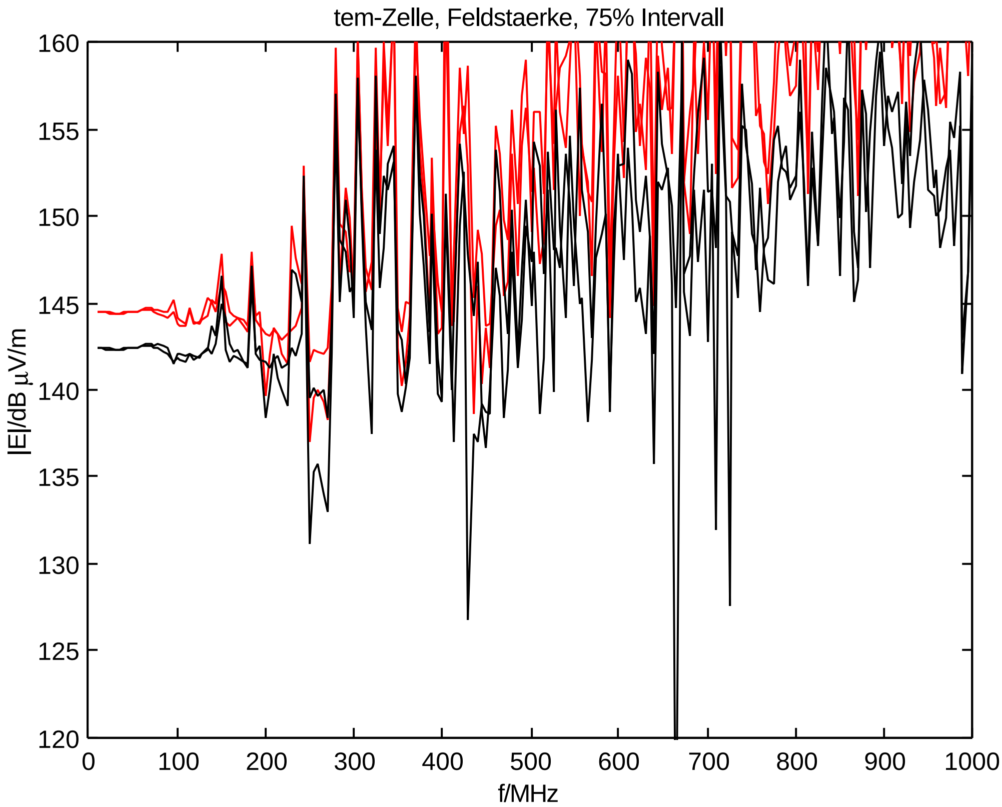


Fig. 11d: Field strength 75% interval

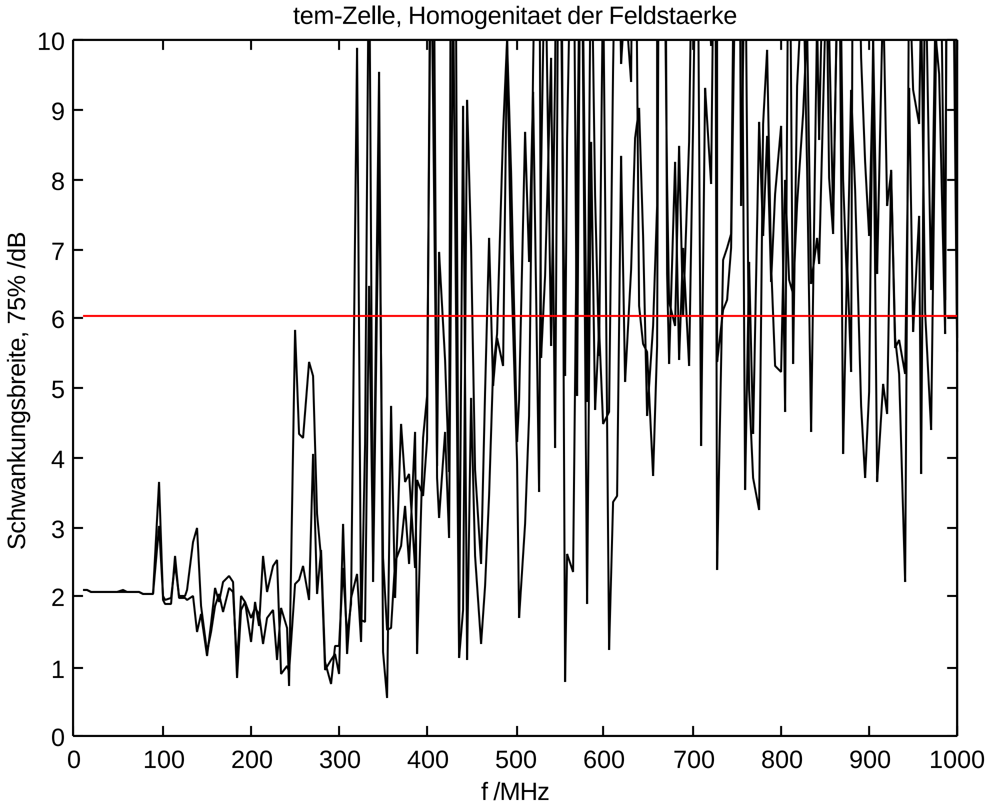


Fig. e: 75% Interval in dB

B GTEM 500

Fig. a: Measurement set-up

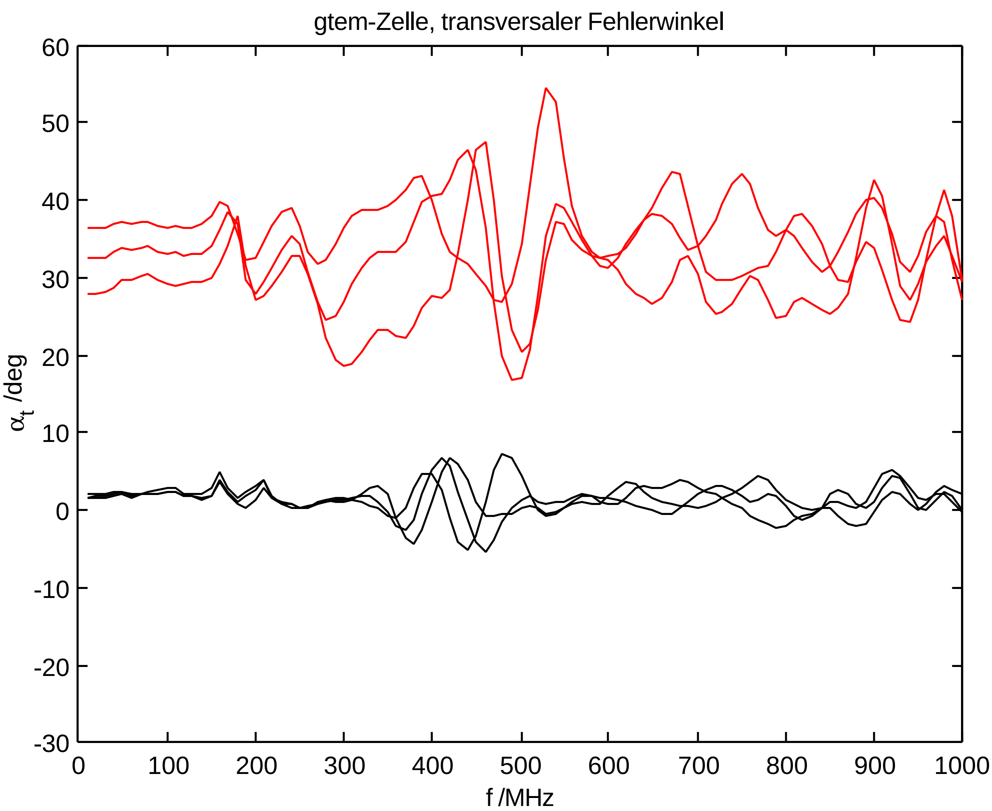


Fig. b: Transversal depolarisation angle

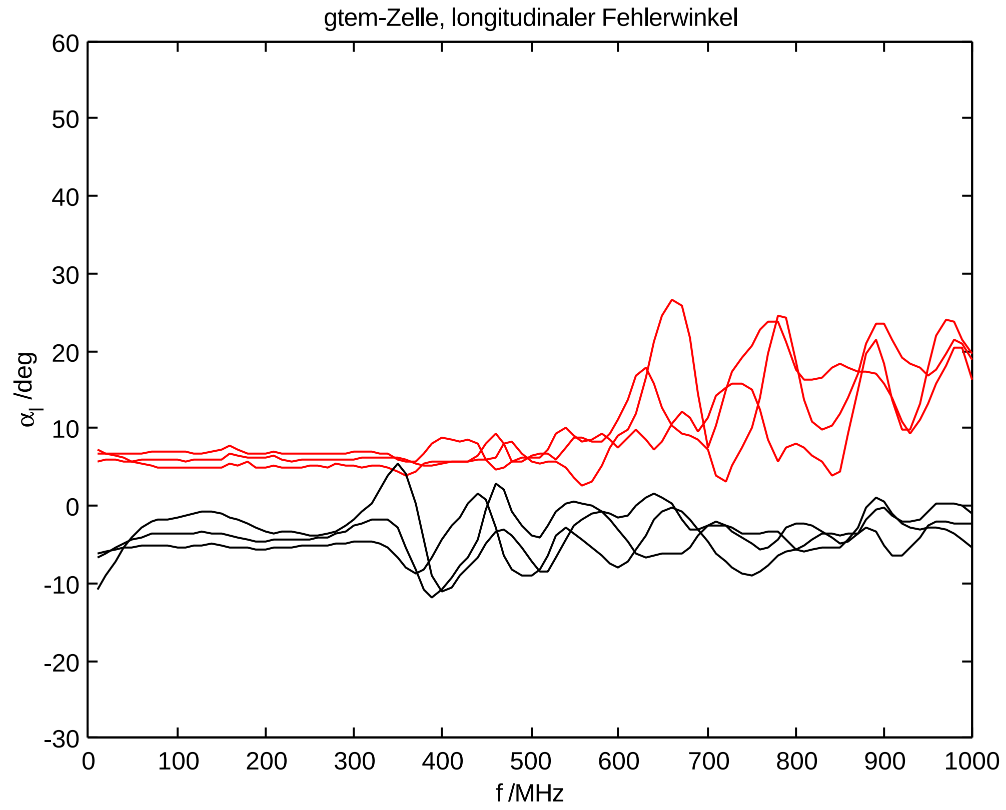


Fig. c: Longitudinal depolarisation angle

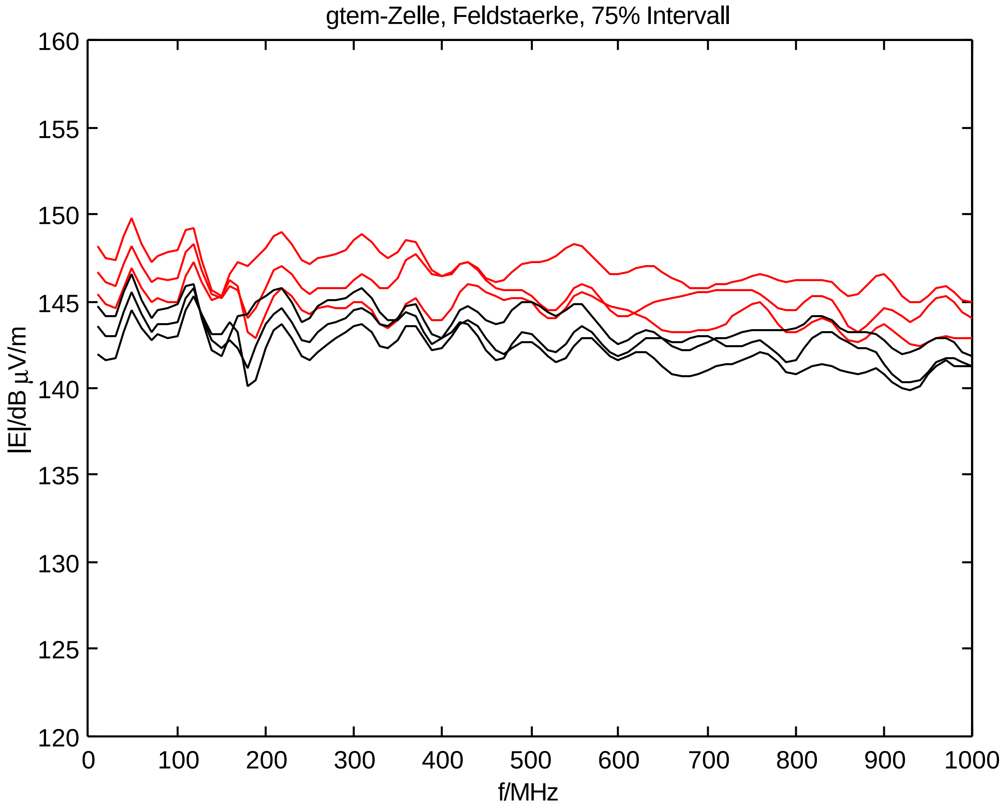


Fig. d: Field strength 75% interval

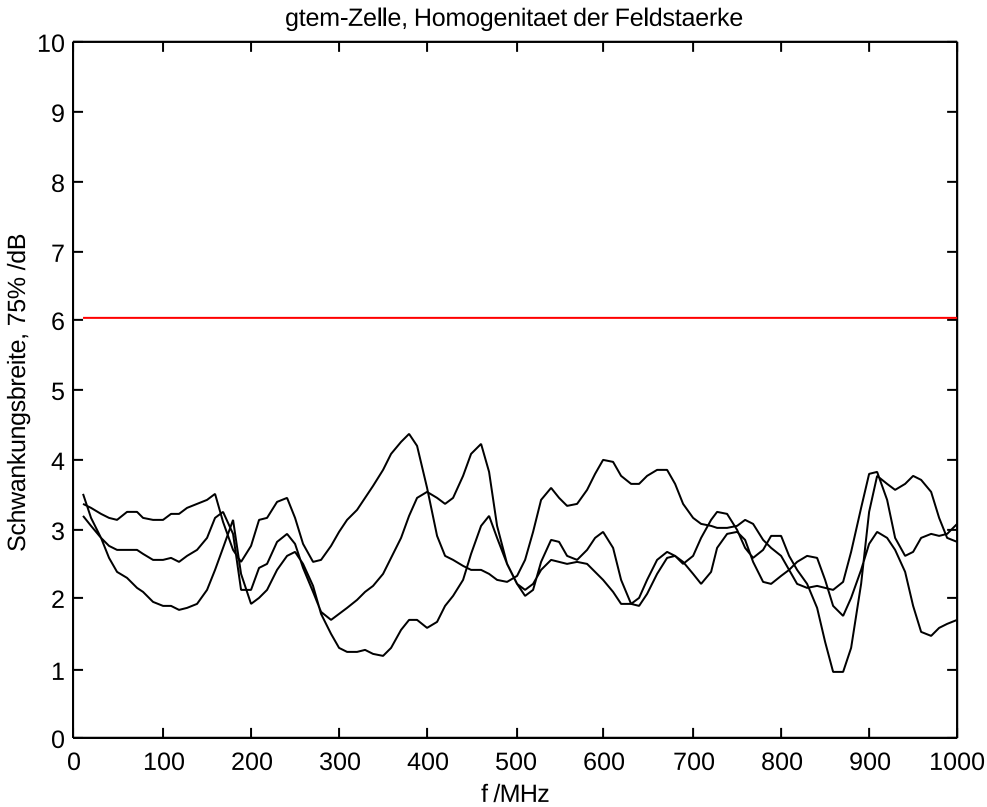


Fig. e: 75% Interval in dB

C GTEM 1250

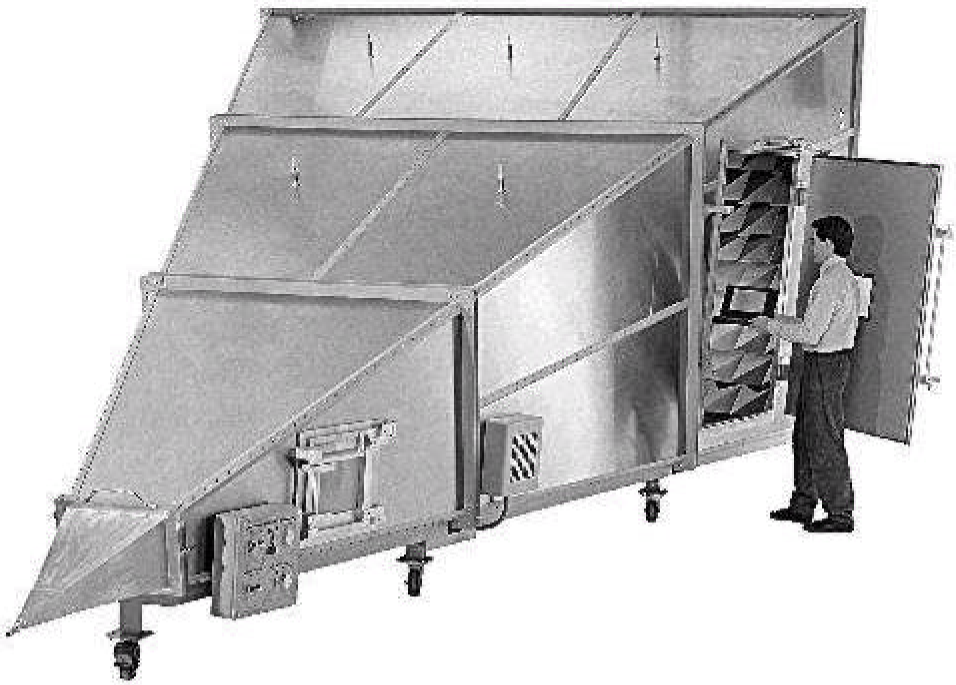


Fig. a: Measurement set-up

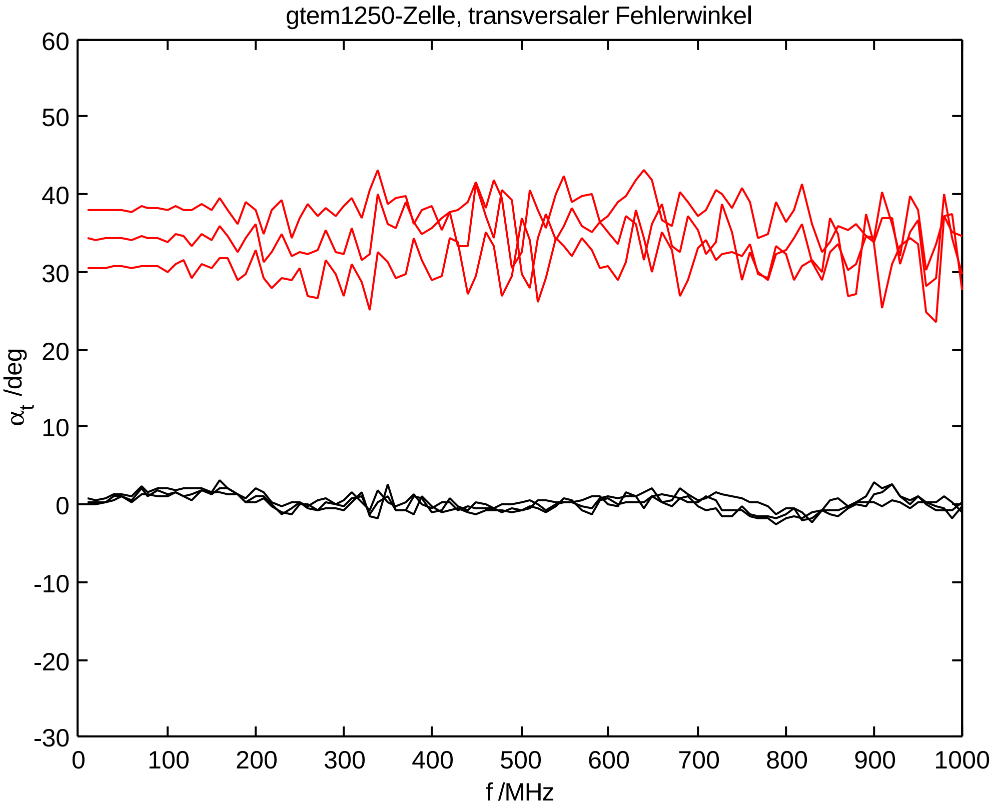


Fig. b: Transversal depolarisation angle

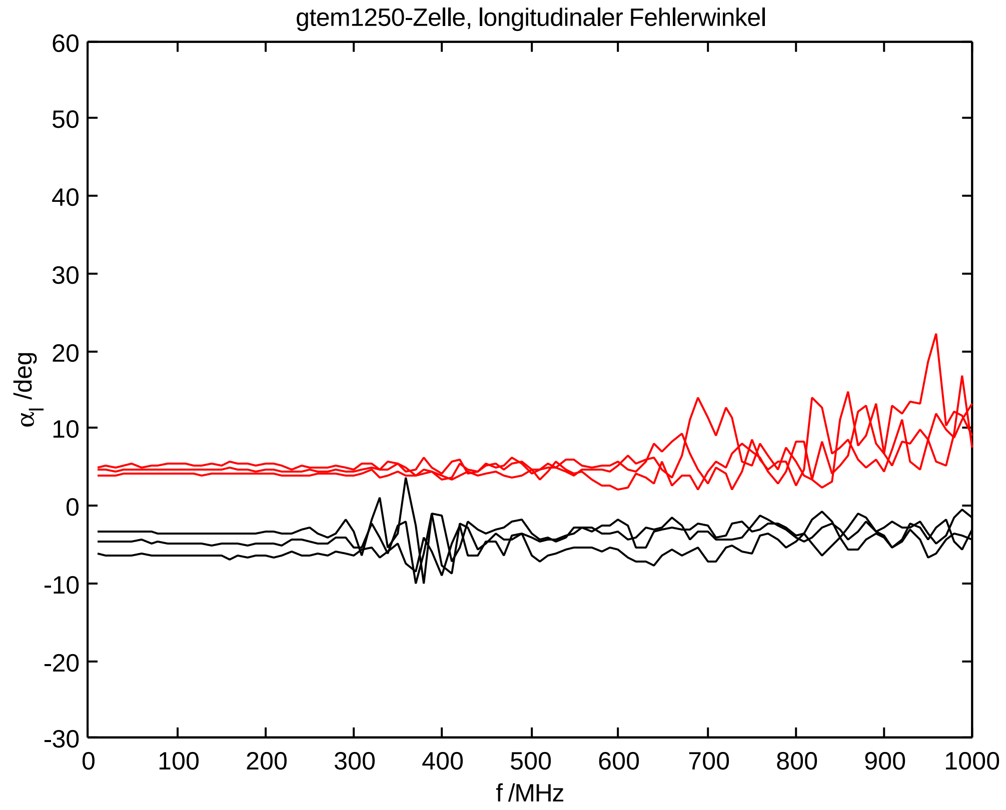


Fig. c: Longitudinal depolarisation angle

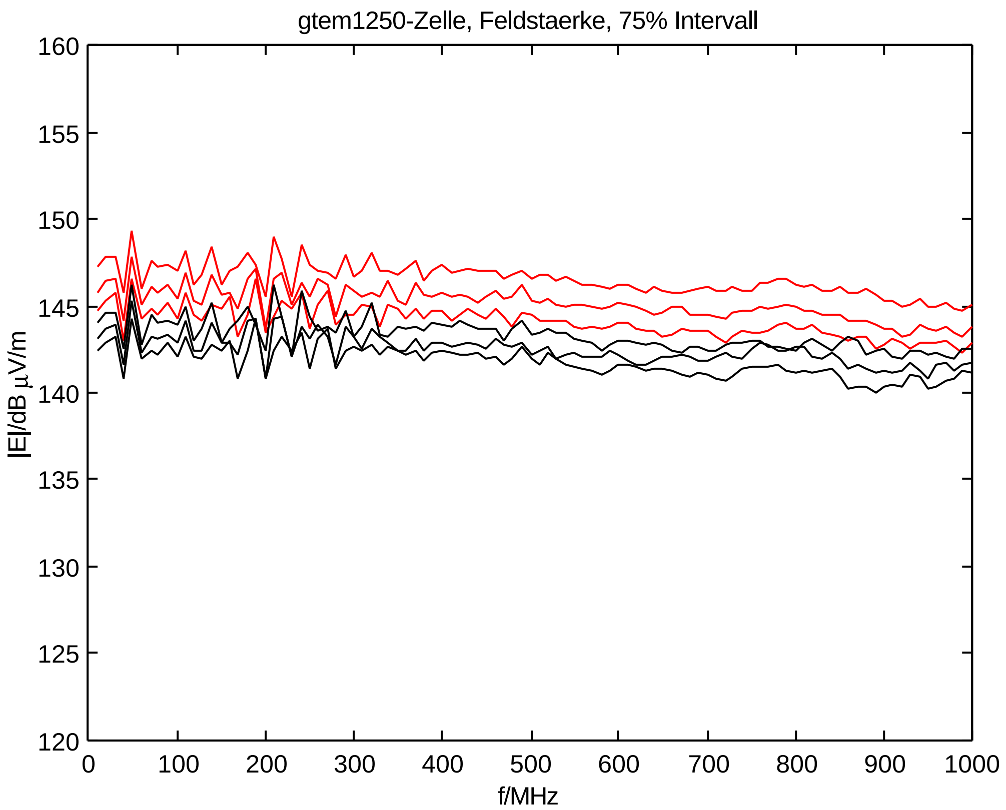


Fig. d: Field strength 75% interval

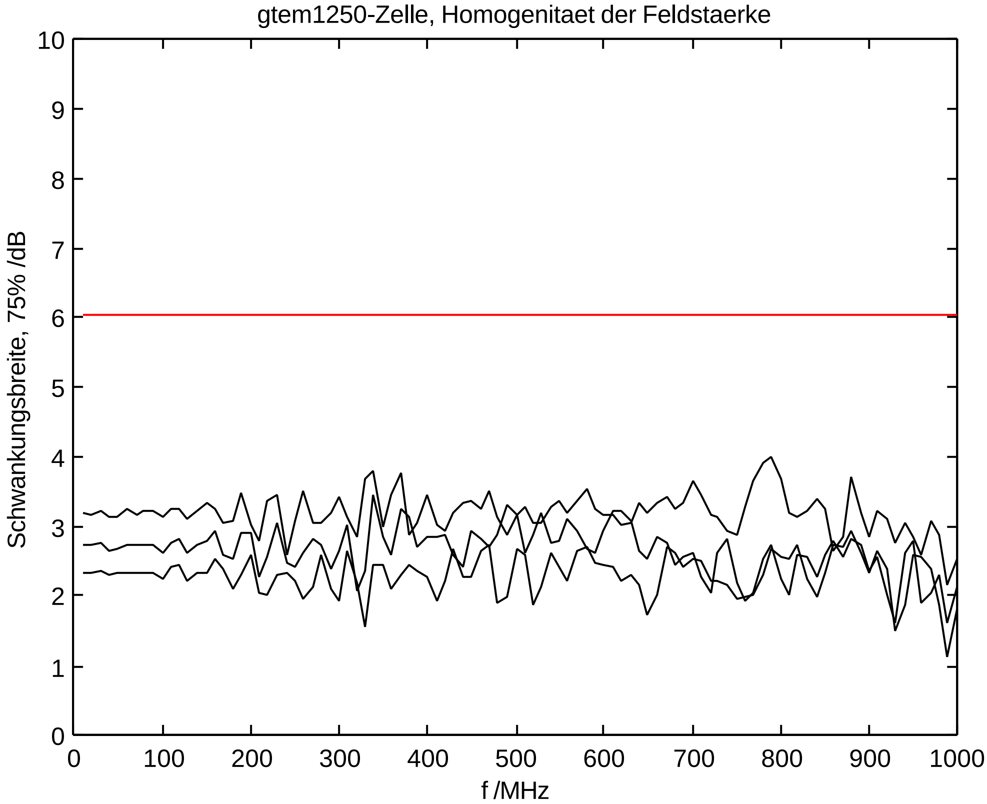


Fig. e: 75% Interval in dB

D G-Strip

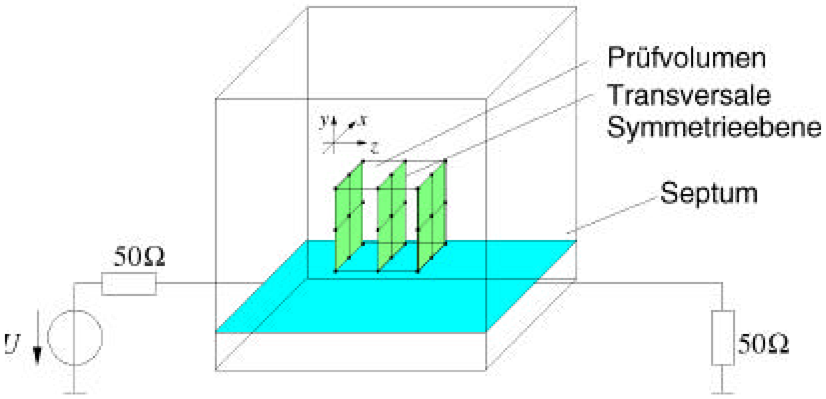


Fig. a: Measurement set-up

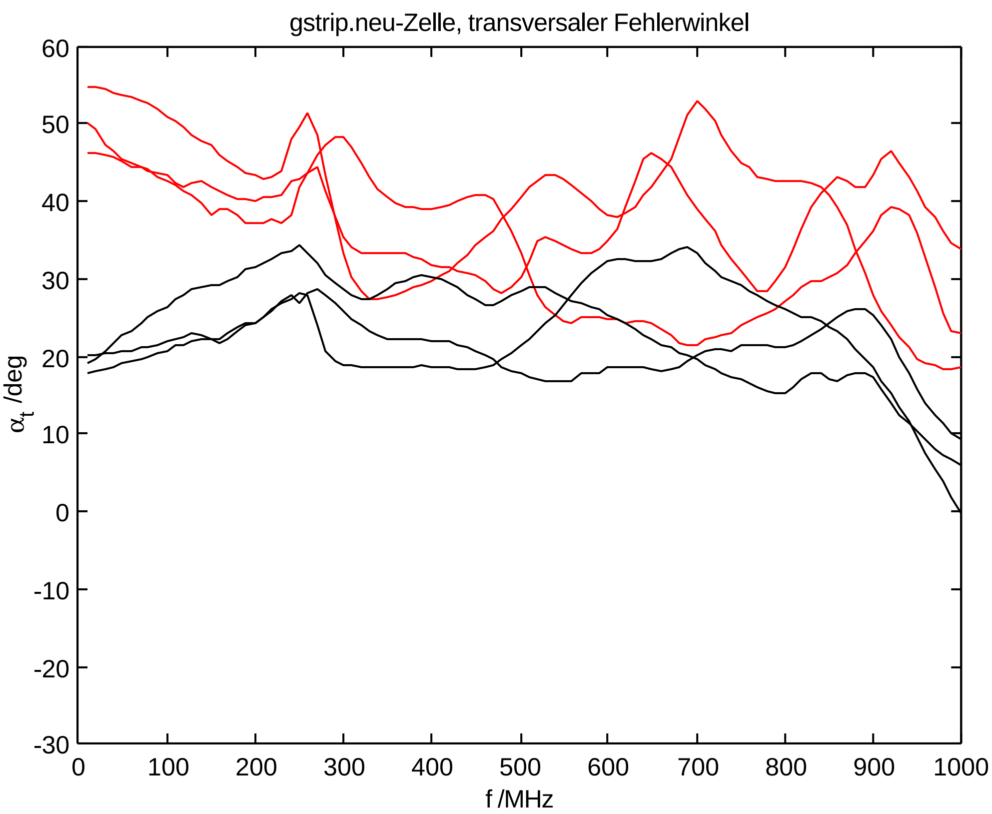


Fig. b: Transversal depolarisation angle

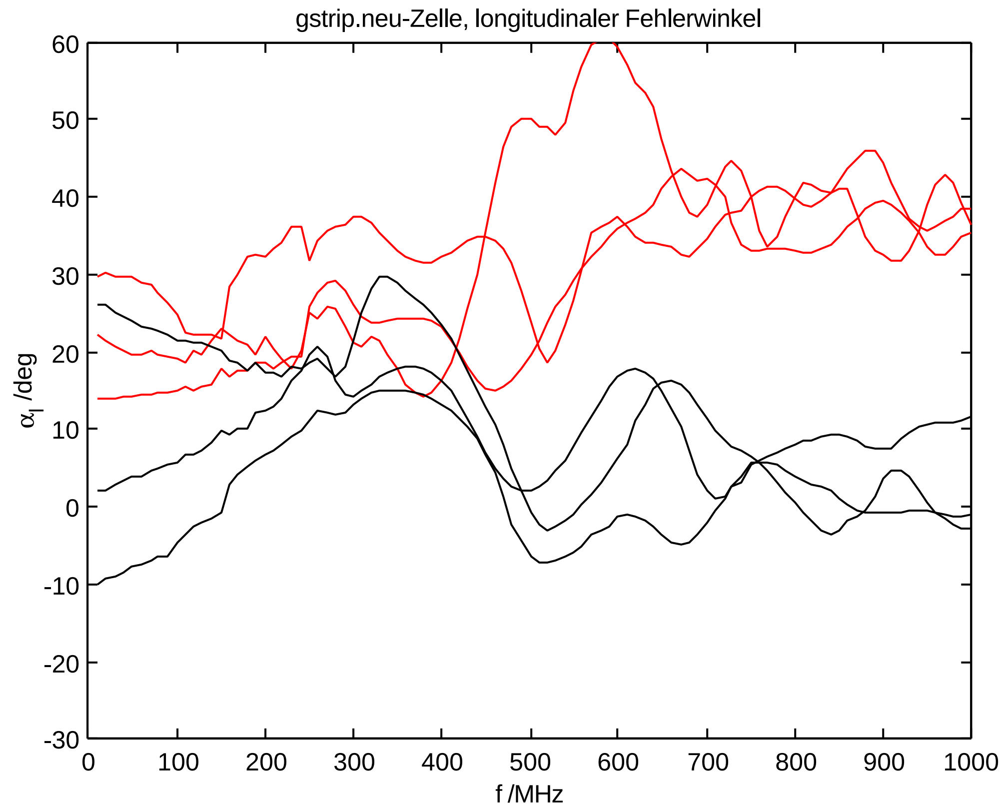


Fig. c: Longitudinal depolarisation angle

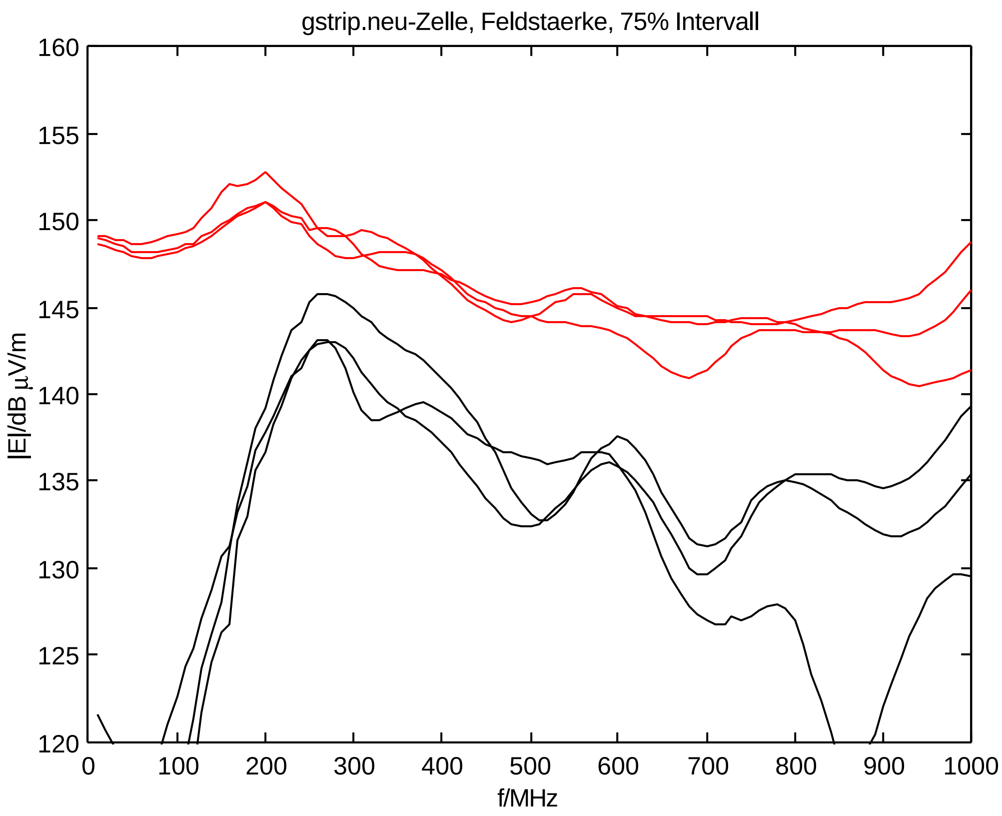


Fig. d: Field strength 75% interval

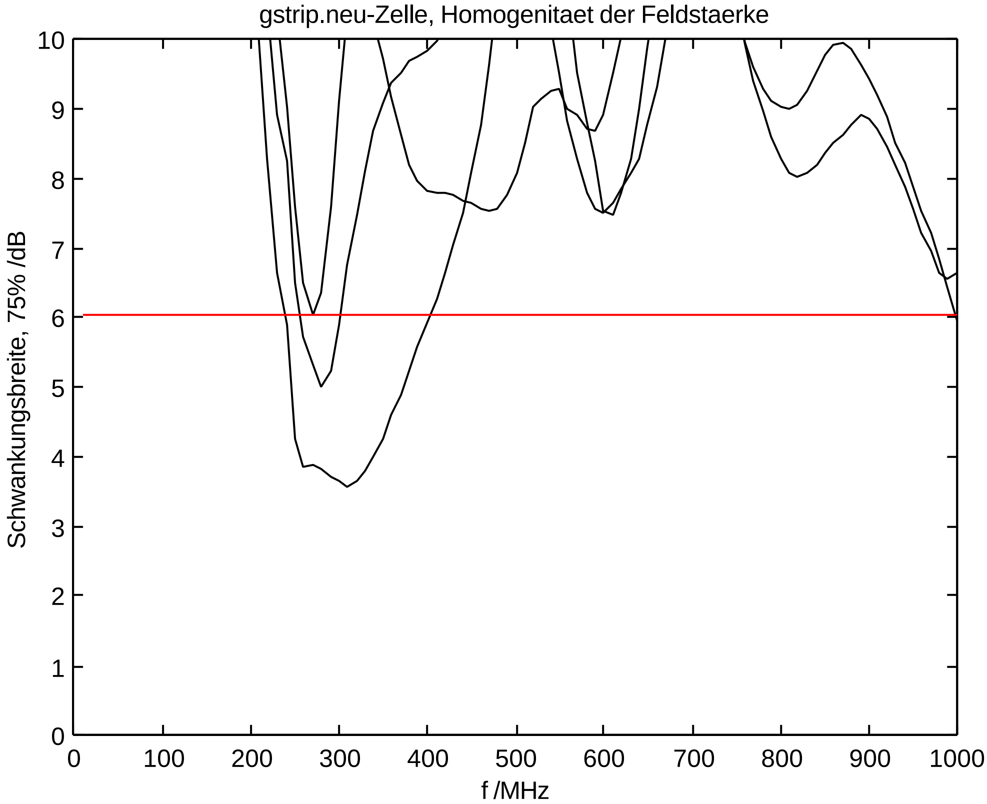


Fig. e: 75% Interval in dB

E MAC

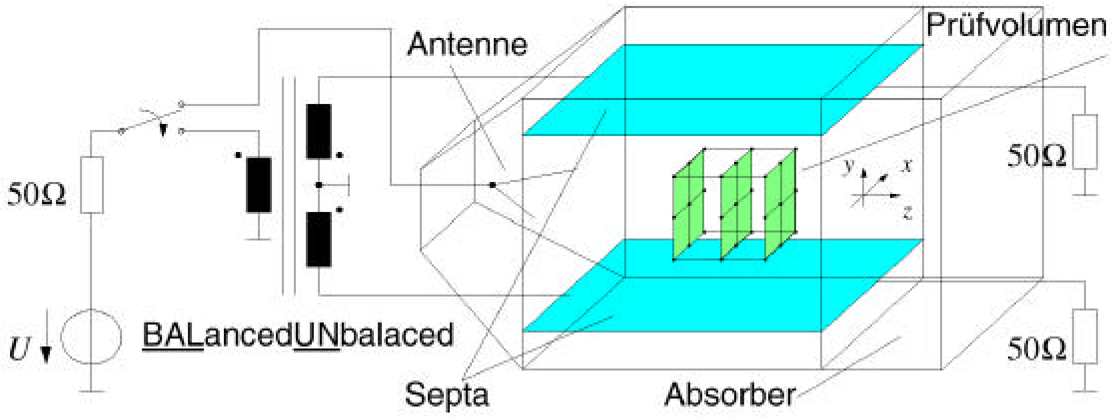


Fig. a: Measurement set-up

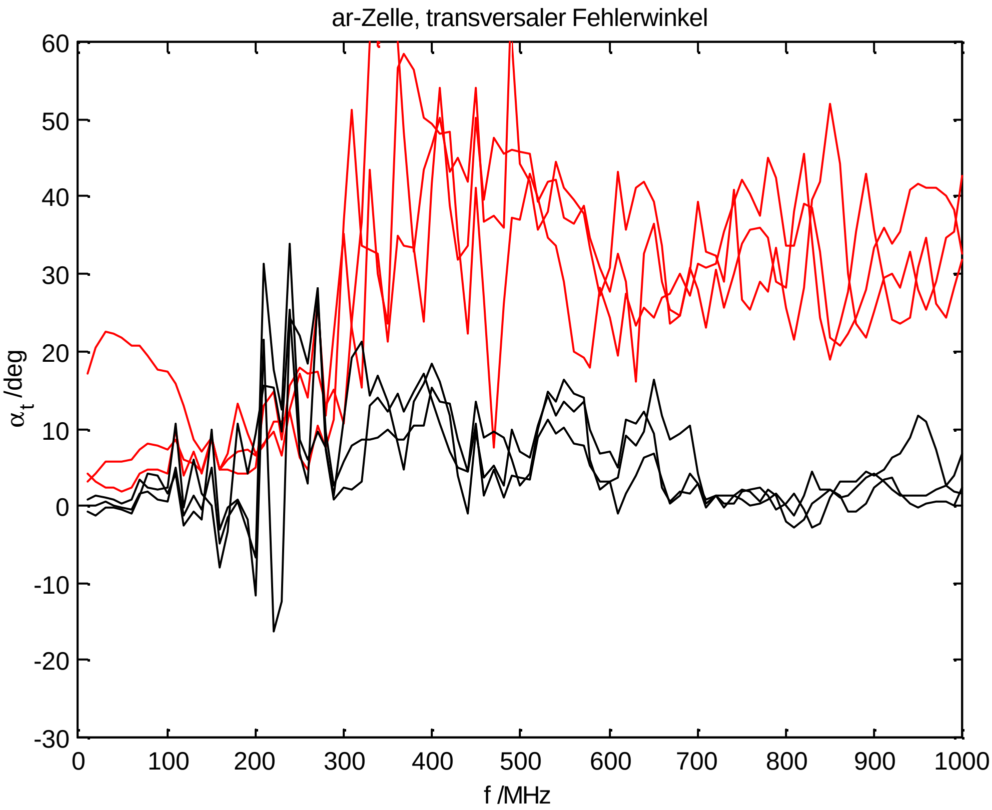


Fig. b: Transversal depolarisation angle

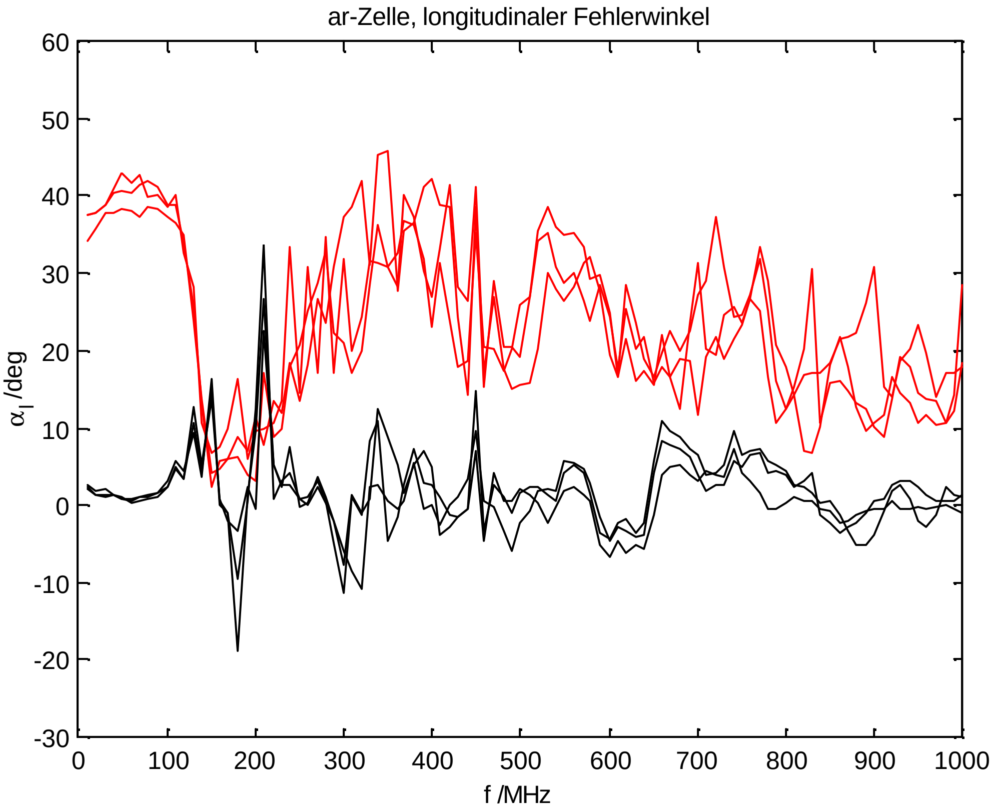
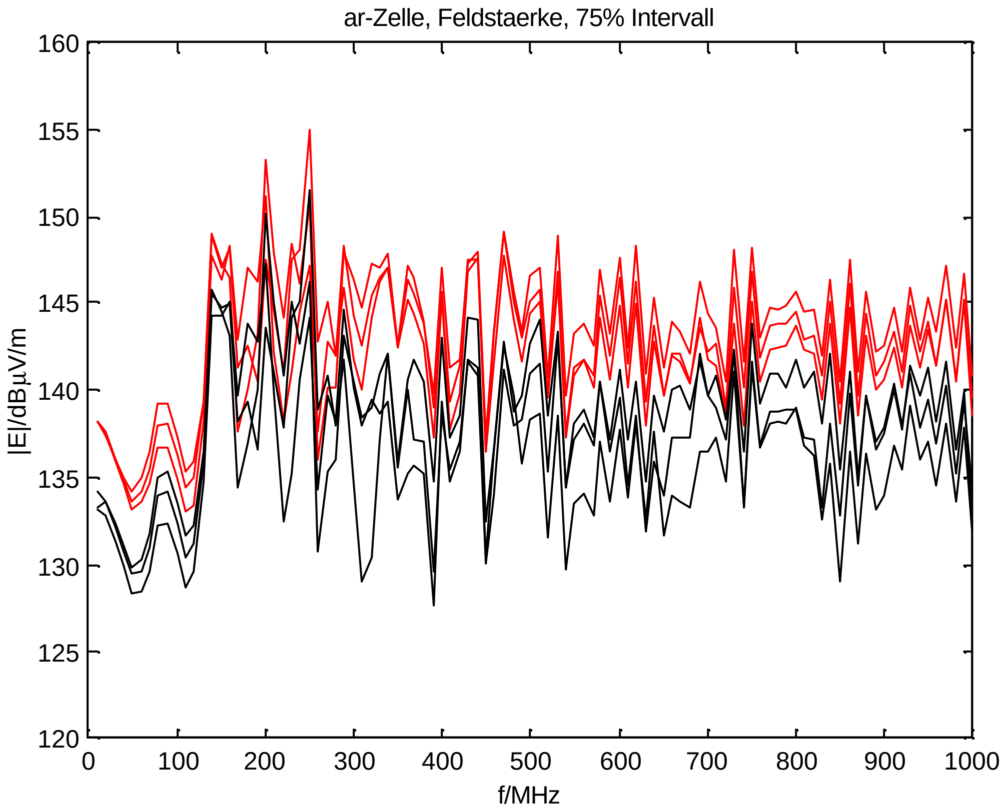


Fig. c: Longitudinal depolarisation angle



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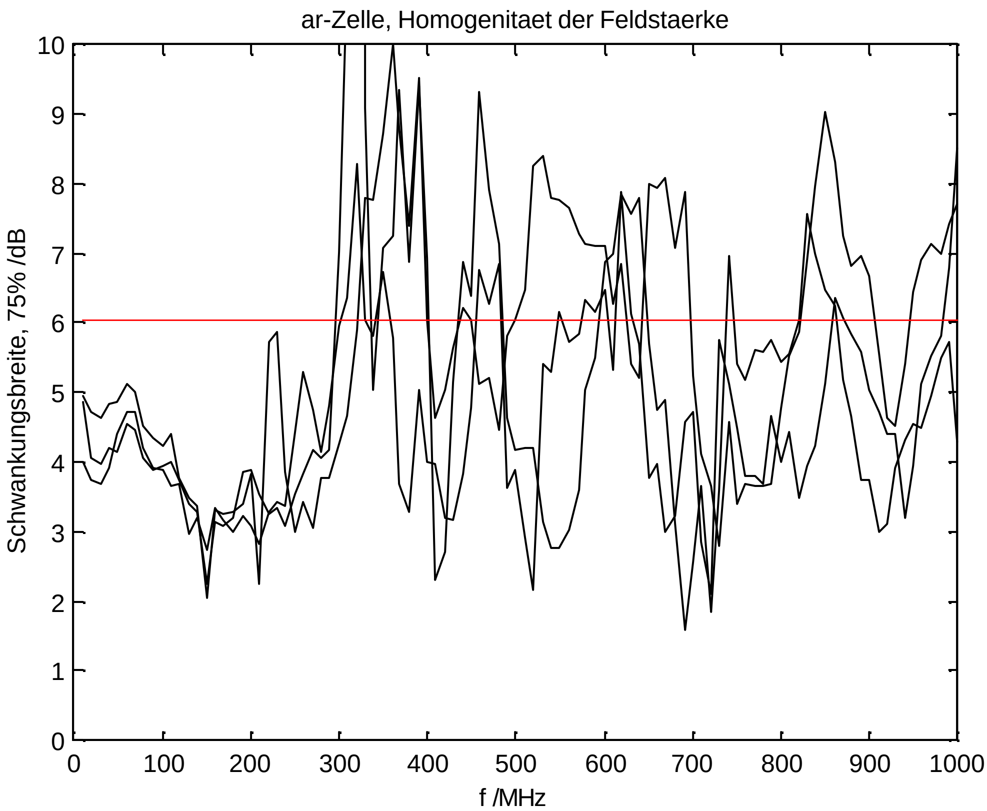

Fig. e: 75% Interval in dB