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in fixed radio systems for environmental issues

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Contents

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Transmission and Multiplexing (TM).

1 Scope

The present document provides guidelines on how to evaluate the electromagnetic fields in the main beam of fixed radio system (Point to Point / Point to Multipoint / Multipoint to Multipoint) using circular parabolic antennas for compliance assessment with human exposure limits.

The RTTE Directive article 3.1a [1], states health and safety as an essential requirement. 1999/519/EC [2] gives recommended limits for exposure to electromagnetic fields based on the ICNIRP guidelines [4]. The present document uses these exposure limits for comparison with calculations and measurements reported.

The methodology given is in line with EN 50383 [5] and may help in the compliance assessment of the above mentioned systems. Definitions from this standard are used in the present document where appropriate.

Sector antennas are under study and currently not included in the present document. The maximum power density evaluation is based on calculations and measurements performed with the most common configurations and the values are tabulated. The measurement and calculation results on real systems that have been used to establish the method are also provided to give an estimation on the accuracy of the method adopted.

2 References

For the purposes of this Technical Report (TR), the following references apply:

[1] Directive 1999/5/EC of the European Parliament and of the Council of 9 March 1999 on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity (RTTE-directive).

[2] Council Recommendation (1999/519/EC) of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz).

[3] Directive 2004/40/EC of the European Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields).

[4] ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz), Health Physics April 1998, Volume 74, Number 4:494-522.

[5] CENELEC EN 50383: (2002): "Basic standard for the calculation and measurement of electromagnetic field strength and SAR related to human exposure from radio base stations and fixed terminal stations for wireless telecommunications systems (110 MHz - 40 GHz)".

[6] ETSI EN 302 217-1: "Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 1: Overview and system-independent common characteristics".

[7] ETSI EN 302 326: "Fixed Radio Systems; Multipoint Equipment and Antennas".

[8] ETSI TR 102 243-1: "Fixed Radio Systems; Representative values for transmitter power and antenna gain to support inter- and intra-compatibility and sharing analysis; Part 1: Digital point-to-point systems".

[9] OET Bulletin No. 56: "Questions and Answers About Biological Effects Potential Hazards of Radiofrequency Electromagnetic Fields", (US-) Federal Communications Commission- Office of Engineering and Technology (OET) (4. Ed., August 1999).

[10] OET Bulletin No. 65: "Evaluating Compliance With FCC Guide lines for Human Exposure to Radio frequency Electromagnetic Fields", (US-) Federal Communications Commission- Office of Engineering and Technology (OET).

[11] IEEE Engineering in Medicine and Biology Magazine TECHNICAL INFORMATION STATEMENT ON: "Human Exposure to Microwaves and Other Radio Frequency Electromagnetic Fields", vol.14, 1995 no.3, p.336-337.

[12] IEEE Transact. EMC: "Rapid Calculation of Near-field Fluence of High Power Microwave Antennas".

[13] "Advanced engineering electromagnetics", Balanis.

[14] "Aperture Antennas and Diffraction Theory", Jull.

[15] "Electromagnetic Radiation from Selected Telecommunication Systems", Petersen.

[16] "Microwave Frequency Radiation Power Densities from 4 GHz and 6 GHz Radio Relay", Hathaway.

[17] "Circular-Aperture Axial Power Density", Hansen.

[18] "Avoidance of radiation hazards from microwave antennas", Shinn.

[19] Antennas and Propagation, IEEE Transactions on: "Measurements of Near-fields of Antennas and Scatterers", Dyson.

[20] "Antenna Power Densities in the Fresnel Region", Bickmore and Hansen.

[21] ETSI EG 202 373: "Electromagnetic compatibility and Radio spectrum Matters (ERM); Guide to the methods of measurement of Radio Frequency (RF) fields".

3 Definitions, symbols and abbreviations

3.1 Definitions

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

antenna: device that serves as a transducer between a guided wave (e.g. coaxial cable) and a free space wave, or vice versa

antenna gain: ratio of the maximum radiation intensity from an (assumed lossless) antenna to the radiation intensity that would be obtained if the same power were radiated isotropically by a similarly lossless antenna

basic restrictions: restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields that are based directly on established health effects

NOTE: In the frequency range from 110 MHz to 10 GHz, the physical quantity used is the specific absorption rate (SAR). Between 10 GHz and 300 GHz, the physical quantity is the power density.

Base Station (BS): radio base stations and/or fixed terminal stations intended for use in wireless telecommunications networks

compliance boundary: volume outside which any point of investigation is deemed to be compliant with exposure limits

NOTE: Outside the compliance boundary, the exposure levels do not exceed the basic restrictions irrespective of the time of exposure.

Electric field strength (*E*): magnitude of a field vector at a point that represents the force (*F*) on a positive small charge (*q*) divided by the charge

NOTE: Electric field strength is expressed in units of volt per metre (V/m).

Equivalent Isotropically Radiated Power (EIRP): product of the power supplied to the antenna and the maximum antenna gain relative to an isotropic antenna

NOTE: EIRP = G * P
where:
P is the emitted power;
G is the maximum gain of the antenna relative to an isotropic antenna

Equipment Under Test (EUT): device (such as transmitter, base station or antenna as appropriate) that is the subject of the specific test investigation being described

Point Of Investigation (POI): location in space at which the value of E-field, H-field, Power flux density or SAR is evaluated

NOTE: This location is defined in cartesian, cylindrical or spherical co-ordinates relative to the reference point on the EUT.

Power flux density (S): power per unit area normal to the direction of electromagnetic wave propagation

radio base station: radio base station, usually associated with the network, comprises the hardware, including transceivers, necessary to transmit and receive radio signals

NOTE: Radio base stations with integrated antennas, radio base stations with connectors for external antennas and radio base stations intended for use with external antennas not supplied by the same manufacturer are covered.
In EN 50383 [5], radio base stations are covered by the term "base station".

Radio Frequency (RF): for purposes of these safety considerations, the frequency range of interest is 110 MHz to 300 GHz

Specific Absorption Rate (SAR): time derivative of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of given mass density (ρ)

NOTE 1: $SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right)$

SAR is expressed in units of watt per kilogram (W/kg).

NOTE 2: SAR can be calculated by:

$$SAR = \frac{\sigma E_i^{\,2}}{\rho}$$

where:

E_i is rms value of the electric field strength in the tissue in V/m

σ is conductivity of body tissue in S/m

ρ is density of body tissue in kg/m^3

3.2 Symbols

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

ξ	Normalized variable for the antenna radius $\xi \in (0,1)$
γ	Factor for spatial averaging
λ	Wavelength (m)
η_A	Antenna aperture efficiency (see annex A, equation A.5)
a	Radius of the antenna (m), a=D/2
A	Geometric antenna aperture (m^2)
A_0	Reference area 20 cm^2 for spatial averaging
CD_{los}	Compliance distance in the line of sight
Din	Inner diameter of the antenna (m)
Dout	Outer diameter of the antenna (m)
E	Electromagnetic field (V/m)
G	Antenna gain
m_0	Reference mass 10 g for spatial averaging
P	Power transmitted by the antenna
r	Distance between the point of investigation and the antenna
R_{ff}	Far-field distance
R_{lim}	Extension of compliance bondary

S	Power density (W/m^2) at distance r (m) from the antenna
S_{ff}	Power density at a distance R_{ff} from the antenna
S_{lim}	Applicable legislation limit
S_{max}	Maximum power density spatially averaged over 20 cm^2
S_n	Power density normalized with P/D^2
SAR_{lim}	$_{10g}$ Applicable legislation limit
x	Ratio of distance to the antenna (r) and R_{ff}

3.3 Abbreviations

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

BS	Base Station
CAD	Computer Aided Design
EIRP	Equivalent Isotropically Radiated Power
EMC	ElectroMagnetic Compatibility
EUT	Equipment Under Test
FCC	Federal Communications Commission
MoM	Method of Moments
PO	Physical Optics
POI	Point Of Investigation
RF	Radio Frequency
SAR	Specific Absorption Rate

4 Some properties of fixed radio systems

4.1 General

4.1.1 Frequency bands

Frequency bands for the fixed radio systems range from 1,4 GHz up to 58 GHz and beyond. Details are given in EN 302 217-1 [6] and EN 302 326 [7].

4.1.2 Transmit power levels

Transmit power levels are in general determined by EIRP restrictions or power flux density restrictions. Thus the restrictions are placed for a combination of transmit power and antenna gain. Representative values can be found in TR 102 243-1 [8].

4.1.3 Antennas

4.1.3.1 Directive antennas

This class of antennas are generally used to send and/or receive a signal from a single location.

The most common antenna type is a parabolic dish antenna. Prominent characteristics are high directivity and low radiation outside the main beam direction.

For the purpose to calculate the maximum power flux density from these antennas only a few parameters are needed like transmitted power, frequency, antenna diameter, aperture efficiency and antenna gain.

4.1.3.2 Sectorial antennas

This class of antennas are generally used for multipoint central stations to send a signal to (or to receive a signal from) multiple locations. Typical sectorial coverage is 90 degrees. Sectorial antennas are not in the scope of the current document.

4.2 Point-to-point communication systems

Point-to-point communication systems are installed in towers, masts, on rooftops or in similar locations. The main design criteria consists in having the two locations in line of sight, so there is no possibility that some building be "crossed" by the radio signal, since, in such case, an attenuation would be produced and the connection would not work properly.

Outdoor units and antennas are normally required to be inaccessible by the general public to prevent intentional or unintentional damage to the equipment or to the radio link. This establishes a special condition for these systems: unavailability of the radio path for the general public.

4.3 Multipoint communication systems

Multipoint communication systems are communication systems between multiple (source) accesspoints and a single (destination) accesspoint for bi-directional asymmetric, bi-directional symmetric, or unidirectional communication. Multipoint communication systems are installed in towers, masts, on rooftops or in similar locations.

5 Antenna properties

5.1 Near-field - Far-field concept

A very common subdivision of the space surrounding an antenna consists in defining two regions of space, called "near-field" and "far-field".

Although there are not sharp boundaries between these regions, the near-field is the region of space nearest to the antenna, where the wave is still nearly plane, like in the aperture. The "far-field" region is assumed to start in a location of the space, where the wave can be considered as a spherical wave and free space conditions can be adopted.

For the parabolic reflector, a common shape of reflector that is frequently met on microwave antennas, the lower boundary of near-field region is situated at a distance R_{nf} from the antenna given by the formula $R_{nf} = D^2/2\lambda$ (called Rayleigh distance), where D, R_{nf} and λ are respectively the antenna diameter, the near-field distance and the wavelength. At this distance the degradation of the main beam is moderate low, but the gain is reduced.

For the same type of reflector, the far-field limit (R_{ff}), is assumed at a distance equal to $R_{ff} = 2D^2/\lambda$, (called Fraunhofer distance) where D, R_{ff} and λ are respectively the antenna diameter, the far-field distance and the wavelength.

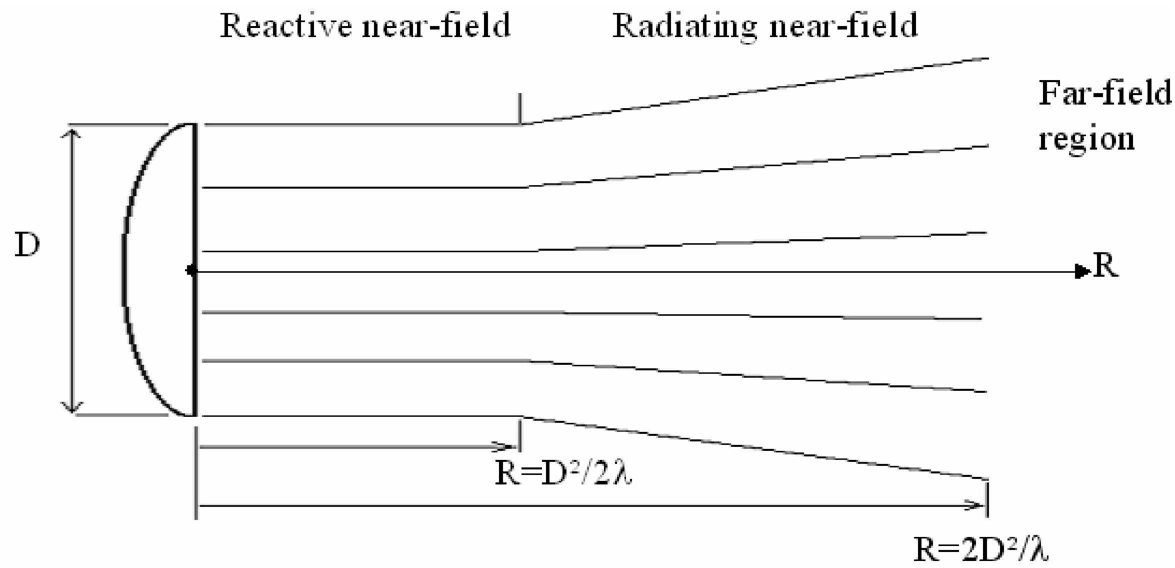


Figure 5.1: Near-field / far-field representation

5.2 Emission parameters

The parameters needed for calculations are:

- antenna gain;
- transmission power at antenna input port;
- transmission frequency;
- the antenna radiation pattern;
- the antenna diameter (in case of parabolic reflector). The inner diameter is defined as the diameter within the shroud. Because of the plastic cover or radome used in such antennas, this inner diameter can not always be evaluated. In this case, the outer diameter can be used for assessment.

5.3 Parameter description

The physical entities that are normally used on behalf of electromagnetic field exposure are the following:

- **S**: Power Density.
- **E**: Electric field strength (rms).

In the present document, the power density is used to represent the magnitude of the electromagnetic field.

5.4 Relationship between parameters (V/m, W/m^2)

Starting from the lower limit of radiative field (min (3λ, $2D^2/\lambda$)) S, E are related by the following formulae:

$$S\ (W/m^2) = E\ (V/m)^2/120\pi$$

5.5 Variation with distance and power

The power density in the far-field region is inversely proportional to the square of the distance from the antenna. Thus the power density decreases very fast with the distance and the highest levels are expected to appear in the near-field of the antenna. The near-field power density, however, oscillates with distance between maximas and minimas depending on the frequency and the antenna diameter.

The power density is directly proportional to the transmitted power level and any measurements or calculations can easily be scaled to a specific power level.

The effect in the far-field of having more than one transmitter on a single antenna is equivalent to having one single transmitter with a power equal to the sum of the power of all (uncorrelated) transmitters independent of the frequency and polarization (two transmitters of power P will produce the same electric field of a single transmitter of power 2P). Due to the oscillating behaviour with distance, the power density in the near-field is generally not proportional to the sum of the transmitted power unless the frequencies are very close to each other.

6 Exposure limits

The evaluation of compliance boundary should be based on the relevant exposure limits in the country where the equipment is put on the market and/or put into service. The following clauses recall the exposure limits defined in 1999/519/EC [2] and in Directive 2004/40/EC [3] which are used as references in the European commission mandates M.305 and M.351 respectively. These limits for exposure levels are in line with the ICNIRP Guidelines [4] and expressed in terms of basic restrictions and reference levels which depend on the frequency (f) of emissions.

6.1 General public exposure

Basic restrictions for the general public:

- For 10 MHz < f < 10 GHz the Specific Absorbtion Rate is used. Localized SAR limit: SAR_{lim10g} = 2 W/kg.
- For f > 10 GHz the power density is used. S_{lim} = 10 W/m^2.

Reference levels for the general public:

- For 2 GHz < f < 300 GHz the power density is used. S_{lim} = 10 W/m^2.

6.2 Occupational exposure

Exposure limit values:

- For 10 MHz < f < 10 GHz the Specific Absorbtion Rate is used. Localized SAR limit: SAR_{lim10g} = 10 W/kg.
- For f > 10 GHz the power density is used. S_{lim} = 50 W/m^2.

Action values:

- For 2 GHz < f < 300 GHz the power density is used. S_{lim} = 50 W/m^2.

7 Calculations and measurements of power density

7.1 General

This clause covers calculations and simulations of power density in the far-field and in the near-field. The calculations are backed with measurements for a number of parabolic dish antennas. Based on the results an upper bound for the power density is formulated.

7.2 Far-field power density

The calculation of the far-field power density is straight forward and is based on an isotropic radiator. The power density in the far-field is given by:

$$S = \frac{PG}{4\pi r^2} \tag{7.1}$$

Knowing the power density S_{ff} at distance R_{ff} the equation (7.1) reduces to:

$$S = S_{ff}\left(\frac{R_{ff}}{r}\right)^2 \tag{7.2}$$

This method is equivalent to the far-field model in clause 8.3.2 of EN 50383 [5]. The far-field equation over estimates the power density in the near-field region as can be seen in the graphs in annex A.

Inserting equation (A.4) from clause A.1.2 in (7.2) gives the power density S_n normalized to P/D_2 where η_A is given by equation (A.5) in clause A.1.2.

$$S_n = \frac{\pi\eta_A}{16}\left(\frac{R_{ff}}{r}\right)^2 \tag{7.3}$$

7.3 Near-field power density

Calculation of the near-field power density is in general complex and requires knowledge of the field distribution in the aperture plane. Approximations are available and an upper bound can be formulated to cover antennas under consideration. The methods described below are equivalent to the synthetic model in clause 8.3.3 of EN 50383 [5].

Annex A outlines the method and gives examples of calculations for some aperture distributions. The calculations are made for circular apertures for a single linear polarization and gives the result on axis.

Simulations and measurements of near-field power density are presented in annex B.

Clause B.1 reports near-field FEKO simulations and measurements of a 0,24 m 38 GHz antenna.

Clause B.2 reports near-field FEKO simulations and measurements of a 0,6 m 8,1 GHz antenna.

Clause B.3 reports simulations and measurements of power density on parabolic antennas from 5 to 38 GHz.

Clause B.4 reports simulations of a 1,2 m 8 GHz antenna and a 1,2 m 13 GHz antenna.

Conclusions from these simulations and measurements are:

- The simple equations 7.1 to 7.3 overestimate the power density very close to the antenna.
- The envelope template proposed in clause 7.4 overestimates the simulation and measurement results provided in annexes.
- The compliance boundary is contained in a cylinder with diameter D in the direction of the principal axis.
- Spatial averaging over 20 cm^2 reduces the peak values close to the antenna by about 1 dB at high frequencies.
- Since power density measurement without shroud overestimates power density measurement with shroud, it is recommended not to include the antenna shroud in the simulation model.
- Simulation accuracy strongly depend on the chosen mesh.

7.4 Power density upper bound

According to the series of measurement and simulation results presented in annexes, the upper bound of the power density in the near-field in the main lobe of the antenna is defined by the following envelope template.

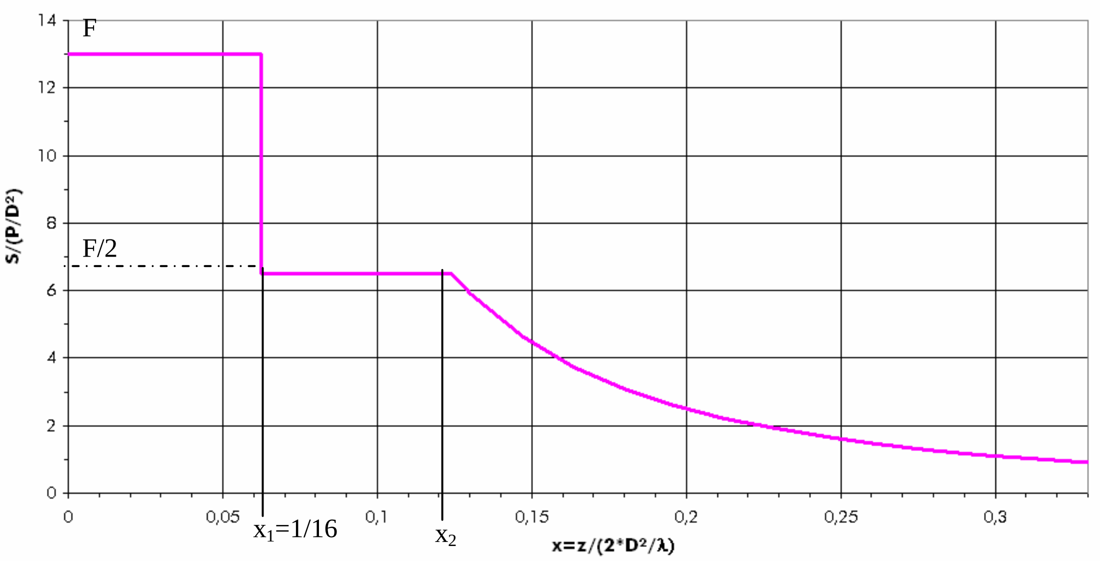


Figure 7.1: Envelope template for the power density in the main lobe of parabolic antennas

Where:

- F=13 if the following formulas are based on the inner diameter and F=15 if the following formulas are based on the outer diameter of the antenna.
- D is the diameter of the antenna (either Din or Dout).
- $R_{ff} = \frac{2D^2}{\lambda}$.
- χ_1 corresponds to the first zero for a uniform taper using Fresnel transform (cf. annex A, clause 1.4.1).
- $\chi_2 = \frac{\lambda}{4D}\sqrt{\frac{2 \cdot 10^{G/10}}{F\pi}}$ with D and G expressed in meter and dBi respectively. X_2 is also given using the formula $\chi_2 = \sqrt{\frac{\pi\eta_A}{8F}}$; with η_A = 0,5 and F = 13 and $\chi_2 = 0.12$.
- Values $x \geq x_2$ are equivalent to $S_n \leq F/2$ and R_{lim} is calculated alternatively from equations (7.1), (7.2) or (7.3).

8 Assessment of compliance to limits

8.1 General

1999/519/EC [2] and the Directive EMF at work [3] define limits as basic restrictions and reference levels. Basic restrictions are based on established health effects and biological considerations while reference levels are defined for practical exposure-assessment purposes to determine whether the basic restrictions are likely to be exceeded.

Basic restrictions below 10 GHz are expressed as SAR-values whereas power density is used for frequencies above 10 GHz. Reference levels are expressed as power density from 2 GHz to 200 GHz that covers almost all frequencies used for fixed radio services. Thus compliance to the basic restrictions can be achieved by compliance to the reference levels throughout that frequency range. In cases where necessary the basic restrictions can be used below 10 GHz to demonstrate compliance.

NOTE 1: The reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded.

NOTE 2: For frequencies between 10 and 300 GHz, the basic restriction is the power density averaged over 20 cm² provided that spatial maximum power density, averaged over 1 cm² do not exceed 20 times the averaged value.

8.2 Compliance boundaries evaluation

Compliance boundaries shall be evaluated according to the flowchart presented in figure 8.2, which applies to both general public and occupational exposure situations. They are based on the following assumptions:

- Compliance touch means that exposure limits are not exceeded while touching the radome of the equipment under test.
- The coefficient γ (0,8) relates to the 1 dB attenuation due to spatial averaging in a plane perpendicular to the antenna main direction, according to EU recommendation and ICNIRP applicable limits between 10 GHz and 300 GHz.
- The compliance boundary, if not zero, is a cylinder defined by the line of sight axis and the diameter Dout up to the compliance distance CD_{los} (cf. figure 8.1).

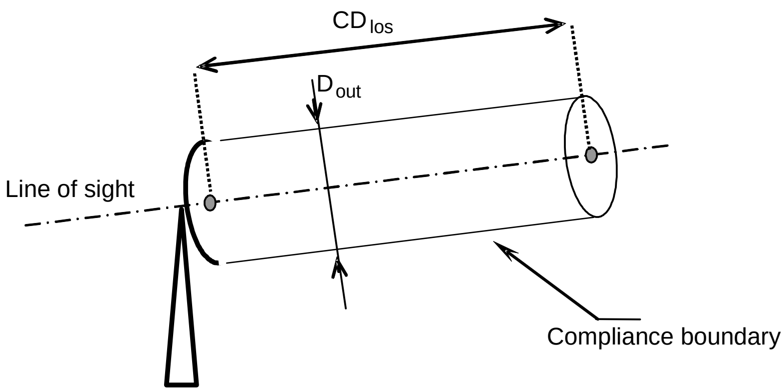


Figure 8.1: Transmitter compliance boundary

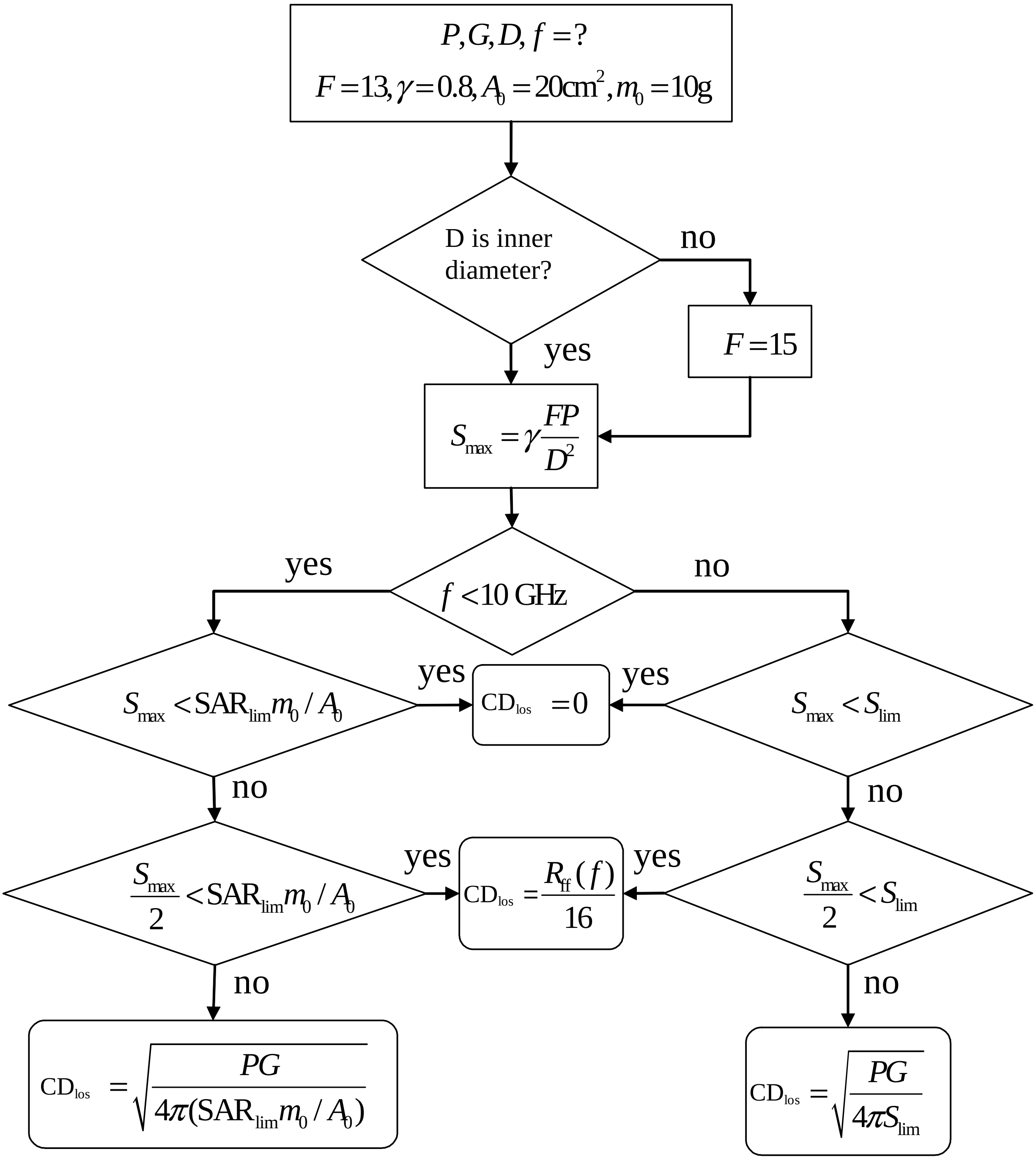


Figure 8.2: Flowchart for the evaluation of compliance distance in the line of sight of parabolic antennas

8.3 Tabulated values

Compliance distances for typical systems defined in TR 102 243-1 [8] are provided in table 8.1 based on the equations provided in figure 8.2. These power levels are considered typical highest for real equipment and when combined with typical smallest antennas an almost worst case scenario is achieved.

Table 8.1: Evaluation of compliance distance for the general public for some typical classes of transmitters

System type	Frequency (GHz)	Power (dBm)	Antenna inner diameter (m)	CD_{los} (m)
C1	6	32	1.8	0
B2	8	32	1.2	4.8
D1	18	27	0,6	2,7
E1	23	25	0,3	3,2
E3	38	23	0,2	1,6
E1 (see note)	23	25	1,2	0
E3 (see note)	38	23	0,6	0
E7	55	9	0,1	0
NOTE: Following typical maximum antenna gain values given in TR 102 243-1 [8], type E1 and E3 are respectively considered with 47 dBi and 45 dBi antenna gain.				

Figure 8.3 gives a graphic view of the equations given in the flowchart considering spatial averaging with the limit 10 W/m^2 according to 1999/519/EC [2]. Combinations of power and antenna inner diameters below the lower line have a zero compliance distance. Between the lines the compliance distance is given by χ_1 and above the upper line the compliance distance is given by equations (7.1), (7.2) or (7.3). Dots in the figure represent the data in table 8.1.

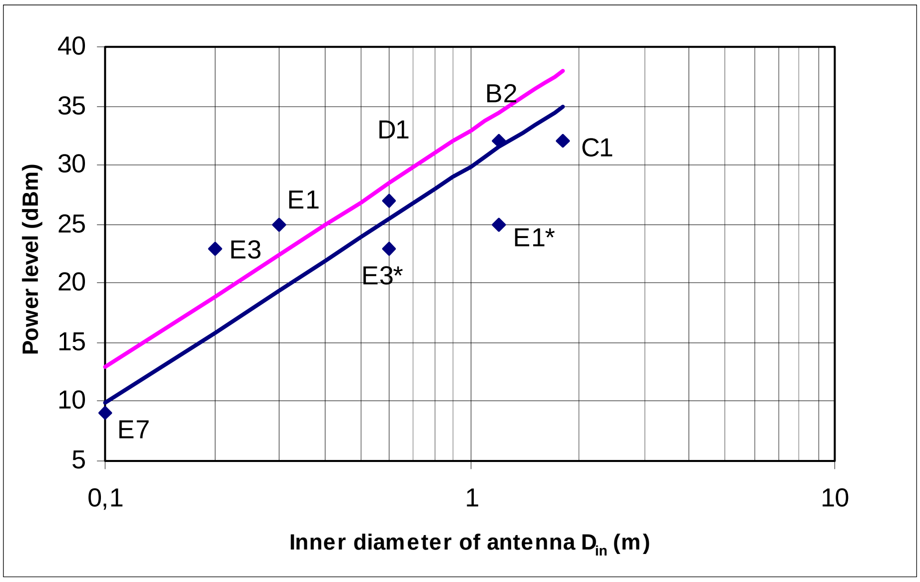


Figure 8.3: Graphical assessment of compliance boundary

Figure 8.4 relates the compliance distance corresponding to χ_1 versus frequency and antenna size with the limit 10 W/m^2.

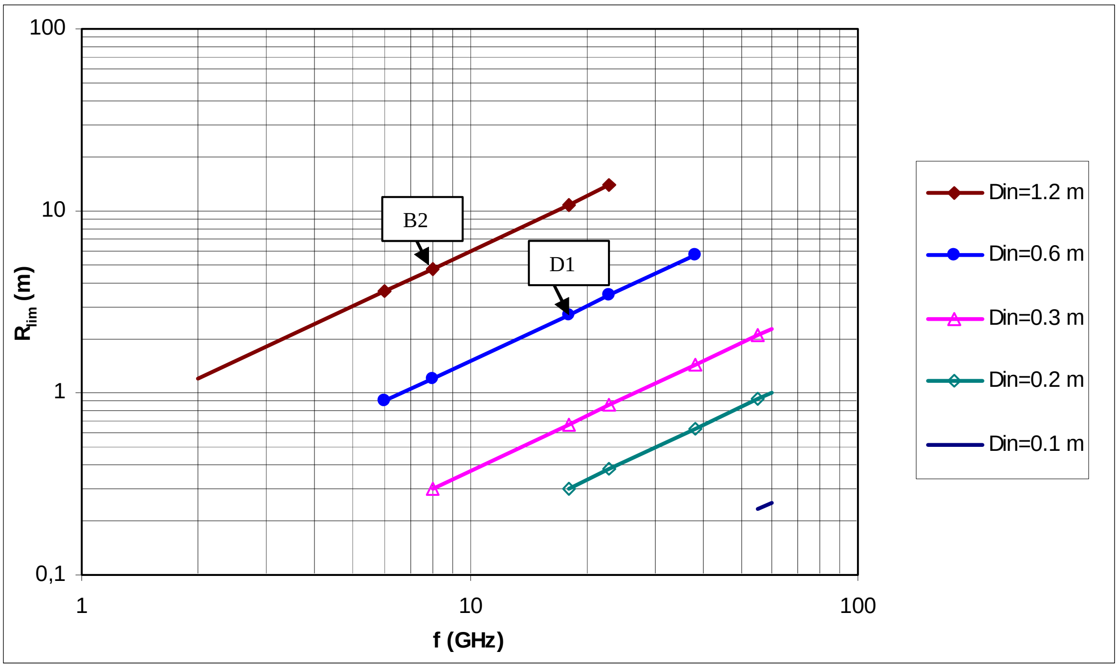


Figure 8.4: Limit distance versus frequency for 0,1 m to 1,2 m antennas

Annex A: Power density calculations

A.1 Near-field calculations using the Fresnel transform

The near-field high frequency limit field on the axis is expressed via the Fresnel transform (Jull 1981 p.32 [14], Bickmore/Hansen 1959 [20] and Hansen 1976 [17]). For finite frequencies the result is a lower power density. The full Maxwell solution is found in e.g. Balanis [13]. According to Hansen-Libelo 1992 [12] the Fresnel transform yields accurate results on the principal axis and for small angular deviations.

The calculations are made for circular apertures for a single linear polarization and only the power density on the principal has been calculated.

A.1.1 Region of validity

The Fresnel Transform is used to calculate the near-field on the principal axis, not too close to the antenna. The validity of this method is discussed in e.g. IEEE Transact. EMC vol. 34 [12] and Jull Edvard J. [14]. The Fresnel transform is an approximation in two respects, namely:

- high frequency $D \gg \lambda$;
- first order correction to the far-field source-to-field point distance.

The first point makes it suitable for large antennas, and in addition the finite frequency results yield lower peak values due to an additional taper effect. Thus, the Fresnel transform is suitable for compliance assessment issues, since only the largest possible values are of interest.

The second point reveals a lack of validity near the antenna where measurements and/or simulations must be regarded.

A.1.2 Scaling factors

The radial distance on the principal axis is scaled with far-field distance:

$$r = xR_{ff} \quad \text{(A.1)}$$

where:

$$R_{ff} = \frac{2D^2}{\lambda} \quad \text{(A.2)}$$

The power density is normalized to power and diameter of the aperture.

$$S_n = \frac{S}{P / D^2} \quad \text{(A.3)}$$

For a circular aperture the power density at x=1 is

$$S_{ff} = \frac{PG}{4\pi(2D^2/\lambda)^2} = \frac{4\pi A\eta_A P/\lambda^2}{4\pi(2D^2/\lambda)^2} = \frac{\pi P\,\eta_A}{16D^2} \qquad \text{(A.4)}$$

where $\eta_A \leq 1$ is the aperture efficiency and calculated as:

$$\eta_A = \frac{G\lambda^2}{\pi^2 D^2} \qquad \text{(A.5)}$$

The interpretation of aperture efficiency is a reduction of effective antenna aperture (effective antenna diameter) due to decreasing illumination towards the rim of the antenna dish. This gives a lower gain of the antenna in the far-field as can be seen from equation (A.4) but has the opposite effect in the near-field. A smaller antenna produces a higher peak value as can be seen comparing e.g. figures A.1 and A.2.

A.1.3 Electric field calculation

The electric field is calculated on the principal axis under the assumption that $\frac{D}{\lambda} >> 1$

$$E_f(x) = const\,\frac{1}{x}\int_0^1 E_a(\xi)e^{-j\left(\frac{\xi^2}{8x}\right)}\xi.d\xi \qquad \text{(A.6)}$$

E_a is the electric field distribution over the antenna aperture. The constant is evaluated knowing the power density at normalized distance $x = 1$ given by equation (4).

A.1.4 Results

The overall trend is that an increased taper (lower aperture efficiency) seems to concentrate the field in a smaller area, and thereby the power density increases.

A.1.4.1 High frequency approximation

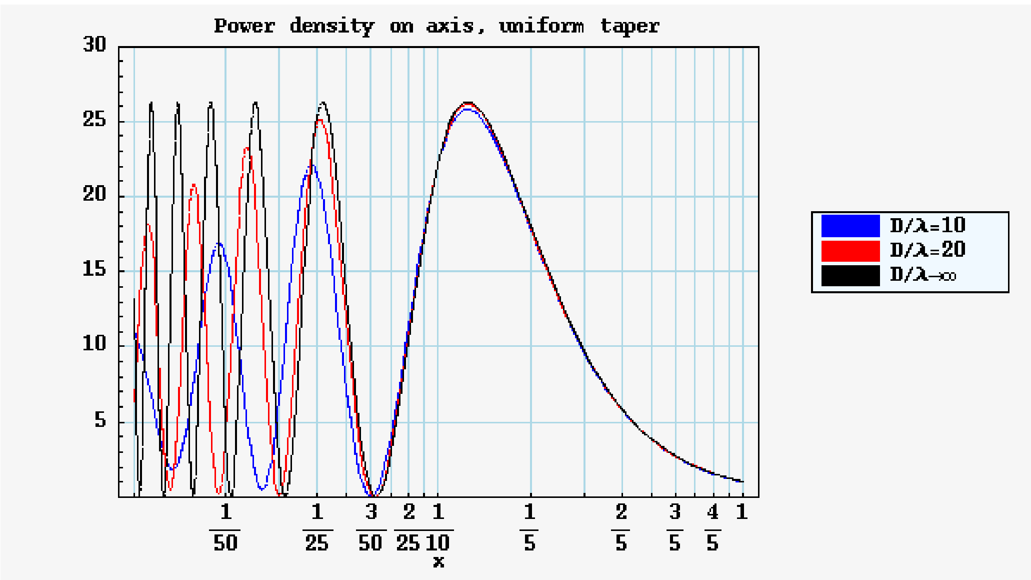


Figure A.1: The Fresnel transform (black curve) compared to exact results using finite frequencies (red and blue curves)

NOTE: Clearly the highest peaks are found in the Fresnel transform. Similar results are obtained for other tapers.

For the uniform taper there is a closed form solution for the power density s = 1 on the principal axis

$$s(x) = \frac{1-\cos(\pi/8x)}{1-\cos(\pi/8)} \quad \text{(A.7)}$$

Note, the normalization to unity at x = 1 following Bickmore and Hansen [20]. Moreover, the Fresnel zones are manifest and distinct with boundaries (the zeros or local minima of equation (A4)) at:

$$x = \frac{1}{16n} \quad \text{where} \quad n = 1,2,... \quad \text{(A.8)}$$

The first zero (n = 1) is chosen as a breakpoint in the proposed near-field envelope template, see clause 7.4.

A.1.4.2 Results using realistic tapers

For comparison the upper bound proposed in clause 7.4 is included in the figures.

The parabola on a pedestal, see figure A.2.

$$E(\rho) = a + (1-a)(1-(\rho/a)^2)^N \quad \text{(A.9)}$$

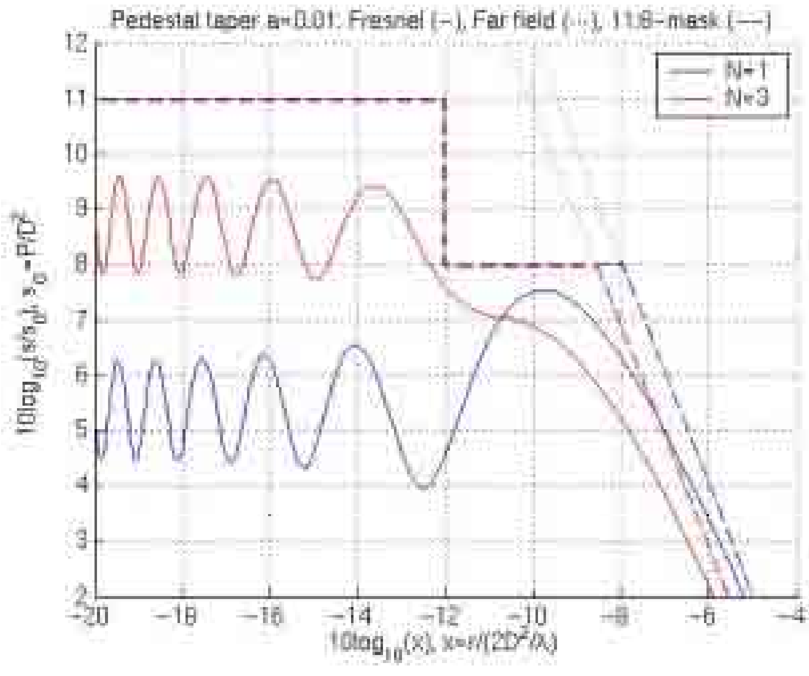
and the circular Taylor taper [17] and figure A.3.

$$E(\rho) = I_0(\pi H\sqrt{1-(\rho/a)^2}) \quad \text{(A.10)}$$

Another widely spread near-field expression, see figure A.4, corresponds to the parabolic taper.

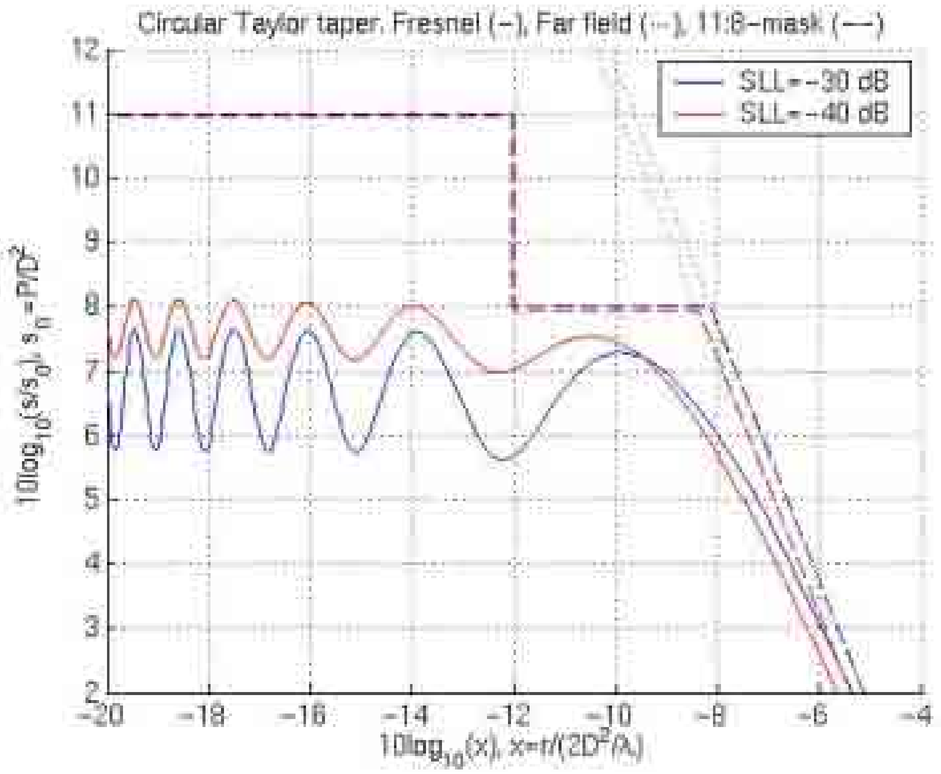
$$E(\rho) = 1-(\rho/a)^2 \quad \text{(A.11)}$$

for which an analytic expression was found by Bickmore and Hansen [20].



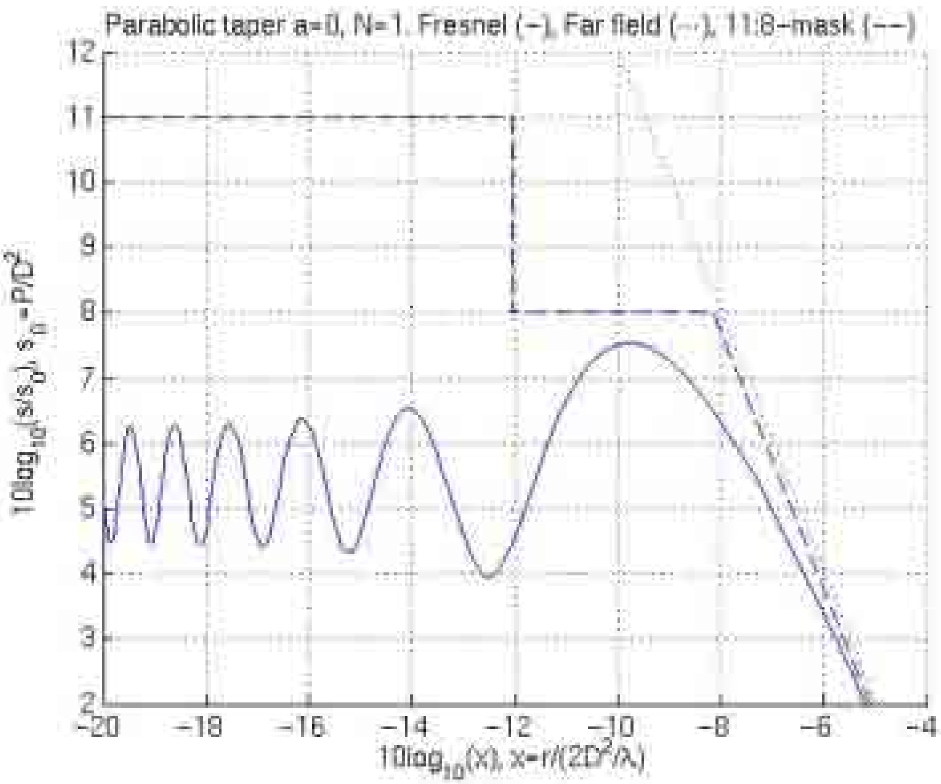
NOTE: The mask is clearly above the chosen test cases. The corresponding aperture efficiencies are 0,82 (N=1) and 0,62 (N=3), of which 0,62 or slightly lower is what is typically find in real products

Figure A.2: Parabola on pedestal



NOTE: The mask is valid also for the Taylor taper near fields depicted here. Note that for lower sidelobe levels the aperture efficiency and the effective area of the antenna decreases which yields an increase in the near field power density, especially close to the antenna.

Figure A.3: Circular Talor taper



NOTE: The parabolic taper near field also complies with the proposed mask. However, it is not a realistic case, especially due to low power density levels close to the antenna x<1/16 (-12 on the scale).

Figure A.4: Parabolic taper

Annex B: Simulations and measurements

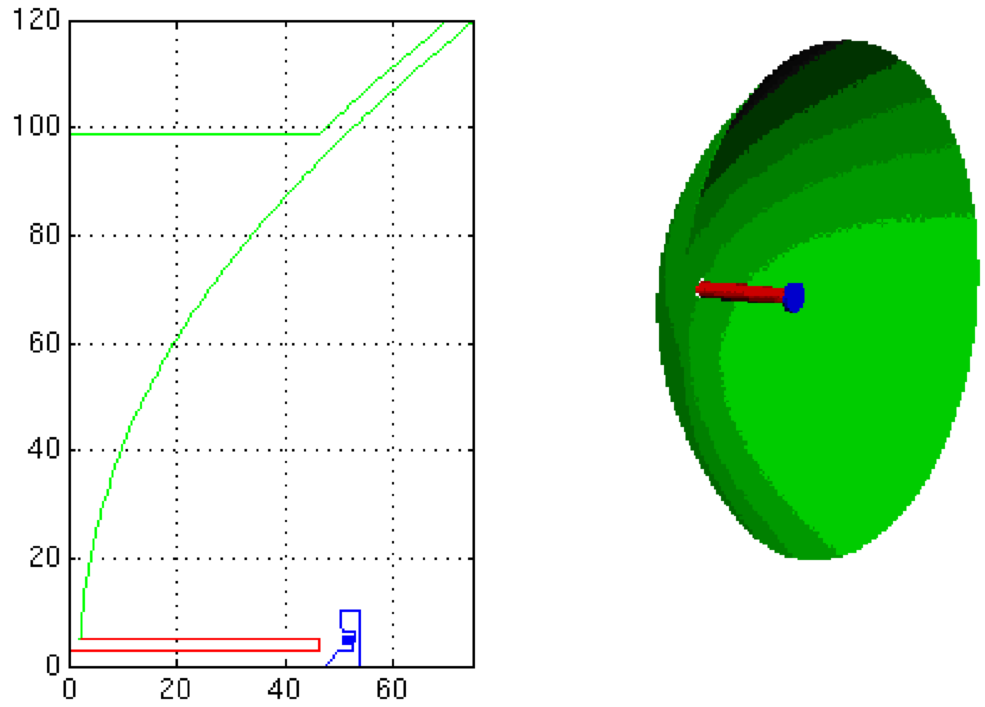
B.1 Simulations and measurements of a 0,24 m 38 GHz antenna

B.1.1 FEKO simulations of a 0,24 m 38 GHz antenna

B.1.1.1 Physical layout of the antenna

The FEKO software (see note) was used. For the feeder wave guide and hat reflector (red and blue in figure B.1.1) a Method-of-Moments solver was used, and for the reflector the high-frequency approximation Physical Optics (PO) was used. The field was calculated in a volume around the antenna which gave information both about off-axis power density and the effect of spatial averaging. Specifically a 20 cm^2 area was used for spatial averages in three perpendicular planes.

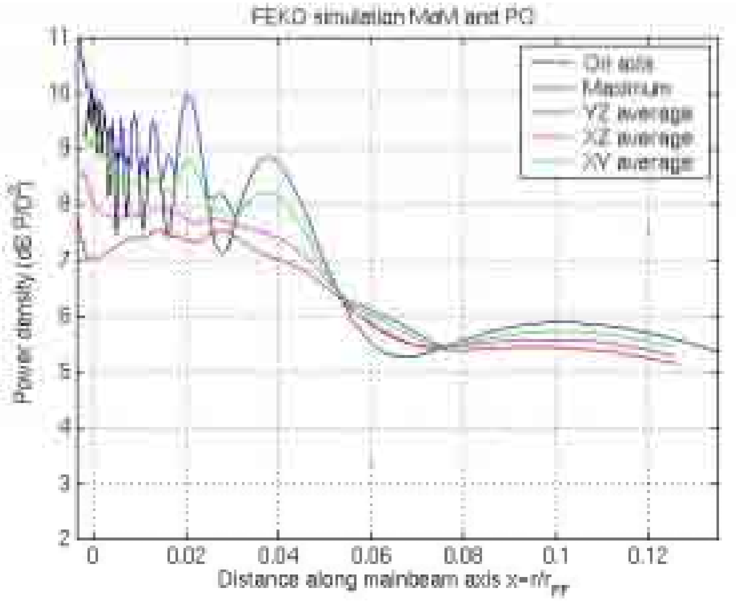
NOTE: FEKO a full wave, method of moments (MoM) based, computer code for the analysis of electromagnetic problems developed by EM Software & Systems-SA (Pty) Ltd.



NOTE: The feeder is a circular waveguide (red) ended by a hat reflector (blue).

Figure B.1.1: Layout of the 38 GHz 24 cm axis-symmetric parabolic reflector antenna

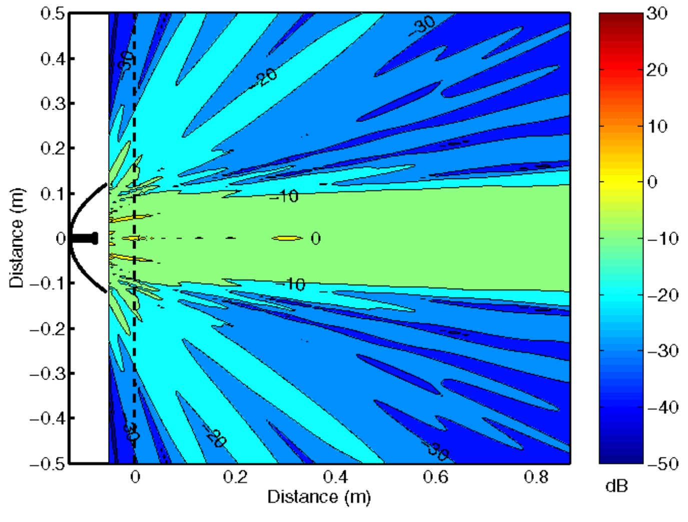
B.1.1.2 On-axis results



NOTE: The FEKO simulation reveals that the highest peaks are found on the axis, and that spatial averaging in xy-planes (perpendicular to the principal axis) yields the highest values. In this case spatial averaging lowers the power density values by approximately 1 dB near the antenna.

Figure B.1.2: FEKO simulation MoM and PO

B.1.1.3 Off-axis results



NOTE: A cross section of the power density distribution in a volume around the 38 GHz 24 cm antenna (to the left). The 0 dB level is the overall peak level. The power densities outside a circular tube along, and centered at, the main axis, are below -10 dB.

Figure B.1.3

B.1.2 Measurements

B.1.2.1 Test setup

Near-field measurements were carried out in an an-echoic chamber at Ericsson Microwave Systems AB, Möndal, Sweden. The near-field was measured on the main axis and also on two parallel axes, one half-way towards the rim of the reflector and one axis at the rim. Rectangular waveguide probes WR62 @ 15 Ghz and WR28 @ 38 GHz were used to minimize the probe influence on the field and to have a well-defined probe for probe correction analysis.

In addition gain-normalized full-sphere measurements were carried out to determine the gain and directivity of the antennas. These data were used to obtain correct levels of the near-field power density distributions.

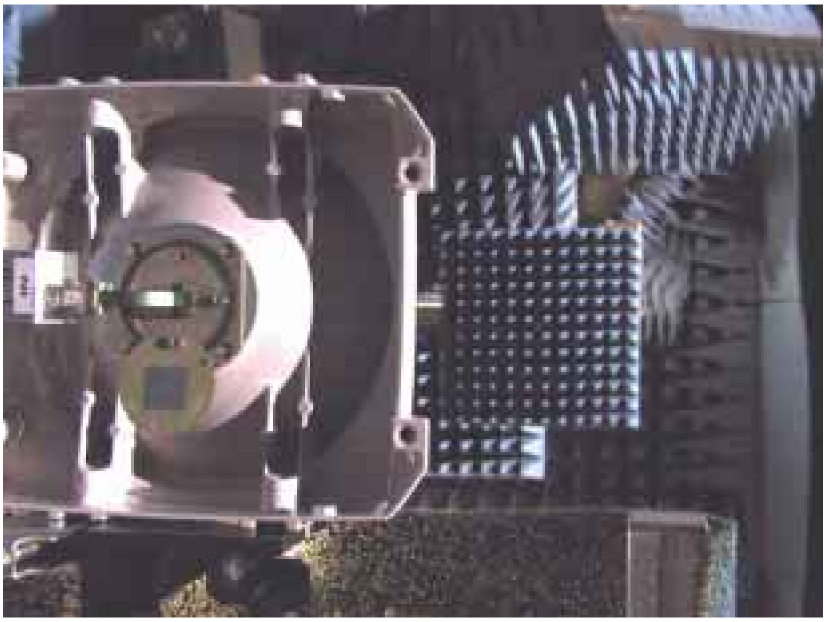


Figure B.1.4: Rear side of the 38 GHz 24 cm reflector antenna with a rectangular waveguide interface

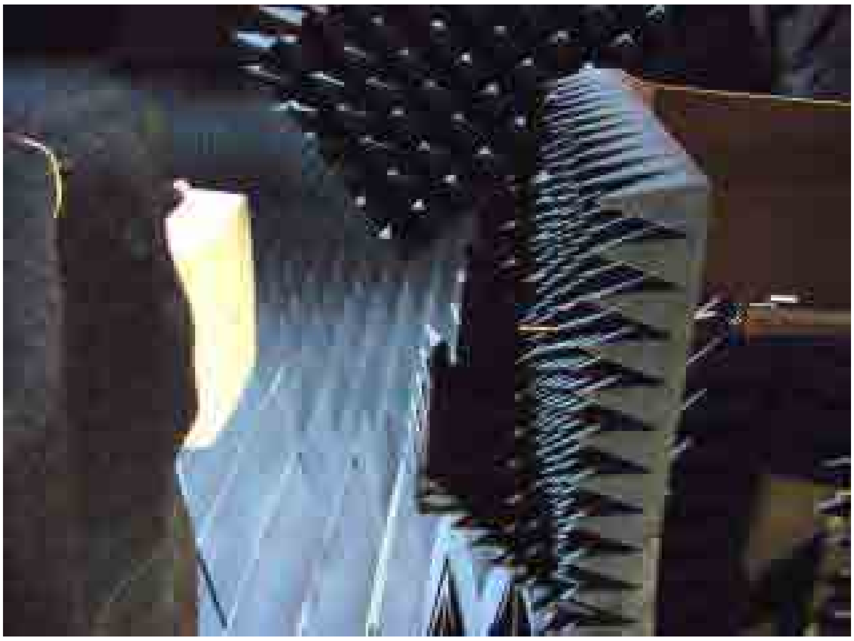
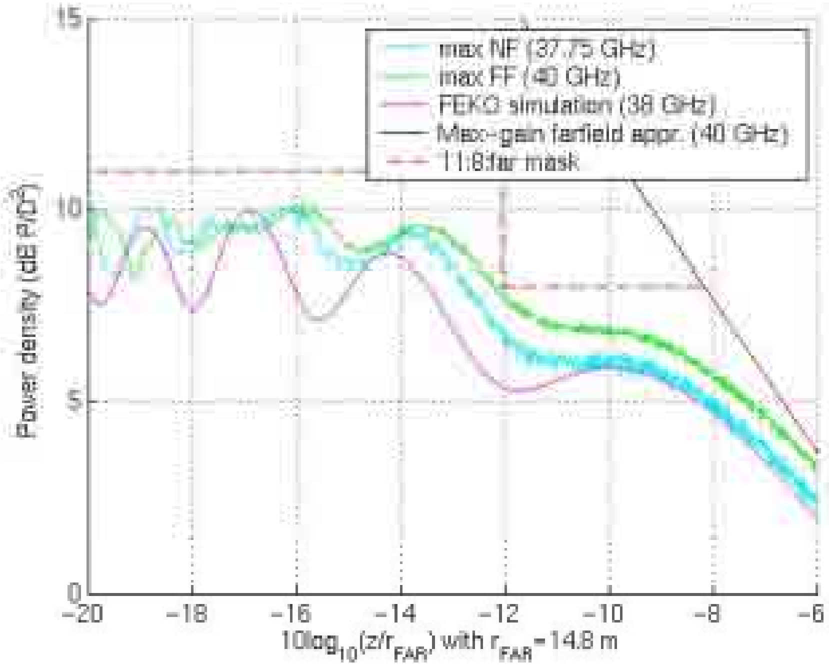


Figure B.1.5: Antenna to the left and the WR28 rectangular wave guide probe to the right

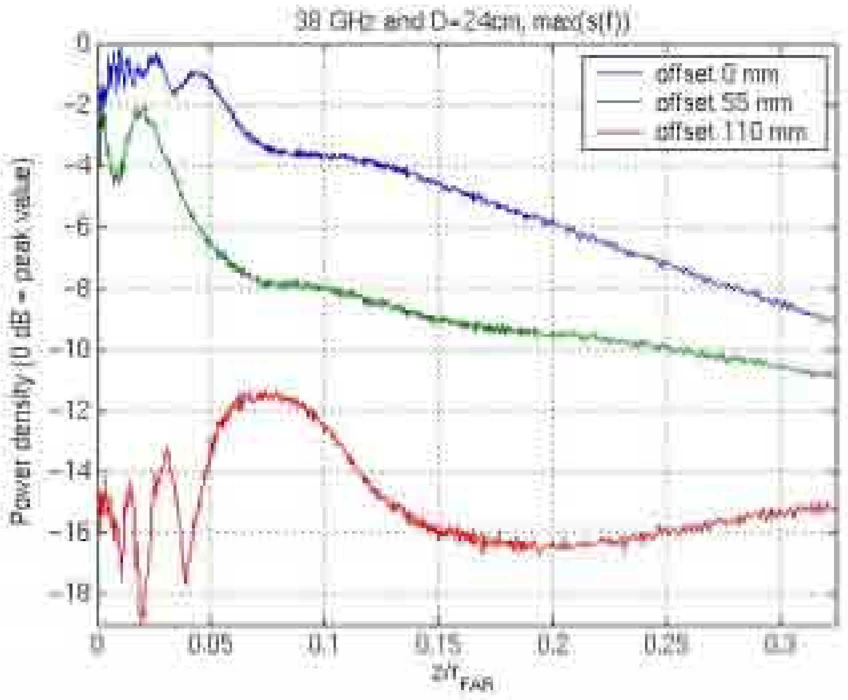
B.1.2.2 On-axis results



NOTE: The proposed mask clearly complies with the data and there is also a good agreement with simulations (magenta curve).

Figure B.1.6: Measured power density on the axis for the 38 GHz 24 cm antenna

B.1.2.3 Off-axis results



NOTE: At the rim (red curve), power densities 10 dB lower relative to the overall peak are found. The curves depict the maximum with respect to frequency as a function of distance.

Figure B.1.7: The off-axis measurements for the 38 Ghz 24 cm antenna

B.1.3 Conclusions

The proposed envelope template complies with:

a) near-field measurements;

b) FEKO simulations; and

c) Fresnel transform analysis of realistic aperture tapers.

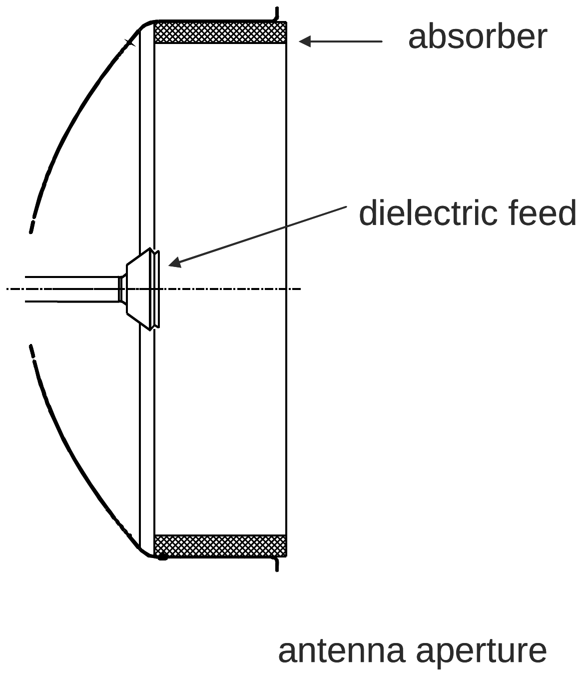
Outside a circular tube surrounding the parabolic reflector and parallel to the main axis, the power density is below -10 dB relative to the overall peak value.

Spatial averaging should be applied in a plane perpendicular to the main axis. However, the effect is rather small at 38 Ghz and frequency-dependent.

B.2 Simulations and measurements of a 0,6 m 8,1 GHz antenna

B.2.1 Simulation model and test device

A 0,6 m parabolic antenna with shroud at 8,1 GHz is used for test and simulation. Two test cases with and without absorber are considered.



B.2.2 Measurement setup

The electrical field strength along the main beam axis of a 0,6m parabolic antenna at 8,1 GHz has been measured using a EM Radiation Meter EMR-300 with an E-Field Sensor 10 MHz-18 GHz.

The isotropic field sensor measures the effective field strength independent of the polarization and the direction of the radiating source.

The sensor, aligned in the center of the aperture, is continuously moved in front of the antenna aperture up to 3 m.

Calibration is done at $r = \frac{D^2}{2 \cdot \lambda}$

NOTE: Probe calibration was performed according to the state of the art, e.g. defined in the relevant standard such as EG 202 373 [21] or EN 50383 [5].

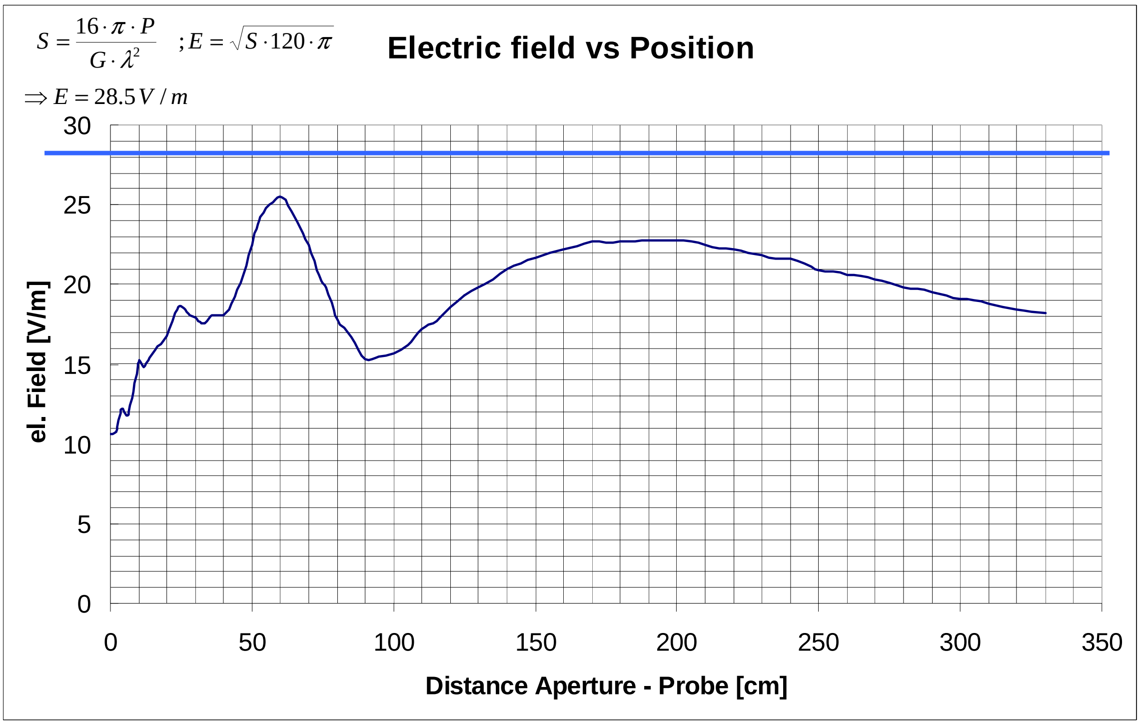
Antenna data: 6 m; G = 31,7 dBi; P = 19,4 dBm; f = 8,1 GHz.

The EM field is measured with an isotropic field probe:

Figure B.2.1: EM Radiation Meter EMR-300

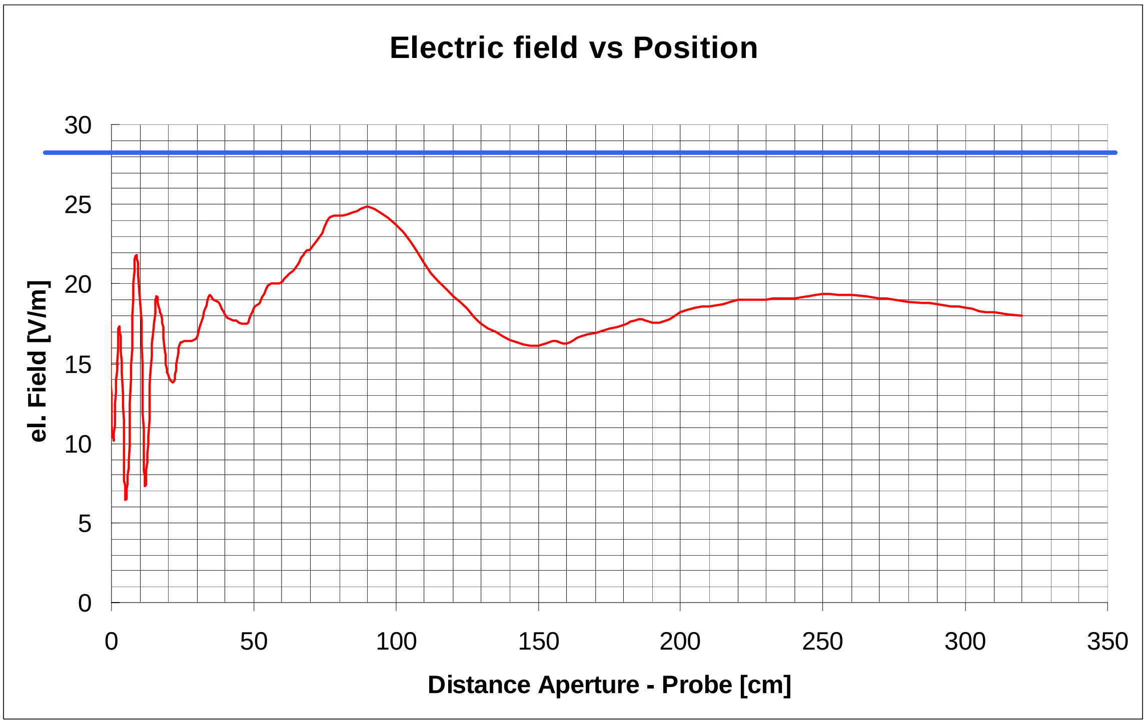
B.2.3 Measurement results

B.2.3.1 Measurement result with absorber



These measurements confirm that the electric field does not exceed the maximum value defined by the envelope template (see clause 8) which is 34,4 V/m for this particular antenna.

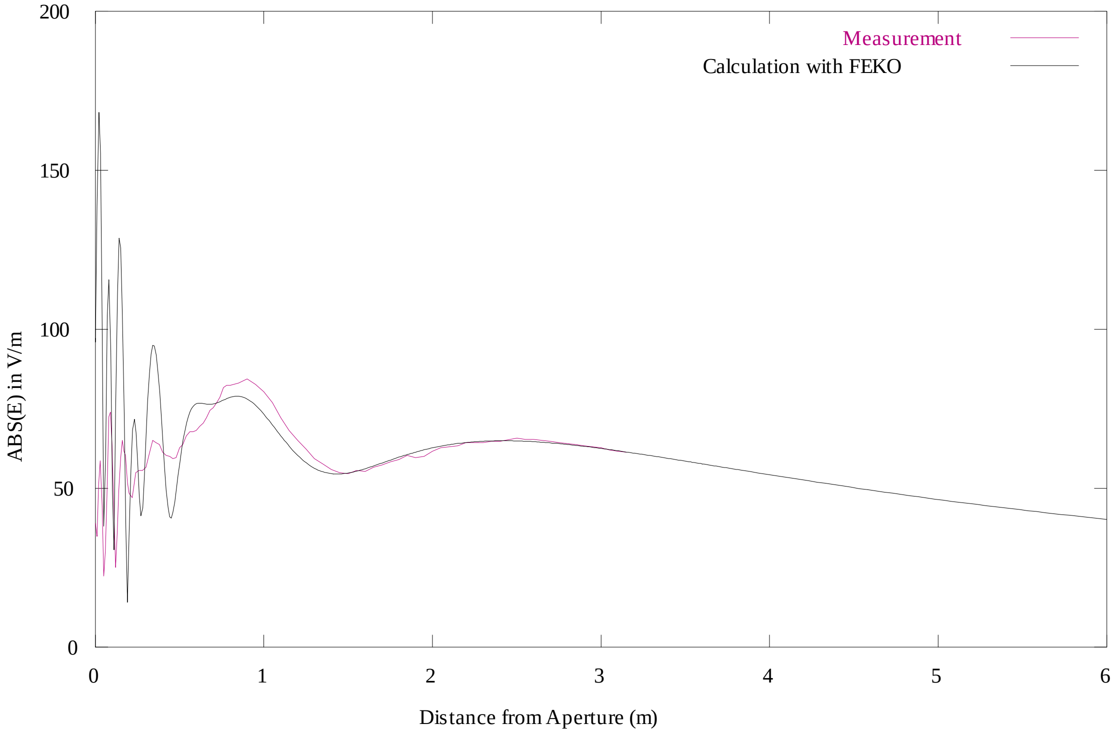
B.2.3.2 Measurement result without absorber



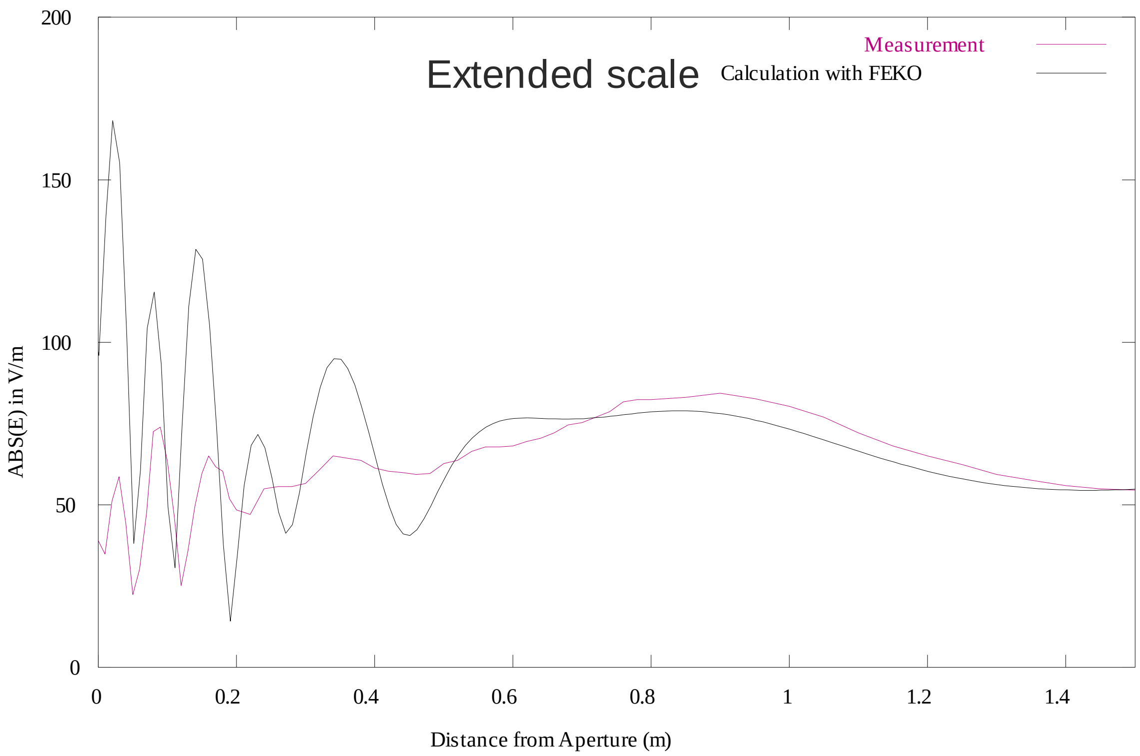
These measurements confirm that the electric field does not exceed the maximum value defined by the envelope template (cf. clause 8) which is 34,4 V/m for this particular antenna.

B.2.4 Comparison of measurement and calculations

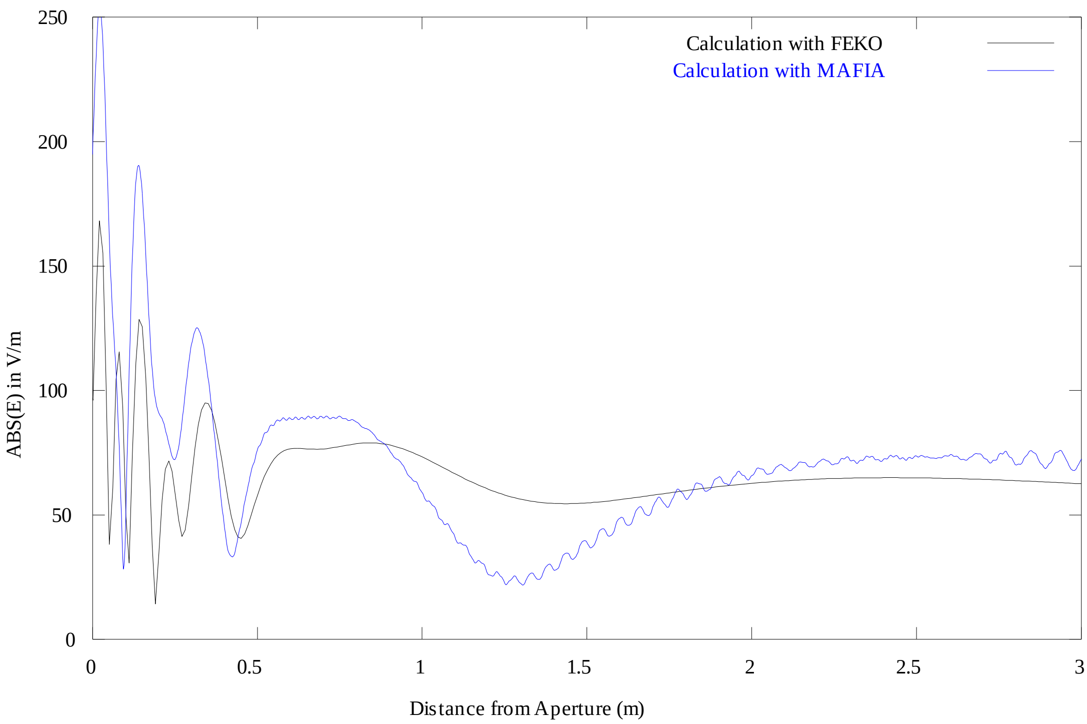
Measured electric field strength in front of the antenna aperture - Calculation with FEKO:



Measured electric field strength in front of the antenna aperture - Calculation with FEKO:



Calculation with MAFIA / FEKO:



B.2.5 Conclusions

- To achieve realistic simulation values a detailed model based on CAD data of an existing antenna is necessary.
- Measurements and Calculations without absorber mainly for comparison reason (no practical antenna).

- Simulation accuracy strongly depends on mesh density.
- Simulation with FEKO and MAFIA (shroud wo absorber) in line with measurement results up to 0,5 m close to the antenna aperture.
- Equations provided in figure 8.2 are confirmed by measurements.

B.3 RFS investigation on antennas from 5 to 38 GHz

B.3.1 Detailed analysis of a 7 GHz antenna (2 feet) and a 19 GHz antenna (1 foot)

B.3.1.1 Description of test cases

Description of antennas under test:

SU2-W71A

- Inner/outer diameter: 0,67 / 0,7 meter;
- Frequency: 7,8 GHz;
- Pe = 1 watt.

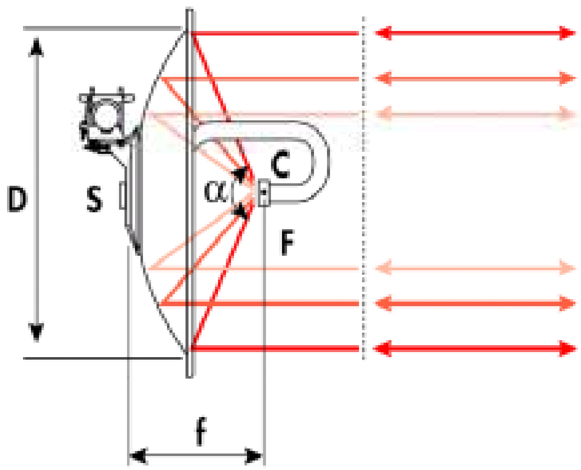
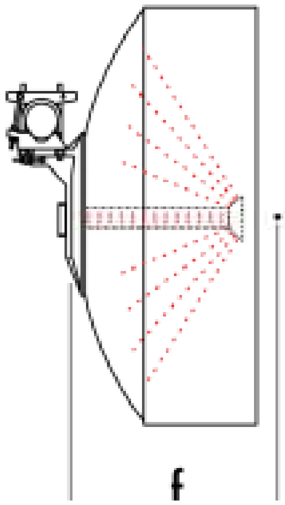


Figure B.3.1.1: SU2-W71A

SB1-190A

- Inner/outer diameter: 0,35 / 0,38 meter;
- Frequency 18,7 GHz;
- Pe = 1 watt.



B.3.1.2: SB1-190A

B.3.1.2 Simulations

Simulation method:

- Method of Moments / Physical optics (FEKO).

Model:

- Based on mechanical CAD data.

Validation of the model:

- based on far field results (gain, aperture);
- SU2-W71A:
  - Gain: sim. 31,6 dBi / meas. 32,2 dBi (wo shroud);
  - Aperture: sim. 4,1° / meas. 4,3°;

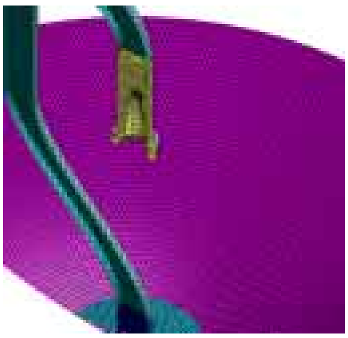


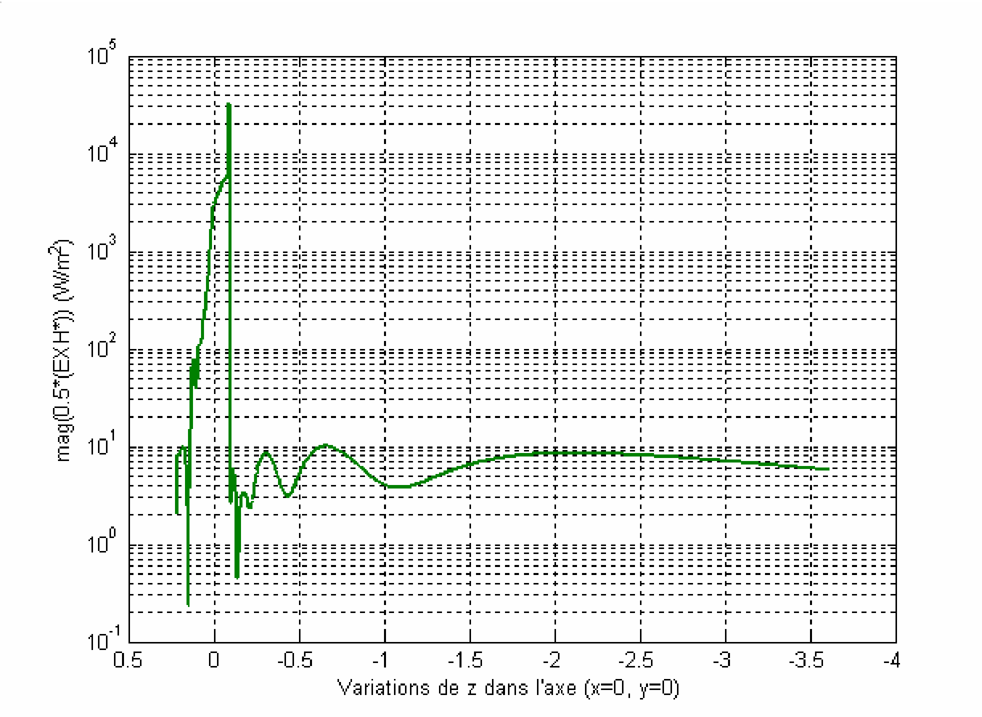
Figure B.3.2.1: SU2-W71A - simulated model of radiating source

- SB1-190A:
  - Gain: sim. 34 dBi / meas. 34,1 dBi (wo shroud);
  - Aperture: sim. 3,3° / meas. 3,4.

Figure B.3.2.2: SB1-190A - simulated model of radiating source

B.3.1.3 Simulation results

Power density on the axis (SU2-W71A upper and SB1-190A lower).



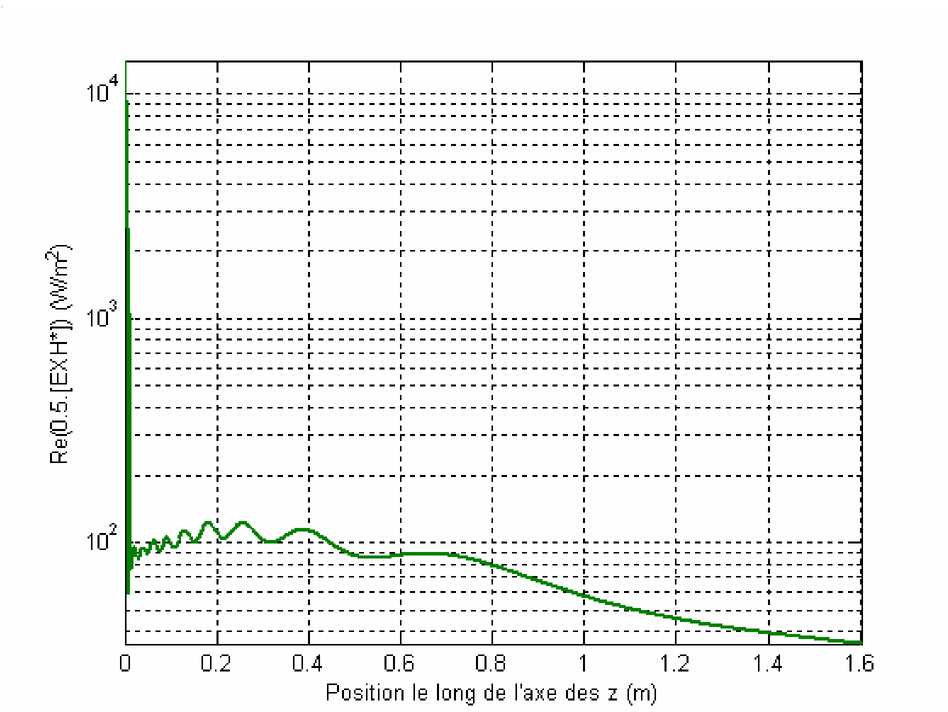


Figure B.3.3(a): Simulation results of power density on the main axis (Axial)

Power density on a radial (SU2-W71A upper and SB1-190A lower)

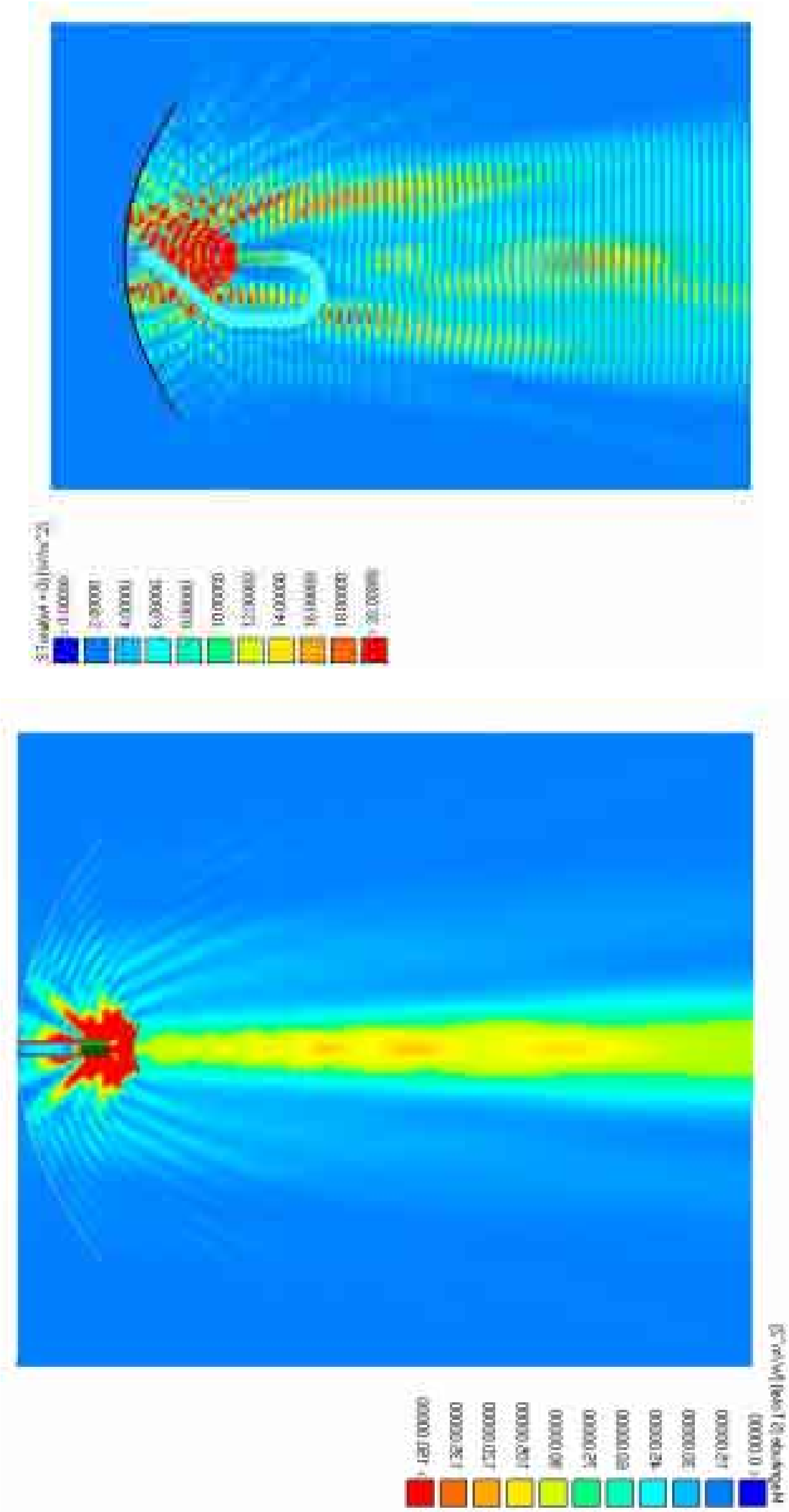


Figure B.3.3(b): Simulation results of power density on the main axis (radial pattern)

B.3.1.4 Measurement setup

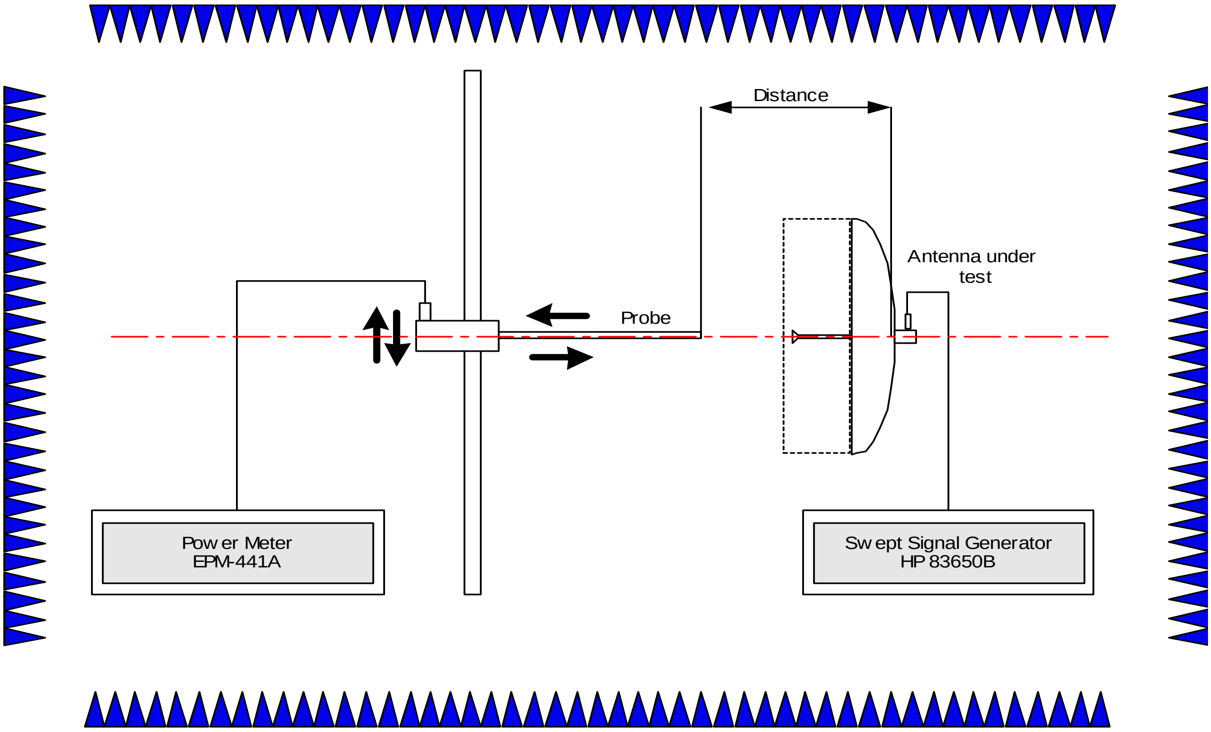


Figure B.3.4: Measurement setup for power density measurement

NOTE: Probe calibration was performed according to the state of the art, e.g. defined in the relevant standard such as EG 202 373 [21] or EN 50383 [5].

B.3.1.5 Measurement results

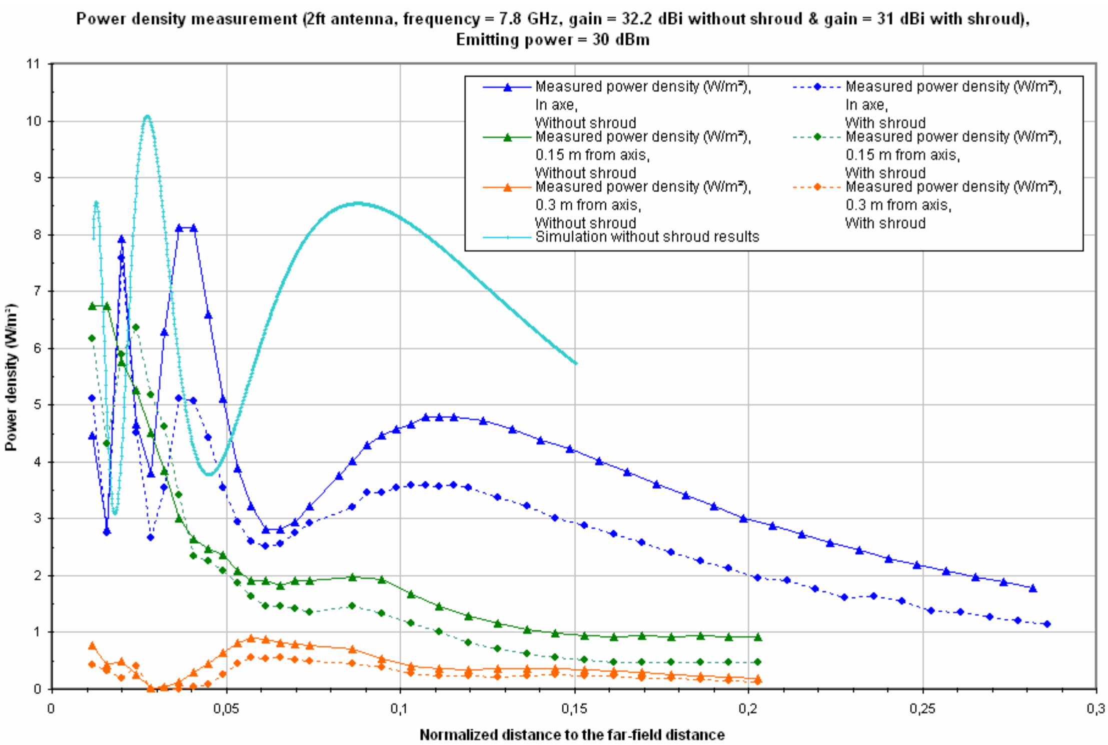


Figure B.3.5: Measurement results for antenna model SU2-W71A

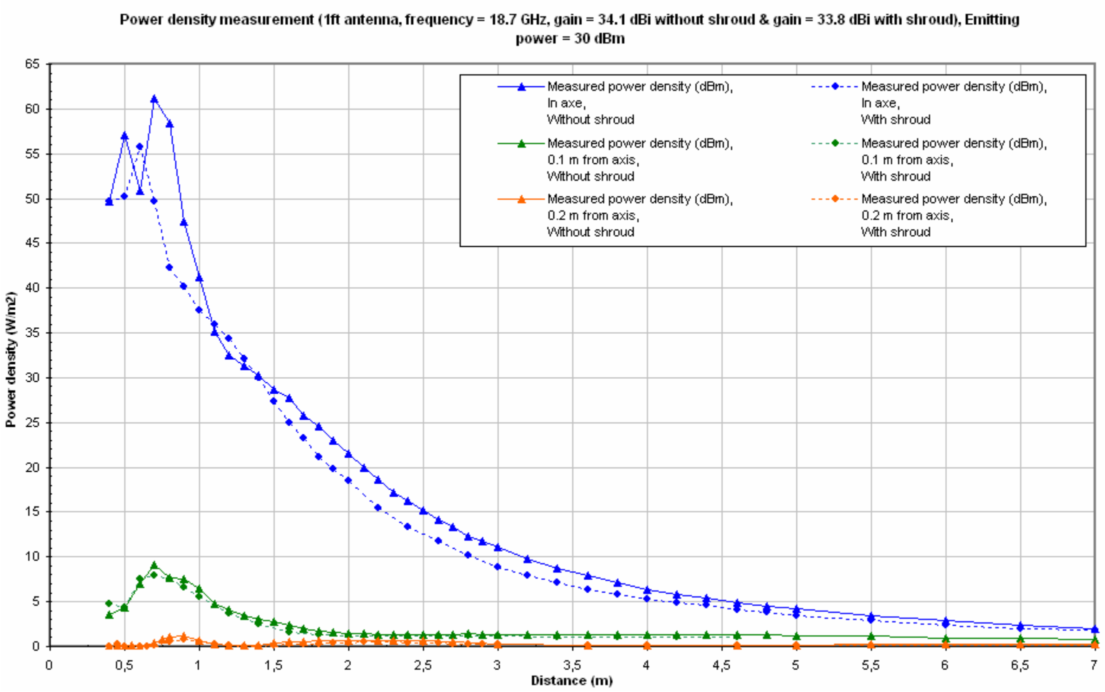


Figure B.3.6: Measurement results for antenna model SB1-190A

B.3.1.6 Evaluation of the factor F

According to figures B.3.5 and B.3.6, $S \leq \frac{FP}{A}$ where *F* takes the following values:

SU2-W71A

- F (meas., wo shroud) = 2,9.
- F (meas., w shroud)(see note) = 2,8.
- F (sim., wo shroud, max) = 3.
- F (sim., wo shroud, 20 m^2) = 2,9.

SB1-190A

- F (meas., wo shroud) = 6,9.
- F (meas., w shroud)(see note) = 6,4.
- F (sim., wo shroud, max) = 11,2.
- F (sim., wo shroud, 20 cm^2) = 8,6.

NOTE: Effective diameter wo shroud is higher than diameter with shroud, due to absorbing material inside shroud.

B.3.1.7 Conclusions

Consequent to this investigation, the following recommendation have been agreed at the joint MMF/ETSI TM4 workshop of January 14th 2005:

- Use spatial averaging (20 cm^2 disk)
  - Below 10 GHz to derive local SAR using a 10 g cylinder of 5 mm height,
  - Above 10 GHz for direct power density assessment.
- Use time averaging rules, in particular for workers exposure.
- Because of the high directivity, the power density outside the tubular volume in front of the antenna is more than 10 dB below the maximum power density in the axis.
- Simulations (e.g. MoM) provide good but conservative results about compliance boundaries
  - It is not necessary to simulate the shroud because it reduces the power density level (absorbing materials).

It has been recommended to investigate a larger number of antennas and provide estimation of actual human exposure considering spatial and time averaging. The following clause presents the results of these additional tests.

B.3.2 Power density measurement on the axis

Following this first stage of investigation, RFS and Alcatel worked together to extend the approach to a wider range of antenna's frequencies and sizes. These results have been presented according to the new envelope template.

B.3.2.1 Description test cases

In table B.3.1 are found the description of the antennas under test. Outer diameter means overall external diameter and inner diameter takes into account the presence of the absorbing material inside the shroud.

Table B.3.1: Description of antennas under test

Antenna model	Outer diameter (with shroud) (mm)	Inner diameter (with shroud) (mm)	Mid-band frequency (GHz)	Mid-band gain (dBi)
SU2-190AB	700	670	18,7	38,6
SB2-190BB	700	670	18,7	39
SB1-380BB	380	350	38,25	40
SB4-W71AN	1 260	1 230	7,8	37,4
SB1-190BB	380	350	18,7	33,8
SU2-W71A	700	670	7,8	31
SB2-44AN	700	670	4,8	7,3
SB1-142BB	380	350	14,8	31,1
SB1-220BB	380	350	22,4	34,9

Measurements were carried out using the same procedure as described above in clause B.3.1.4. The transmitted power was 1 watt and the emitting frequency was selected in the middle of each antenna frequency range.

B.3.2.2 Description of the envelope template

In agreement with the study presented in annex A, an envelope template encompassing the antenna under test power density is proposed.

This envelope template is divided into 3 stages: a first step corresponding to power density normalized to P/D² with a factor F upper bound level, a second step with a factor F/2 upper bound level, and a third section with normalized far-field curve (see figure B.3.7).

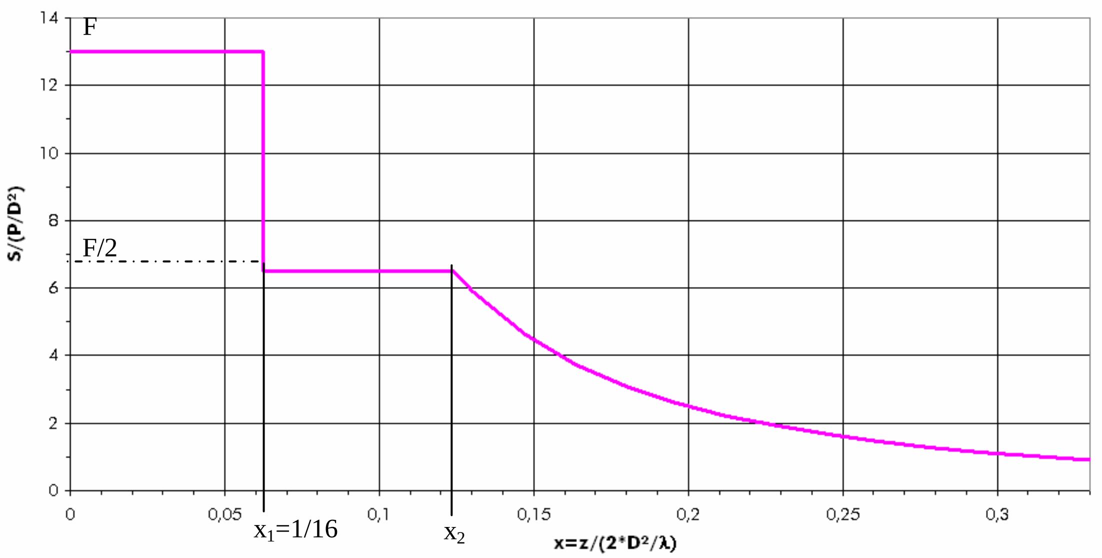


Figure B.3.7: Proposed envelope template for power density upper bound.

Where:

- D is the diameter of the antenna.
- $R_{ff} = \dfrac{2D^2}{\lambda}$.
- x_1 corresponds to the first zero for a uniform taper using Fresnel transform (cf. annex A, clause 1.4.1).
- $x_2 = \dfrac{\lambda}{4D}\sqrt{\dfrac{2 \cdot 10^{G/10}}{F\pi}}$ with D and G expressed in meter and dBi respectively.

NOTE: On a physical basis, the inner diameter, representing the physical aperture, is more relevant to evaluate the power density. However, this information is not always available. In this case, the outer diameter can be used with the appropriate factor F.

A slight increase of factor F is operated for the envelope template using the external diameter because of the normalization of power density (see paragraph two in clause B.3.2.4 for explanation).

B.3.2.3 Measurement and calculation results on the axis using inner diameter

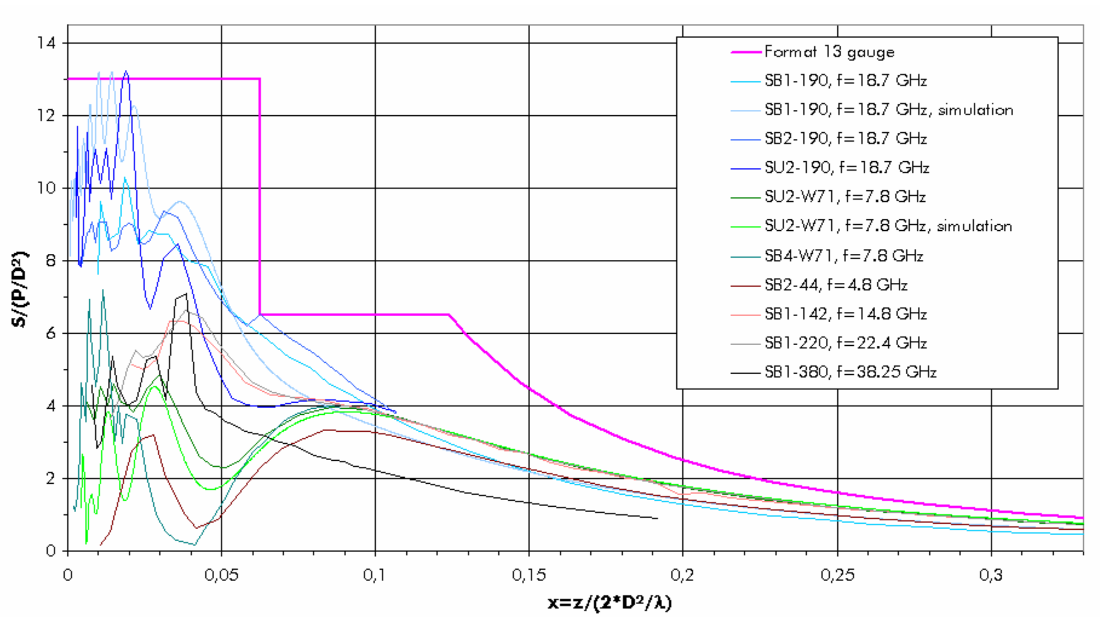


Figure B.3.8: Power density measurement and simulation results with format 13 envelope template using inner diameter (aperture)

Both simulations and measurements on all tested antennas (9) are compliant with the proposed 13 format envelope template ($S_{Max} \le 13\frac{P}{D_{in}^2}$). The slight exceedings of the envelope template seen on 2 curves can be neglected due to spatial averaging, which should be applied in a plane perpendicular to the main axis.

B.3.2.4 Proposal of envelope template using outer diameter

Inner diameter is not available to anybody. So an alternative solution should be proposed based on external diameter. According to the antennas that have been tested the ratio between inner diameter and external diameter is about 8,5 % in the worst case. Thus, adapting the proposed factor F to the outer diameter consists in a multiplication by a factor 1,18 (square of 8,5 % increase). Thus the proposed value for factor F, linearly expressed and with P/D² is 15

(i.e. $S_{Max} \le 15\frac{P}{D_{out}^2}$).

In figure B.3.9 are presented the power density measurements results in the main axis with this format 15 envelope template.

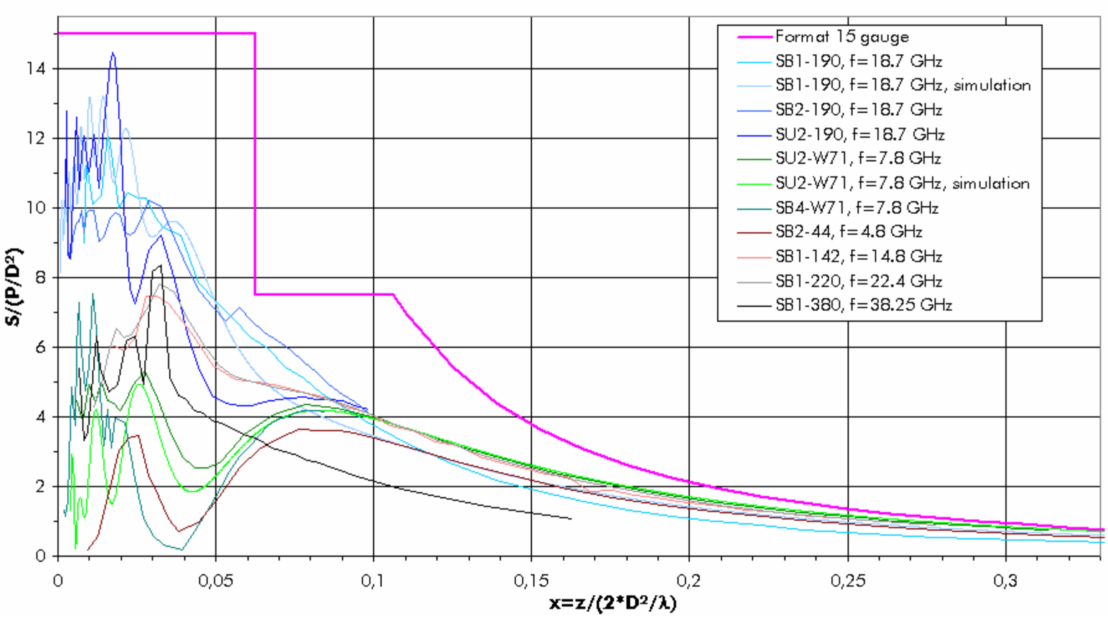


Figure B.3.9: Power density measurement and simulation results with format 15 envelope template using outer diameter

B.3.3 Rationale for using SAR below 10 GHz

As defined by ICNIRP and European Recommendation, SAR can be evaluated by averaging absorbed power over a volume of 10 g for frequencies between 100 kHz and 10 GHz. It is assumed in this clause that:

- most equipment considered in the present document operate at a frequency higher than 1,4 GHz, thus having a penetration depth in body tissues below 30 mm;
- the exposed body tissues are mainly superficials and of high water content, thus having a density ρ close to 1 000 kg/m^3;
- the 10 g averaging volume presents a surface of 20 cm² in order to ensure the continuity of basic restrictions at 10 GHz and therefore the averaging volume has a depth of 0,5 cm;
- no significant power is radiated radially.

Therefore, considering an incident wave with power density S_{in} as presented in figure B.3.10 showing the energy transfer curve (in red) and the associated skin thickness:

$$SAR_{10g} \approx \frac{S_{in} \times 20\,cm^2}{10\,g} - \frac{S_{out} \times 20\,cm^2}{10\,g}$$

$$SAR_{10g} \leq \frac{S_{in} \times 20cm^2}{10g}$$

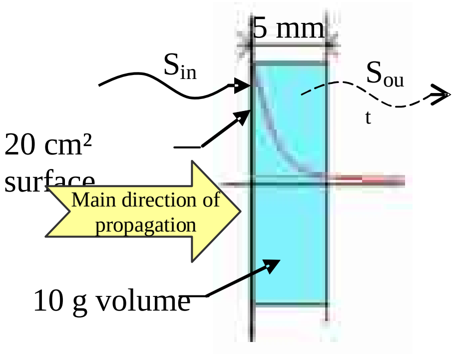


Figure B.3.10: Illustration of SAR and skin thickness

B.3.4 Conclusions

The measurements and simulations performed in this clause confirm the validity of the flow chart proposed in clause 8.

B.4 Simulations using SRSR tool on 8 GHz and 13 GHz antennas

B.4.1 SRSR

Simulation of real parabolic antennas using SRSR:

- Well proven tool (17 years of experience in antenna design).
- Full-wave integral equation formulation for axisymmetric antennas.
- Used for parametric analysis.

B.4.2 Factor F, peak to average ratio

Near to the parabolic antenna, the electromagnetic field is concentrated in a "tube".

The average power density (S_{av}) is simply the ratio of the emitted power P by the surface A of the aperture:

$$S_{av} = P/A.$$

The actual power density is not uniform, a peak-to-average or factor F can be defined:

$$Smax = F*Sav.$$

FCC defined F = 4, derived from a uniform field distribution in the aperture.

Real antennas: tapered source.

Relation with antenna efficiency or aperture efficiency $A_e = \eta$ A.

Efficiency η: $\eta = G/G_{max}$, $G_{max}=4\pi A/\lambda^2$.

$S_{max} = 4P/A_e = 4P/(\eta\ A)$.

B.4.3 Antenna data

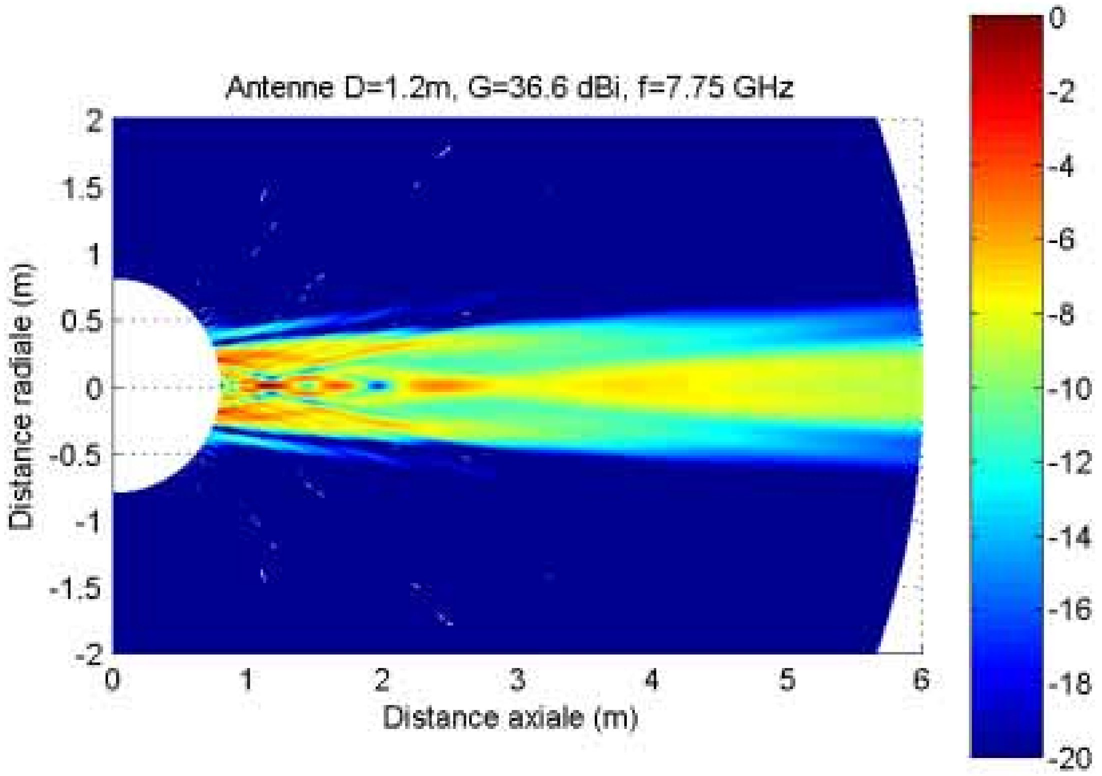
Table B.4.1: Antenna 8 GHz: vhpx4-77

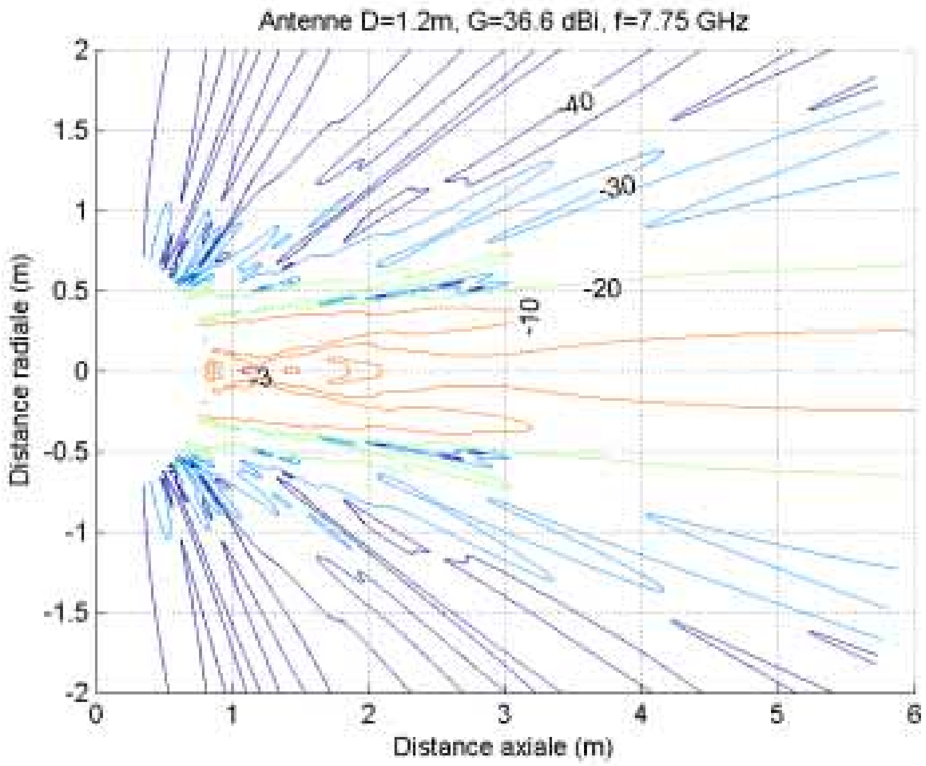
Frequency band (GHz)	7,75 to 8,5
Diameter (m)	1,2
Gain, low (dBi)	36,6
Gain, mid (dBi)	37,0
Gain, high (dBi)	37,4
Main loob width (degrees)	2,2
Cross polar discrimination (dB)	32,0
Front to back ratio	60,0
Standing wave ratio, max	1,15

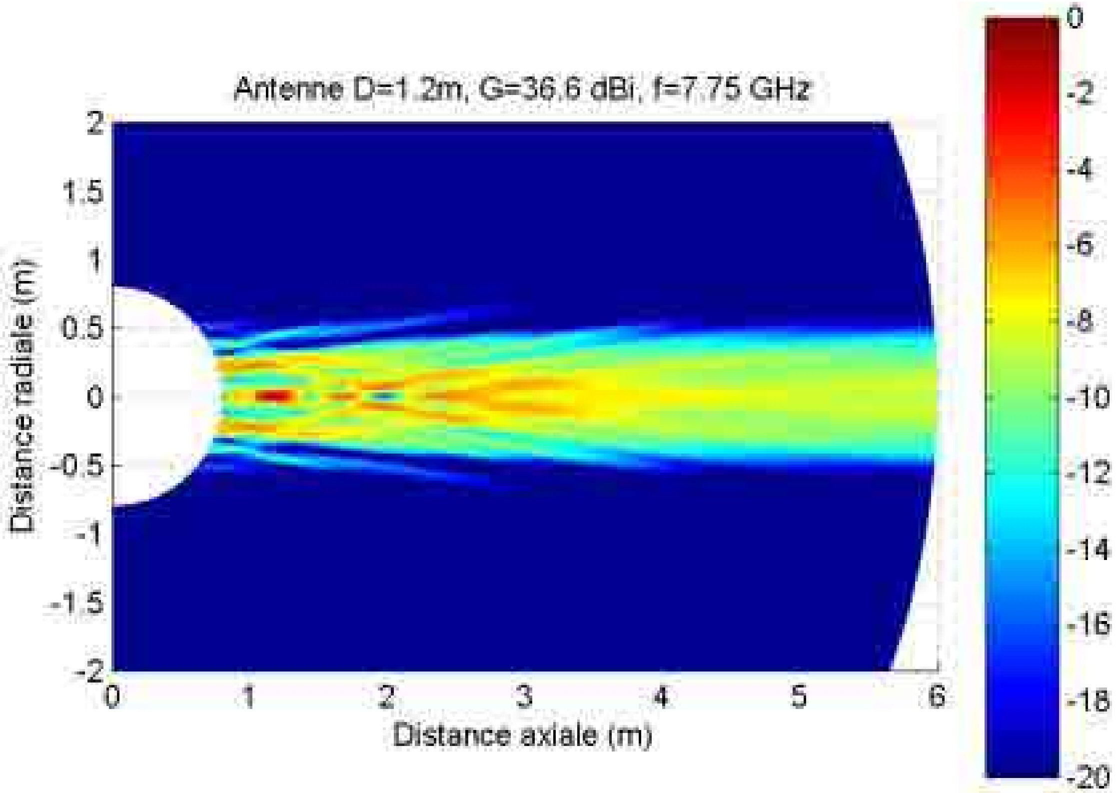
Table B.4.2: Antenna 13 GHz: vhpx4-130

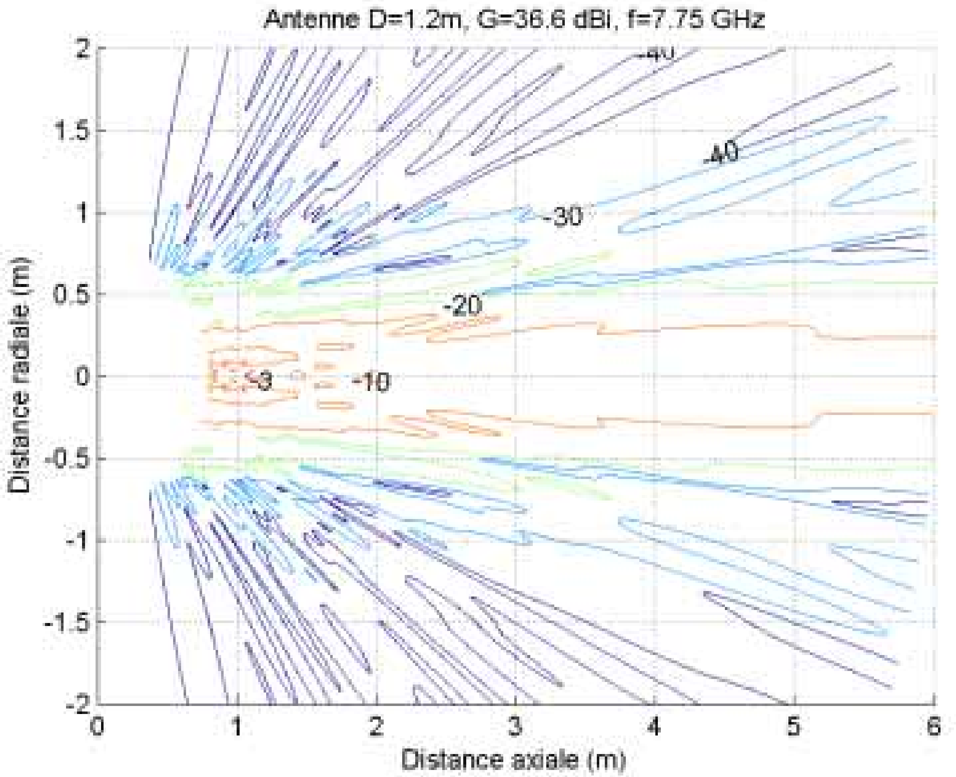
Frequency band (GHz)	12,7 to 13,25
Diameter (m)	1,2
Gain, low (dBi)	41,0
Gain, mid (dBi)	41,2
Gain, high (dBi)	41,3
Main loob width (degrees)	1,3
Cross polar discrimination (dB)	32,0
Front to back ratio	67,0
Standing wave ratio, max	1,25

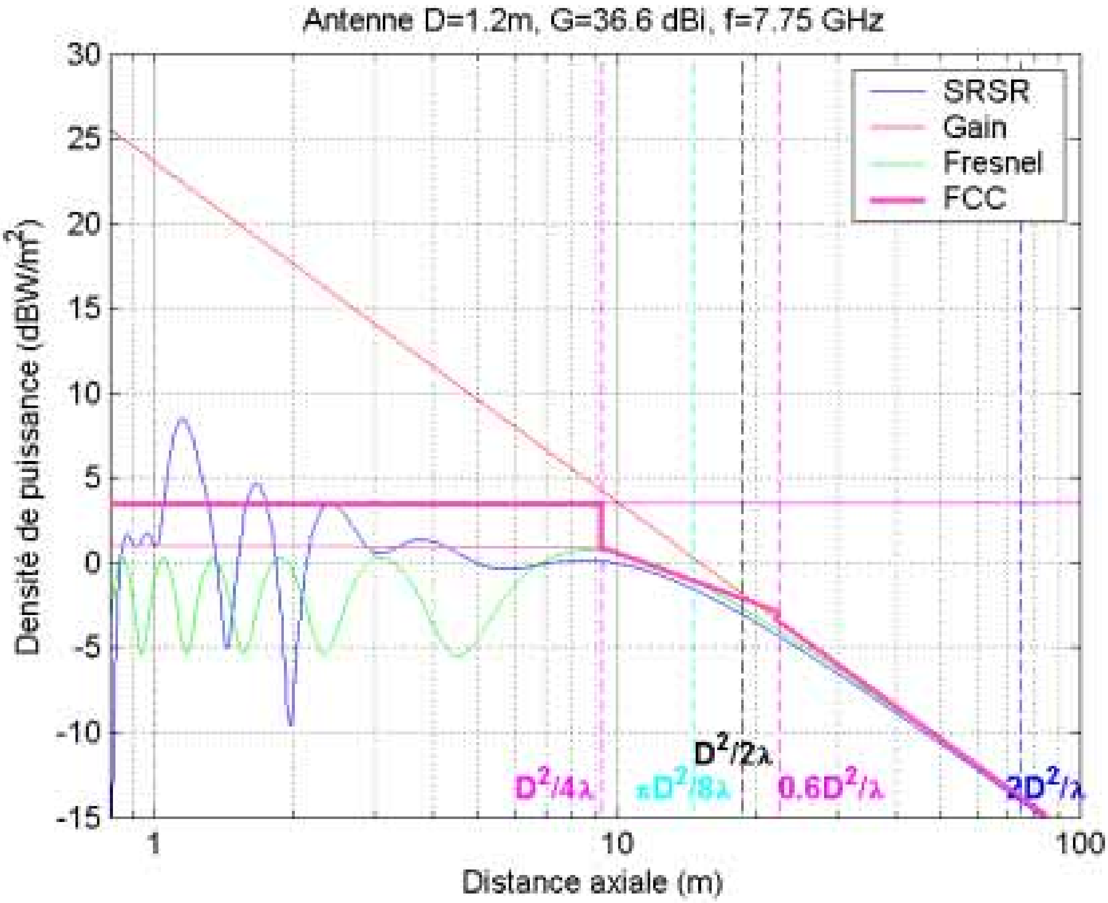
B.4.4 Simulation results 8 GHz



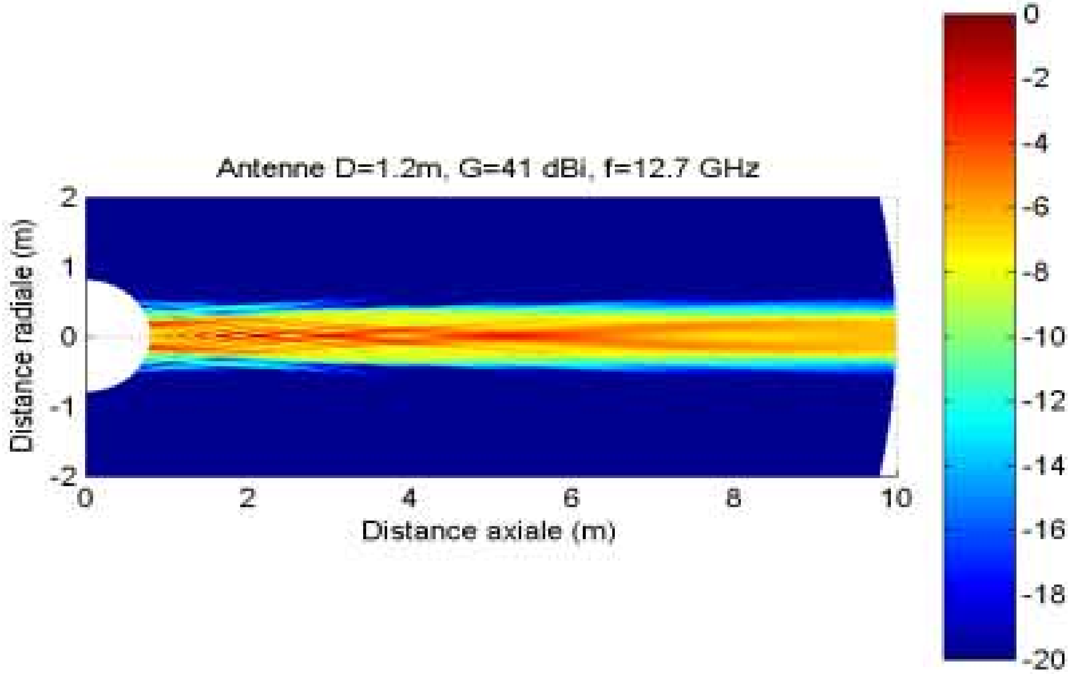


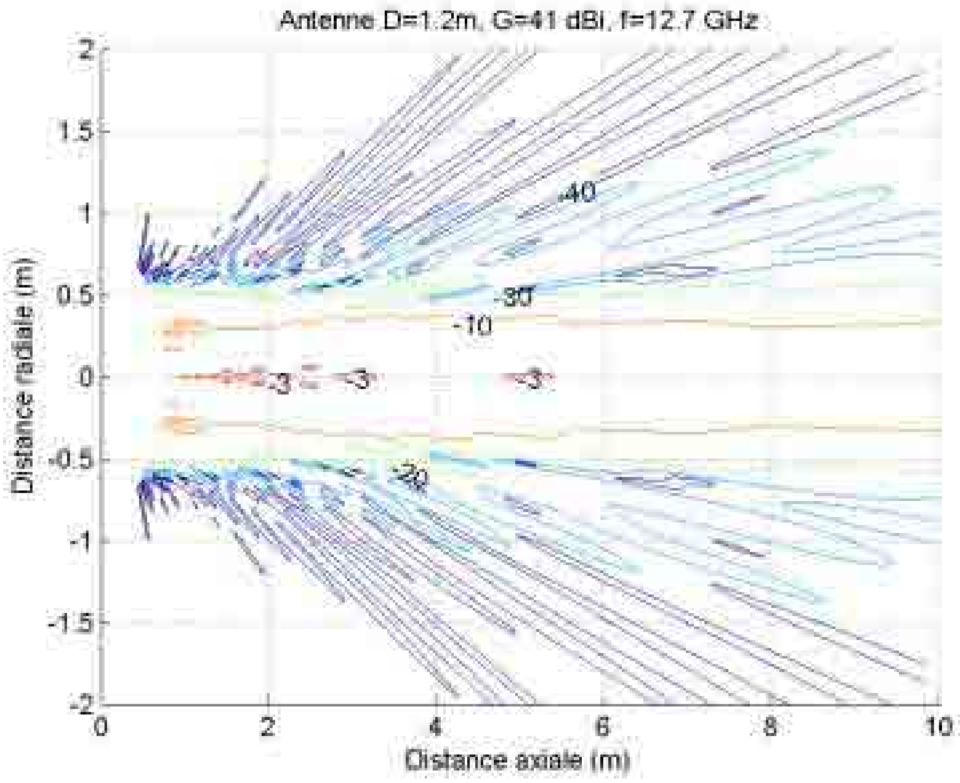

Antenne D=1.2m, G=36.6 dBi, f=7.75 GHz
Distance radiale (m)
Distance axiale (m)

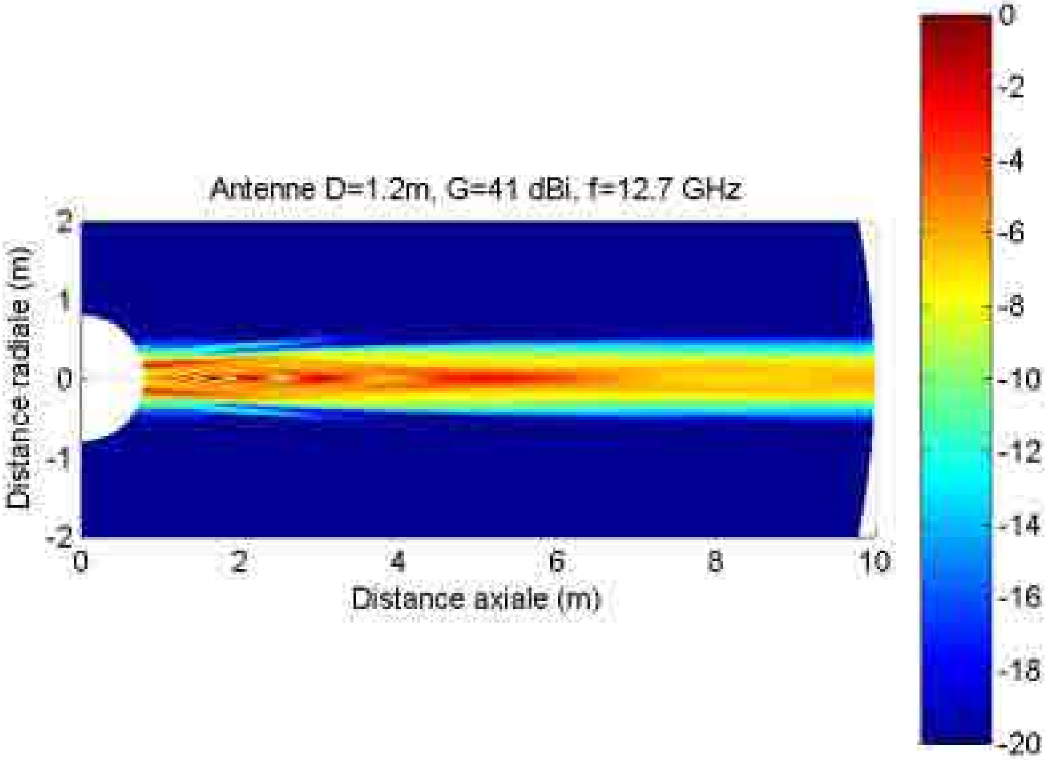

Antenne D=1.2m, G=36.6 dBi, f=7.75 GHz
-40
-30
-20
-3
-10
Distance radiale (m)
Distance axiale (m)

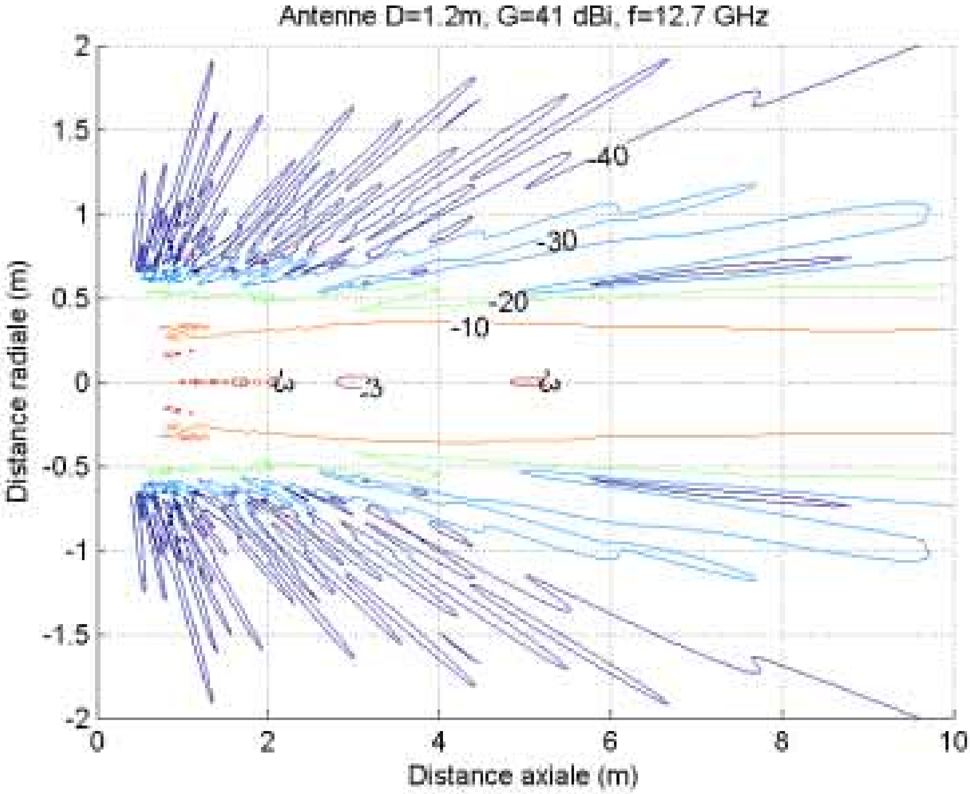


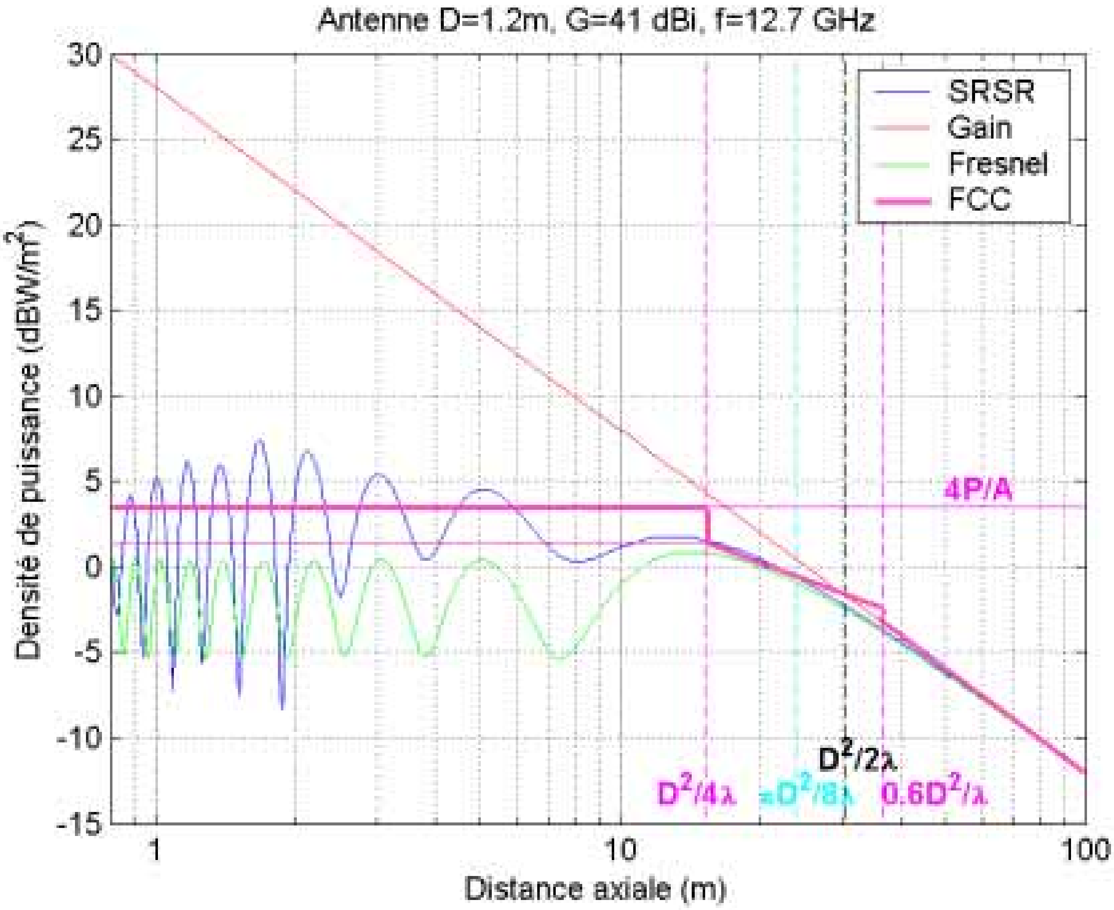
B.4.5 Simulation results 13 GHz




Antenne D=1.2m, G=41 dBi, f=12.7 GHz
Distance radiale (m)
Distance axiale (m)
-40
-30
-10
-3
-3
-3
-20
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
2
4
6
8
10


Antenne D=1.2m, G=41 dBi, f=12.7 GHz
Distance radiale (m)
Distance axiale (m)
2
1
0
-1
-2
0
2
4
6
8
10
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20


Antenne D=1.2m, G=41 dBi, f=12.7 GHz
-40
-30
-20
-10
-3
Distance radiale (m)
Distance axiale (m)


Antenne D=1.2m, G=41 dBi, f=12.7 GHz
SRSR
Gain
Fresnel
FCC
4P/A
D²/2λ
D²/4λ
≈D²/8λ
0.6D²/λ
Densité de puissance (dBW/m²)
Distance axiale (m)

B.4.6 Modified FCC model

"Tubular" region: Smax = F*P/A

- P: emitted power;
- A: aperture surface;
- F = 4 (FCC) rather 10-12 in the studied cases.

"Cylindrical" region (1/R) from $D^2/4\lambda$ to $0{,}6D^2/\lambda$.

"Spherical" region ($1/R^2$): far-field gain.

B.4.7 SRSR results versus the new envelope template

B.4.7.1 8 GHz and 13 GHz antennas

Figure B.4.1 shows the previous results with the format 13 envelope template. The diameter here is the inner diameter. The two high performance antennas are with shrouds. But these shrouds are without absorbers in the simulation which may explain the overshooting of the format 13 envelope template.

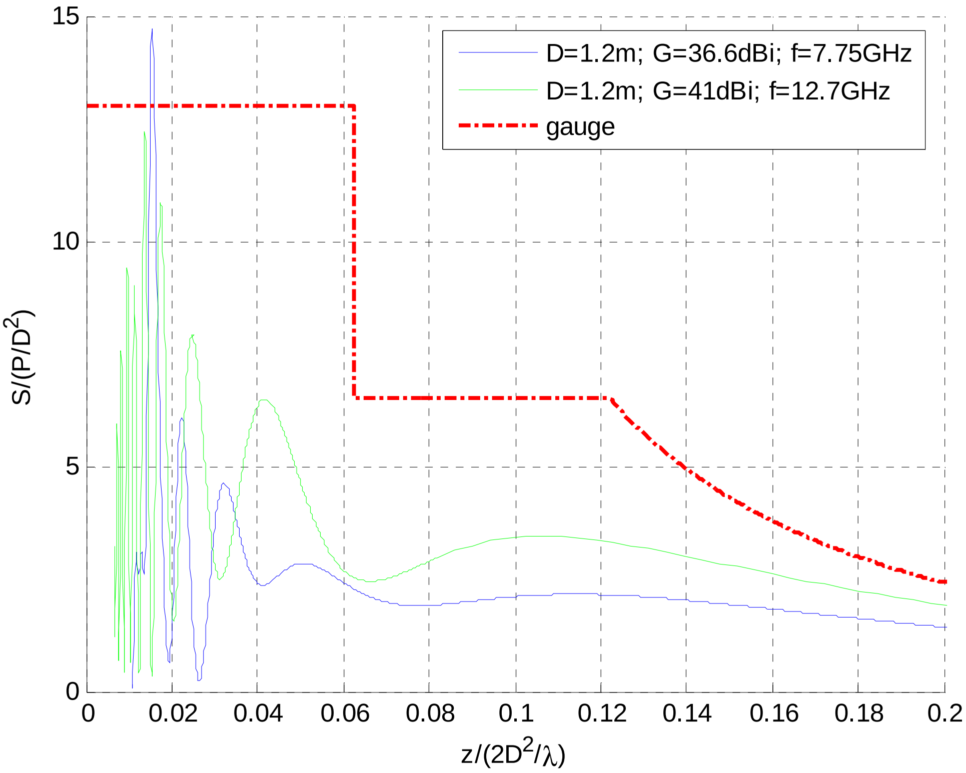


Figure B.4.1: Comparisons of normalized power density vs. format 13 envelope template

B.4.7.2 New 8 GHz 1,2 m diameter antennas

Following the first results, various parameters are varied to study the on-axis power density. The diameter and the frequency are 1,2 m and 7,75 GHz respectively as in the first example.

From a nominal dish antenna, the following configurations are considered:

- "point source": the real source is replaced by a point source with the same radiation pattern such that there is no masking by the source;
- "larger source": a larger source replaces the nominal one;
- "inclined shroud": perfect metallic inclined shroud is added as a model of shroud with absorbers;
- "less directive source": a less directive source replaces the nominal one;
- "lesser directive source": a lesser directive source replaces the nominal one.

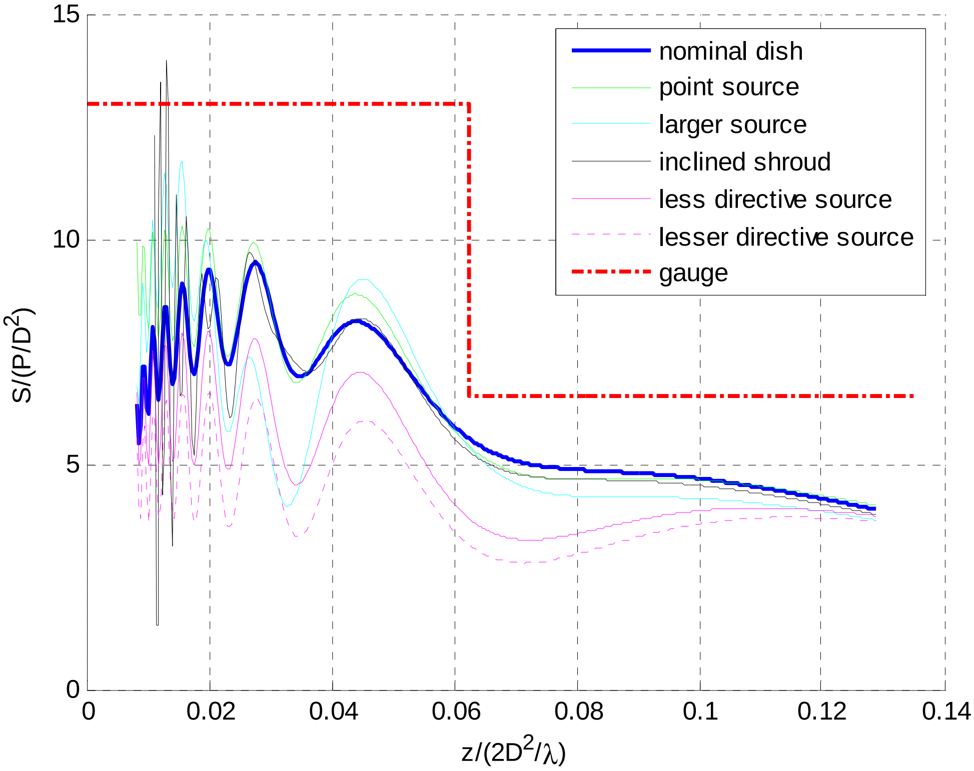


Figure B.4.2: Comparisons of normalized power density vs. format 13 envelope template

Figure B.4.2 compares the different configurations versus the format 13 envelope template. The inclined shroud, assumed to model a real shroud with absorbers, gives more realistic values with a slight exceeding of the envelope template.

In addition, the following observations can be made:

- "point source": as expected the power density is higher than in the nominal case;
- "larger source": the power density is lower on some part of the axis except close to the source;
- "less directive source": the power density is lower because more power is lost by spill-over;
- "lesser directive source": same as above.

B.4.7.3 Focal distance parametric analysis with new 8 and 13 GHz 1,2 m diameter antennas

To show the influence of efficiency on the on-axis power density, the focal distance is varied giving growing efficiency as the focal distance is increased.

Figures B.4.3 and B.4.4 show the results at 8 GHz and 13 GHz respectively. The higher is the efficiency, the lower is the power density.

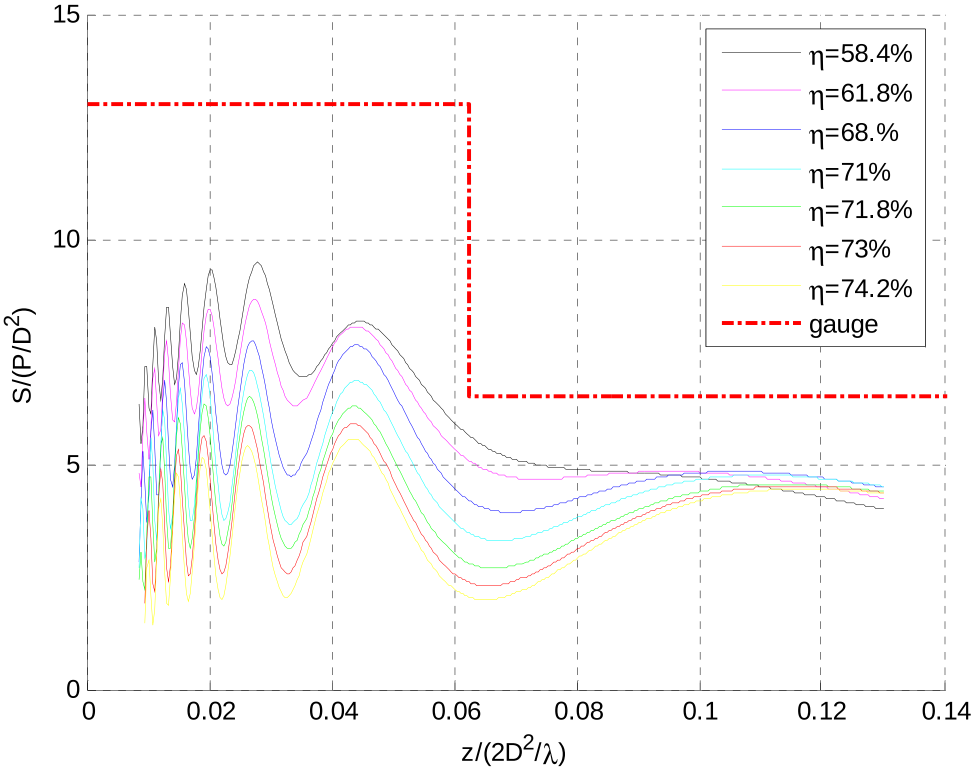


Figure B.4.3: Normalized power density vs. efficiency (focal distances) and format 13 envelope template @ 8GHz

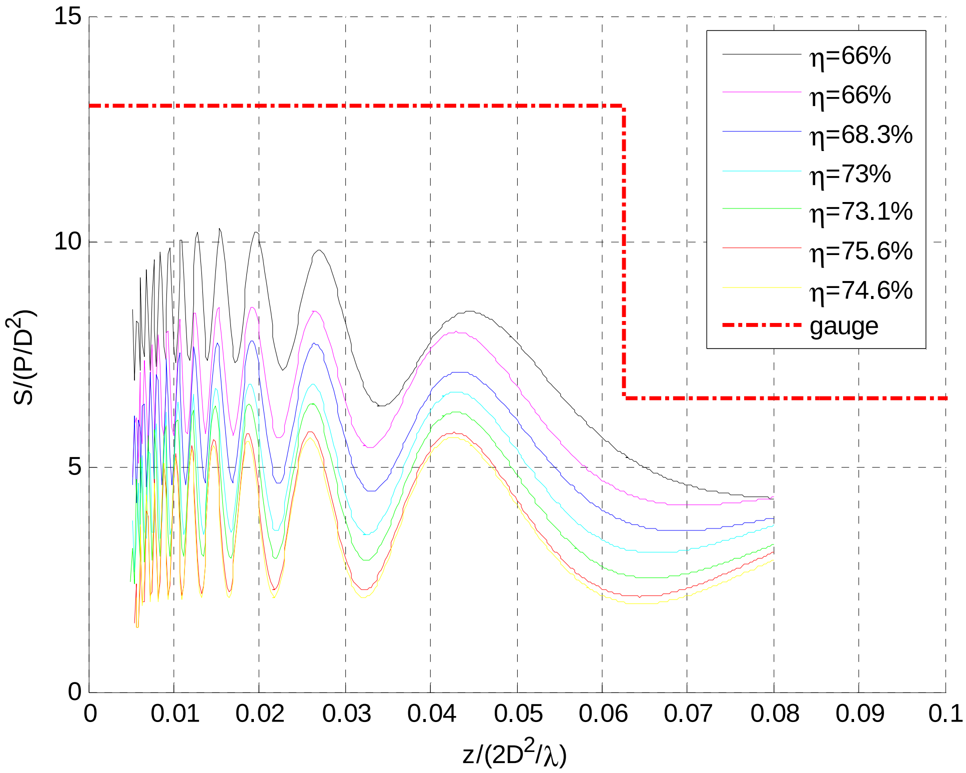


Figure B.4.4: Normalized power density vs. efficiency (focal distances) and format 13 envelope template @ 13GHz

History

Document history		
V1.1.1	August 2006	Publication