ETSI TR 102 457 V2.1.0 (2018-09)

Fixed Radio Systems;
Evaluation of the ElectroMagnetic Field (EMF) radiated by Line-of-Sight (LoS) fixed radio stations using parabolic dish directional antennas

Reference
RTR/ATTM-0444

Keywords
antenna, DFRS, DRRS, EMF, FWS, radio

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Sous-Préfecture de Grasse (06) N° 7803/88

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Access, Terminals, Transmission and Multiplexing (ATTM).

Modal verbs terminology

In the present document "**should**", "**should not**", "**may**", "**need not**", "**will**", "**will not**", "**can**" and "**cannot**" are to be interpreted as described in clause 3.2 of the ETSI Drafting Rules (Verbal forms for the expression of provisions).

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Introduction

The protection of the general public and workers from Electromagnetic Fields (EMF) is subject of EU and national regulations.

Basic information is generally taken from ICNIRP guidelines [i.6], while EU regulations setting harmonised exposure limits are provided in Council Recommendation 1999/519/EC [i.2] for general public and 2013/35/EU Directive [i.3] for workers.

EU member states may set more restrictive national limits for the general public, which will prevail on the EU ones; information on such national limits may be found in a European Commission implementation report [i.5].

EU RF exposure limits are expressed in terms of Basic Restrictions (BR, for general public) or Exposure Limitation Values (ELV, for workers); the entity placing the EMF transmitting equipment on the market and the entity putting it into in the affected environment (either with specific field tests or other specific protection measures) are assessing compliance of RF exposure with the limits defined in the above mentioned EU Recommendation and Directive. However, RF exposure assessment based on BR/ELV may be complex, for example when Specific Absorption Rate (SAR) needs to be measured below 10 GHz (for general public) or 6 GHz (for workers); therefore, both EU Recommendation [i.2] and Directive [i.6] have defined limits in terms of Reference Levels (RL, for general public) or Action Levels (AL, for workers) which are more easily tested/calculated Electric field (E) and/or Power density (S); they indicate that, whenever they are satisfied, also the BR/ELV are fulfilled.

One possible approach to the problem, according the EC Non-binding guide [i.4], is to test or calculate a conservative volume (compliance boundary) around the EMF source where the RL/AL limits are certainly respected; therefore, the need for EMF assessment of BR/ELV is limited only inside that volume, if accessible by general public or by workers.

Radio equipment are subject to 2014/53/EU Directive [i.1], which article 3.1a) requires self declared assessment also the "health" of persons; this might include considerations about the evaluation of the impact of the EMF radiated through the connected antenna based on the above RL or AL limits.

Assessment to article 3.1a of the 2014/53/EU Directive [i.1] of equipment in the scope of the present document may be carried on based on harmonised standards CENELEC EN 50385 [i.9] for placing equipment on the market and CENELEC EN 50401 [i.8] for putting them into service. Both harmonised standards rely on CENELEC EN 62232 [i.7] basic standard that provides the appropriate RF exposure assessment methods.

In case the radio equipment is supplied also with the antenna (or the manufacturer specifies the antenna characteristics to be connected to the equipment, as it is often the case for fixed service radio systems) the manufacturer might consider to calculate the above described compliance boundary within the technical documentation in support of the DoC to 2014/53/EU Directive [i.1] as support for the customer's further RF exposure assessment.

The present document describes one methodology for assessing that compliance boundary when the antenna of the fixed service radio system uses conventional passive directional antennas (parabolic dish).

1 Scope

The present document provides guidelines for assessing the compliance of human exposure to established RF exposure limits based on the evaluation of the electromagnetic fields in the main beam emission of fixed service radio (base) stations when operating in line-of-sight (LoS) using directional parabolic (dish) antennas (e.g. in Point to Point applications). The methodology may be applicable also to other fixed radio stations provided that they use similar directional parabolic antenna type (e.g. for some terminals in Point to Multipoint and Multipoint to Multipoint systems).

Fixed radio stations using sector and omni-directional antennas are not in the scope of the present document.

Fixed service radio stations in the scope of the present document may use integral/integrated antennas or dedicated antennas, supplied by the same manufacturer, or stand-alone antennas from different manufacturer, but compliant to radio equipment manufacturer specifications; detailed definition of those antenna types are found in ETSI EN 302 217-1 [i.10].

Article 3.1a of the 2014/53/EU Directive [i.1], provides essential requirement for health and safety. Council Recommendation 1999/519/EC [i.2] (for general public) and Directive 2013/35/EU (for workers) gives recommended limits for exposure to electromagnetic fields based on the ICNIRP guidelines [i.6]. Assessment of compliance to article 3.1a of the 2014/53/EU Directive [i.1] of equipment in the scope of the present document and to the requirements defined in the Directive 2013/35/EU [i.3] (for workers) and Council Recommendation 1999/519/EC [i.2] (for general public) may be carried on based on harmonised standards CENELEC EN 50385 [i.9] for placing equipment on the market and CENELEC EN 50401 [i.8] for putting them into service.

The present document considers these exposure limits for comparison; calculations and measurements are reported. The guidelines presented may be used for calculation of the compliance boundaries as required by CENELEC EN 50385 [i.9] and CENELEC EN 50401 [i.8].

The simplified assessment method described is derived from measurement and calculation techniques defined in clause 8 of CENELEC EN 62232 [i.7] (see note) and may help in the compliance assessment of the above mentioned fixed service radio stations.

Definitions from the above mentioned EN standards are used in the present document where appropriate.

NOTE: CENELEC EN 62232 [i.7] considers a very broad types of radio antennas used in Base Stations (including Fixed Radio Stations) and is presently limited to 100 GHz; however, in specific case of parabolic (dish) antennas, the electromagnetic field generation is dominated by purely geometrical factors (related to the D/λ ratio); therefore, the methodology in the present document is considered applicable also to fixed service stations operating at higher frequency up to 300 GHz.

The maximum electric field or 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

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative 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.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

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] Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC.

[i.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).

[i.3] Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (20th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC) and repealing Directive 2004/40/EC.

[i.4] Non-binding guide to good practice for implementing Directive 2013/35/EU Electromagnetic Fields: Volume 1 - Practical guide.

NOTE: Available at http://ec.europa.eu/social/main.jsp?catId=738&langId=en&pubId=7845.

[i.5] Report from the Commission on the application of Council Recommendation of 12 July 1999 (1999/519/EC) on the limitation of the exposure of the general public to electromagnetic fields (0 Hz to 300 GHz) - Second Implementation report 2002-2007.

NOTE: Available at http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52008DC0532.

[i.6] 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.

[i.7] CENELEC EN 62232 (2017): "Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure".

[i.8] CENELEC EN 50401 (2017): "Product standard to demonstrate the compliance of base station equipment with radiofrequency electromagnetic field exposure limits (110 MHz - 100 GHz), when put into service".

[i.9] CENELEC EN 50385 (2017): "Product standard to demonstrate the compliance of base station equipment with radiofrequency electromagnetic field exposure limits (110 MHz - 100 GHz), when placed on the market".

[i.10] ETSI EN 302 217-1: "Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 1: Overview, common characteristics and system-independent requirements".

[i.11] ETSI EN 302 326-2: "Fixed Radio Systems; Multipoint Equipment and Antennas; Part 2: Harmonised Standard for access to radio spectrum".

[i.12] 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".

[i.13] R. C. Hansen; L. F. Libelo: "Rapid Calculation of Near-field Fluence of High Power Microwave Antennas". IEEE Transact. EMC Year: 1992, Volume: 34, Issue: 3.

[i.14] C. Balanis: "Advanced engineering electromagnetics", ISBN: 978-0-470-58948-9.

[i.15] E.V. Jull: "Aperture Antennas and Diffraction Theory". IEEE Electromagnetic Waves Series ISBN: 978-0906048528.

[i.16] R. C. Hansen: "Circular-Aperture Axial Power Density". Microwave Journal (vol. 19, pp. 50-52, February 1976).

[i.17] R. W. Bickmore and R. C. Hansen: "Antenna Power Densities in the Fresnel Region". Proceedings IRE, vol. 47, pp. 2119-2120, 1959.

[i.18] 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:

action level (AL): action levels are provided for practical exposure-assessment purposes to establish boundaries, within which the Exposure Limits Values (ELV) are satisfied

NOTE: AL notation used is used in Directive 2013/35/EU [i.3], while "reference level" (RL) notation is used with similar meaning in Recommendation 1999/519/EC [i.2].

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

Base Station (BS): fixed equipment including the radio transmitter and associated antenna(s) as used in wireless telecommunications networks (CENELEC EN 50385 [i.9])

basic restrictions (BR): lawful limit for general public exposure to time-varying electric, magnetic, and electromagnetic fields (EMF) that are based directly on established health effects and biological considerations

NOTE: Basic restriction (BR) notation is used in Recommendation 1999/519/EC [i.2], while "Exposure Limits Values" (ELV) notation is used in Directive 2013/35/EU [i.3] with similar meaning.

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

NOTE: Outside the compliance boundary, the exposure levels do not exceed the basic restrictions (BR) or exposure limit values (ELV) irrespective of the time of exposure.

dish antenna: parabolic antenna usually used for radio-relays or point-to-point communications

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

NOTE 2: RL (for general public) and AL (for workers) are defined in term of E limits. Above 10 MHz (for general public) and above 6 GHz (for workers), alternative equivalent S limits are also defined.

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

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.

Exposure Limit Values (ELV): lawful limit for workers exposure to EMF, established on the basis of biophysical and biological considerations

NOTE 1: ELV notation is used in Directive 2013/35/EU [i.3], while "basic restriction" (BR) notation is used in Recommendation 1999/519/EC [i.2] with similar meaning.

NOTE 2: Same as note 2 to the definition of basic restriction (BR) above.

fixed radio station: radio station used for systems in the Fixed Service; typically for PP or Multipoint systems and included in the broader term "Base Station" in CENELEC EN 50385 [i.9]

parabolic antenna: See dish antenna.

Point Of Investigation: 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

NOTE 1: Lawful limits are expressed in S values above 10 GHz (for general public) or above 6 GHz (for workers).

NOTE 2: AL (for workers above 6 GHz) and RL (for general public) are defined in term of S limits. Alternative equivalent E limits are also defined.

Reference Level (RL): reference levels are provided for practical exposure-assessment purposes to establish boundaries, within which the relevant basic restriction (BR) are satisfied

NOTE: reference level (RL) notation is used in Recommendation 1999/519/EC [i.2], while Action Level (AL) notation is used, with similar meaning, in Directive 2013/35/EU [i.3].

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 (e.g. ICNIRP [i.6] assumes a typical value of 0,2 S/m)
ρ is density of body tissue in kg/m^3 (typically about 1 000 kg/m^3).

NOTE 3: Lawful limits are expressed in SAR values up to 10 GHz (for general public) or up to 6 GHz (for workers).

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_e	Equivalent antenna aperture (m^2)
A_0	Reference area 20 cm^2 for spatial averaging
CD_{los}	Compliance distance (to the AL or in the line of sight
Din	Inner diameter of the antenna (m)
Dout	Outer diameter of the antenna (m)
E	Electromagnetic field (V/m)
E_{lim}	Electromagnetic field limit value (V/m) of AL (for general public) or RL (for workers)
F	Peak to average factor of the power density (S)
G	Antenna gain
m_0	Reference mass 10 g for spatial averaging (expressed in kg)
P	Power transmitted by the antenna
r	Distance between the point of investigation and the antenna

NOTE: Some figures in the annexes the notation "z" is alternatively used and in some phormulas the alternatively notation ρ is alternatively used.

R_{ff}	Far-field distance

NOTE: Some figures in the annexes the notation r_{FAR} is alternatively used.

R_{lim}	Extension of compliance boundary
rms	root mean square
S	Power density (W/m^2) at distance r (m) from the antenna

NOTE: Not to be confused with "S" abbreviation of the unit "Siemens" used as S/m in conductivity (σ).

S_{ff}	Power density at a distance R_{ff} from the antenna
S_{lim}	Power flux density limit value (W/m^2) of AL (for general public) or RL (for workers)
S_{max}	Maximum power density (W/m^2) spatially averaged over 20 cm^2
S_n	Power density normalized to P/D^2
SAR_{lim10g}	Specific Absorption Rate (W/kg) on 10g contiguous tissue; lawful limit value
x	Normalised distance (Ratio of distance to the antenna (r) and Rff)
z	See r

3.3 Abbreviations

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

AL	Action Level
BR	Basic Restriction
BS	Base Station
CAD	Computer Aided Design
EIRP	Equivalent Isotropically Radiated Power
ELV	Exposure Limit Value
EMC	ElectroMagnetic Compatibility
EMF	ElectroMagnetic Field
EUT	Equipment Under Test
FCC	Federal Communications Commission
MMF	Mobile Manufacturers Forum (MMF)

NOTE: From Jan 1st 2017 changed into Mobile & Wireless Forum (MWF).

MoM	Method of Moments

RF	Radio Frequency
RL	Reference Level
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 about 1,3 GHz up to 86 GHz and beyond. Details are given in ETSI EN 302 217-1 [i.10] and ETSI EN 302 326-2 [i.11].

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 both transmit power and antenna gain. Representative values can be found in ETSI TR 102 243-1 [i.12].

Licensed EIRP is generally regulated on link-by-link basis through Remote Transmit Power Control (RTPC) functionality; however, when generic equipment assessment for article 3.1a of the 2014/53/EU Directive [i.1] is concerned (i.e. for placing equipment on the market through application of CENELEC EN 50385 [i.9]) the maximum EIRP delivered by the equipment through the highest foreseen antenna gain may be used for defining the safeguard boundaries valid for all stations.

When put into service (i.e. through application of CENELEC EN 50401 [i.8]) the actual licensed EIRP (including any positive tolerance, if any) could be used; however, the real field conditions should also be considered (e.g. presence of more than one systems in the same location).

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 and omni-directional antennas

Sectorial and omni-directional antennas are not in the scope of the present document.

4.2 Point-to-point fixed radio stations

Point-to-point fixed radio stations , similarly to macro-cells base stations in mobile systems, are installed in towers, masts, on rooftops or in similar locations. The main design criteria consists in having the two corresponding 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.

The above situation establishes a special condition for these systems: unavailability of the radio path for the general public. Nevertheless, care should be taken (see note) when very short links are deployed at street level (i.e. buildings might be immediately beyond the receiver station).

NOTE: In literature, some systems (e.g. high power radars) have an obstruction avoidance mechanism which will immediately (i.e. within less than 1 s) stop the transmission if a person is staying in the main lobe of the antenna. Such mechanism, might also be taken into account when appropriate.

4.3 Multipoint fixed radio stations

Multipoint communication systems are communication systems between multiple (source) terminal stations access points and a single (destination) base station access point for bi-directional asymmetric, bi-directional symmetric, or unidirectional communication.

Base stations for multipoint fixed radio systems, not in the scope of the present document, are installed in towers, masts, on rooftops or in similar locations.

Terminal stations, in the scope of the present document when using directional parabolic-like antennas, are considered similar to point-to-point stations and can be deployed in similar conditions.

5 Antenna properties

5.1 Near-field and 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.

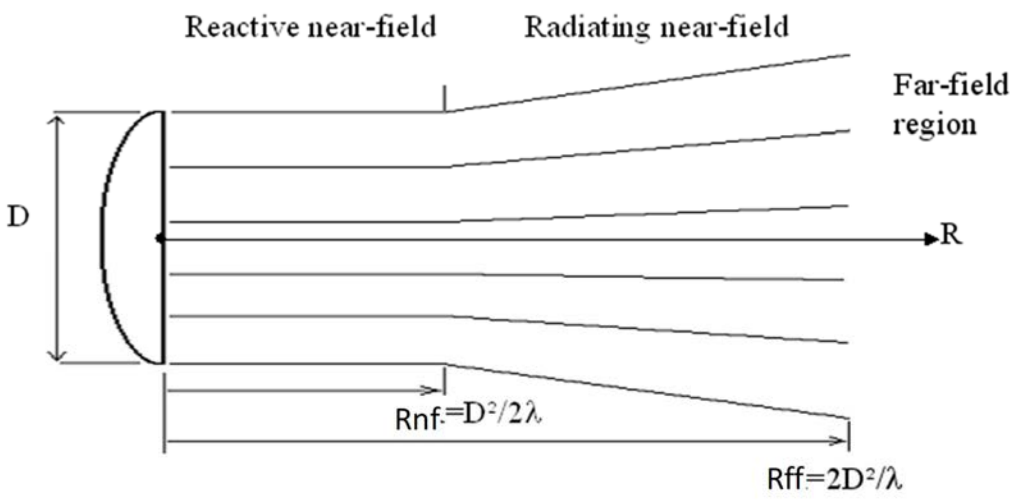


Figure 5.1: Near-field / far-field representation

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 cannot always be evaluated. In this case, the outer diameter can be used for assessment.

5.3 Parameter description

The physical entities that are generally used for RF exposure assessment for dish antennas are the following:

- **S [W/m²]**: Power Flux Density.
- **E [V/m]**: Electric field strength (rms).

In the present document, the power flux density or the electric field strength are used to represent the magnitude of the electromagnetic field using plane wave equivalent assumption.

5.4 Relationship between parameters (localised SAR, S, E)

Starting from the lower limit of reactive field (min (3λ, $D^2/2\lambda$)), S and E are related by the following formula using plane wave equivalent assumption:

$$S_{[W/m^2]} = \frac{E^2_{[V/m]}}{\sqrt{\mu/\varepsilon}} = \frac{E^2_{[V/m]}}{120*\pi} \approx \frac{E^2_{[V/m]}}{377} \quad (5.1)$$

Where RF exposure limits are defined in [i.2] and [i.3] both in terms of E and S, the respective limits are related by the above formula.

ICNIRP guidelines [i.6] as well a European Recommendation (1999/519/EC [i.2]) and European Directive (2013/35/EU [i.3]) consistently define the localized SAR over a mass m_0 = 10 g of contiguous tissues (hence SAR_{10g} notation). They also consistently define that power density (S) should be averaged over A_0 = 20 cm^2 of exposed area.

In the frequency range above 1,3 GHz where SAR is used as BR/ELV, as demonstrated in annex C, the power f lux density can be used to derive a majorant value of local SAR using formula (5.2).

$$\frac{SAR_{10g}\left[W/kg\right] \bullet m_0\left[kg\right]}{A_0\left[m^2\right]} \leq S\left[W/m^2\right] \quad (5.2)$$

In this frequency range, we can then assume that if E ≤ Elim or S ≤ Slim, then SAR ≤ SARlim, using the values of Elim and Slim defined in equations (5.3) and (5.4). This confirms that, compliance criteria based on Elim and Slim (i.e. equivalent to RL/AL) can be considered as a conservative assessment based on localized BR/ELV.

$$E_{\lim}\left[V/m\right] = \sqrt{\frac{120 \bullet \pi \bullet SAR_{\lim 10g}\left[W/kg\right] \bullet m_0\left[kg\right]}{A_0\left[m^2\right]}} \quad (5.3)$$

$$S_{\lim}\left[W/m^2\right]=\frac{SAR_{\lim 10g}\left[W/kg\right]\bullet m_0\left[kg\right]}{A_0\left[m^2\right]} \quad (5.4)$$

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 EMF exposure limits

6.1 Introduction

6.1.1 Applicability of limits

The following clauses recall the RF exposure limits defined in Recommendation 1999/519/EC [i.2] for the general public and in Directive 2013/35/EU [i.3] for workers. These limits for exposure levels are in line with the ICNIRP Guidelines [i.6] and expressed, for general public, in terms of basic restrictions (BR) and reference levels (RL) and, for workers, in terms of exposure limit values (ELV) and action levels (AL), which depend on the frequency (f) of emissions.

However, some countries have adopted more stringent limits in their national legislation; therefore, 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. An informative list of national restrictions for general public is available at [i.5].

NOTE: In the implementation of the Directive 2013/35/EU, only "thermal effects" are considered in the present document; sensory effects (e.g. auditory effects related to peak of low duty cycle EMF pulses at frequency up to 6 GHz), are not referred in the present document because not relevant for FS systems continuous emissions (FDD) or with high duty cycle (about 50 % in TDD systems). See also Appendix B.5 of the EC non binding guide [i.4], which mentions pulse duration in the order of few tenths of microseconds; for example a pulse of 30 microseconds at the maximum 10 mJ/kg limit, presents an average peak power of $0,01/(30\times10^{-6}) = 330$ W/kg, far beyond the 10 W/kg of the localized SAR limit.

6.1.2 Applicable frequency bands

In general, EU and national legislations covers the whole range from 0 to 300 GHz; however, fixed service radio (base) stations, in the scope of the present document, are assumed to operate in the range from about 400 MHz to about 100 GHz for consistency with existing basic standards such as CENELEC EN 50385 [i.9] and CENELEC EN 62232 [i.7]. Therefore, only the regulatory limits within this frequency range are taken into consideration. However, the methodology in the present document is considered applicable also for fixed service stations using dish antennas operating at higher frequencies up to 300 GHz.

6.2 General public exposure

Basic restrictions and reference levels for the general public in Recommendation 1999/519/EC [i.2] are summarized in table 6.1.

Table 6.1: General public EMF exposure limits (for practical fixed links frequency ranges)

Frequency range	Localized SARlim10g (head & trunk) (W/kg) (1) (4)	Plane wave power density S (W/m^2) (1) (2) (3)		Electric field strength E (V/m)
400-2 000 MHz	2	f [MHz]/200 (5)		1,375 * √f [MHz] (5)
2-10 GHz	2	10 (5)		61 (5)
10-300 GHz	–	10	10 (5)	61 (5)

(1) Yellow solid-filled cells contain Basic Restrictions (BR). Other cells give the Reference Levels (RL), within which the basic restrictions are certainly satisfied and specific assessment is not required.
(2) For frequencies up to 10 GHz, S is to be averaged over any period of 6 minutes.
(3) For frequencies exceeding 10 GHz, S is to be averaged over any period of 68/(f^1,05 minutes) (f in GHz).
(4) Only the localized SAR restriction is here reported because the "whole body" restriction is not relevant for LoS fixed links; General public cannot physically stand permanently (> 6 minutes) in the LoS path and their major protection limitation would fall under the "reference levels" restrictions, expressed in term of E or S parameter only.
(5) RL is expressed in equivalent terms for E and S (from equation 5.1 in clause 5.4).

6.3 Occupational exposure

Exposure limits and action levels for the workers in [i.3] are summarized in table 6.2.

Table 6.2: Occupational EMF exposure limits (for practical fixed links frequency ranges)

Frequency range	Localized SARlim10g (head & trunk) (W/kg) (1) (5)	Plane wave power density S (W/m^2) (1) (2) (3)		Electric field strength E (V/m)
400-2 000 MHz	10	(6)		0,003 * √f [Hz]
2 000-6 000 MHz	10	(6)		140
6-300 GHz	-	50 (4)	50 (7)	140 (7)

(1) Jellow solid-filled cells contain Exposure Limit Values (ELV). Other cells give the Action Levels (AL), within which the Exposure Limits are certainly satisfied and specific assessment is not required.
(2) For frequencies between 6 GHz and 10 GHz, S is to be averaged over any period of 6 minutes.
(3) For frequencies exceeding 10 GHz, S is to be averaged over any period of 68/(f^1,05 minutes) (f in GHz).
(4) The power density S should be averaged over any 20 cm^2 of exposed area.
(5) Only the localized SAR restriction is here reported because the "whole body" restriction is not relevant for LoS fixed links; General public can not physically stand permanently (> 6 minutes) in the LoS path and the presence of "Occupational" personnel is only occasional during short periods for equipment maintenance and their major protection limitation would fall under the "action levels" restriction (Annex III of Directive 2013/35/EU [i.3]), expressed in term of E or S restriction only.
(6) AL in the range 400 MHz to 6 000 MHz are defined in electric field strength (E) only; however, S power density may be derived from eqation 5.1 in clause 5.4.
(7) AL is expressed in equivalent terms for E and S (from equation 5.1 in clause 5.4).

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. As defined in CENELEC EN 62232 [i.7] (clause 8.3 and annex B.4.2.1.1.2), the power density in the far-field is given by:

$$S = \frac{PG}{4\pi r^2} \qquad (7.1)$$

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

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

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.

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

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 derived from advanced simulation methods defined in clause 8.3 and annex B.4.4 of CENELEC EN 62232 [i.7].

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 GHz 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/electric field upper bound

According to the series of measurement and simulation results presented in annexes, figure 7.1 shows the normalized envelope templates of the upper bound of the corresponding electric field (E), or of the power density (S), in the near-field in the main lobe of the antenna.

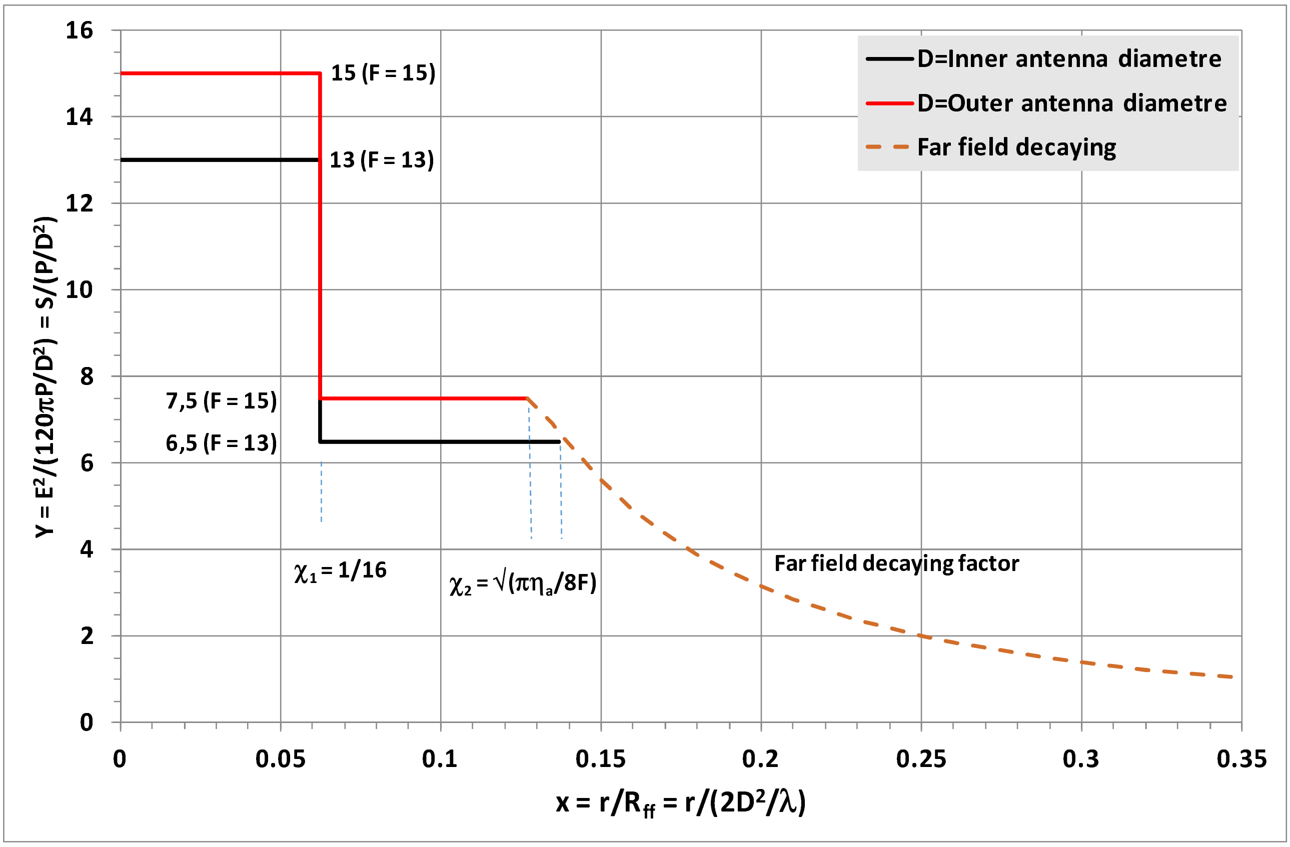


Figure 7.1: Envelope template for the power density in the main lobe of parabolic antennas

Where:

- r is the distance from the antenna.
- P is the power expressed in W.
- F is the peak to average factor of S in the near field (see clause B.3); 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 (see clause A.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; however, they should be consistent each other through the related aperture efficiency η_A.

  Applying the formula (A5), X_2 is also given using the formula $\chi_2 = \sqrt{\frac{\pi\eta_A}{8F}}$;

EXAMPLE: With practical efficiency η_A ranging from 0,5 to 0,75 when using inner diameter (F = 13) χ_2 is ranging from 0,12 to 0,15.
Far field decaying factor, shown in the above graphic example, is derived from figure A.2 according η_A = 0,62 (see note).

- 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).

NOTE: In some practical cases, only the actual gain G is certainly known from the manufacturer data; in this case the "D" parameter of the "inner" template can be converted into "G" parameter through the equation (A.5) in clause A.1.2 with the aperture efficiency parameter η_A set, conservatively to 1.

8 Assessment of compliance to limits

8.1 General

The requirements for the assessment of compliance with the Directives 2014/53/EU [i.1] and 2013/35/EU [i.3], when placing the equipment on the market, are defined in CENELEC EN 50385 [i.9], which requires the evaluation of the *compliance boundary* using the assessment methodologies defined in CENELEC EN 62232 [i.7]. Additional guidance may be found in the "infrastructure" part of table 3.2 of the EC guide [i.4].

From the considerations and equivalence formulas in clause 5.4, the *compliance boundary* may be considered that where S_{lim} or E_{lim} (from equations (5.3) and (5.4) and equivalent to the RL/AL limits) are not exceeded.

8.2 Compliance boundaries evaluation

Based on the rationale presented in clause 5.4 and annex C, RF compliance boundaries should be assessed according to the simplified assess method described in the flow chart represented in figure 8.2, which applies to both general public and occupational exposure situations. They are based on the following assumptions:

- Conservative assessment of BR/ELV using E or S above 1,3 GHz.
- Compliance touch (CD_{los} = 0) means that BR/ELV 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 the simulations and tests reported in annex B (e.g. clause B.1.1.2); spatial averaging is considered appropriate according to all EU regulations, standards and guidelines [i.2], [i.3], [i.4] [i.6], [i.7] and [i.9].
- The compliance boundary, if not zero, is a cylinder defined by the line of sight axis and the diameter D_{out} up to the compliance distance CD_{los} (cf. figure 8.1).

Attention should be given to the use of D and/or G for defining CD_{los}; they are related through the equation (A.5) in clause A.1.2 with the aperture efficiency parameter η_A. In particular, when only G is known, the true D should be evaluated using, conservatively, η_A = 1. Also the examples reported in table 8.1 are calculated from given D values and assuming η_A = 1.

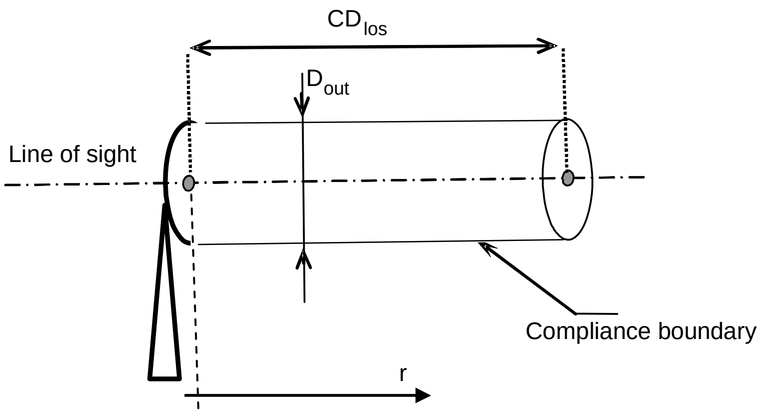
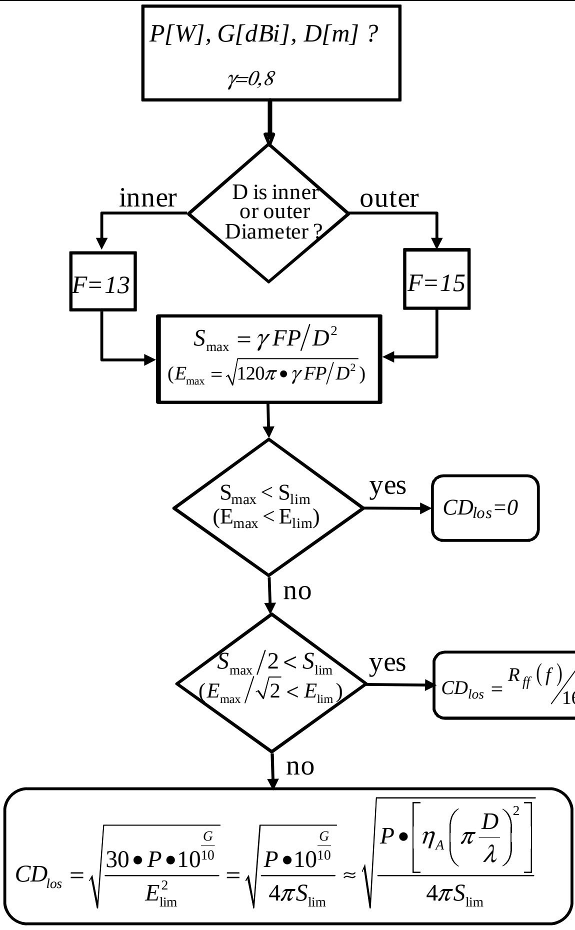


Figure 8.1: Transmitter compliance boundary



Legend:

γ	is the factor used for spatial averaging
λ	is the wavelength (m)
CD_{los}	is the compliance distance in the line of sight (m)
r	is the distance between the point of investigation and the antenna (m)
R_{ff}	is the far-field distance (m) (see clause 5.1)
P	is the power transmitted to the antenna (W)
D	is the diameter of the antenna (m), can be equal to Din (inner diameter) or Dout (outer diameter)
G	is the antenna gain (dBi)
η_A	is the antenna aperture efficiency (see clause A.1.2)
S_{lim}	is the applicable RL/AL limit for power density (W/m^2), equal to BR/ELV (for frequencies where the BR/ELV are also expressed by power density) or equivalent to $SAR_{lim} \times m_0/A_0$ (for frequencies where the BR/ELV are expressed in terms of SAR, see equation (5.4))
m_0	is the 10 g reference mass (expressed in kg) for spatial averaging
A_0	is the 20 cm^2 reference area (expressed in m^2) used for spatial averaging
SAR_{lim}	is the applicable limit for local SAR for m_0
S	is the power density (W/m^2) at distance r (m) from the antenna
S_{max}	is the upper bound of maximum power density spatially averaged over 20 cm^2 produced by the antenna
E_{lim}	is the spacially averaged E-field (V/m) corresponding to Slim (i.e. $E_{lim} = \sqrt{(120 \pi S_{lim})} \approx \sqrt{(377 S_{lim})}$ according to equation (5.1))

Figure 8.2: Simplified method for assessment of the compliance distance in the line of sight of parabolic antennas above 1,3 GHz

8.3 Tabulated values

Compliance distances for typical systems up to 55 GHz defined in ETSI TR 102 243-1 [i.12] are provided in table 8.1 based on the equations provided in figure 8.2 in function of inner D; data for 81 GHz systems are also provided. 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

Case N°	Frequency (GHz)	Max Power (dBm)	Antenna inner diameter (m)	Efficiency η_A = 1 (note 1)		Efficiency η_A = 0,62 (note 2)	
				Estimated G (dBi)	CD_{los} (m)	Estimated G (dBi)	CDlos (m)
1	6	32	1,8	41	0	39	0
2	8	32	1,2	40	4,8	38	4,8
3	18	27	0,6	41	2,7	39	2,7
4	23	25	0,3	37,2	3,6	35,1	2,9
5	23	25	1,2	48,2	0	47,1	0
6	38	23	0,2	38	3,2	36	2,5
7	38	23	0,6	47,5	0	45,5	0
8	55	9	0,1	35,2	0	33,1	0
9	81	18	0,6	54,1	0	52	0
10	81	18	0,2	44,6	1,35	42,5	1,35
11	81	18	0,1	38,6	1,9	36,5	1,5
NOTE 1: Conservative CD_{los} calculation from the inner diameter.							
NOTE 2: Column given for reference to the average CD_{los} typically approaching the limits.							

In table 8.1 two columns of estimated gain and CD_{los} are provided calculated from the inner diameter assuming different efficiency factor η_A for the gain. The typical η_A = 0,62 is that used in figure 7.1 for deriving the far field decaying function, while the η_A = 1 is used for conservative results. However, actual differences are limited only to three cases where a relatively high power coupled to a relatively small antenna so that Smax > Slim (i.e. CD_{los} given by equation (7.1)).

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 Recommendation 1999/519/EC [i.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_i and above the upper line the compliance distance is given by equations (7.1) or (7.2) or (7.3) as convenient. Dots in the figure represent the data in table 8.1 relative to η_A = 1.

Figure 8.4 relates the compliance distance corresponding to χ_1 versus frequency and antenna size with the limit 10 W/m^2. The three cases in figure 8.3 falling inside the lines (i.e. cases 2, 3 and 10) are also evidentiated with their case number.

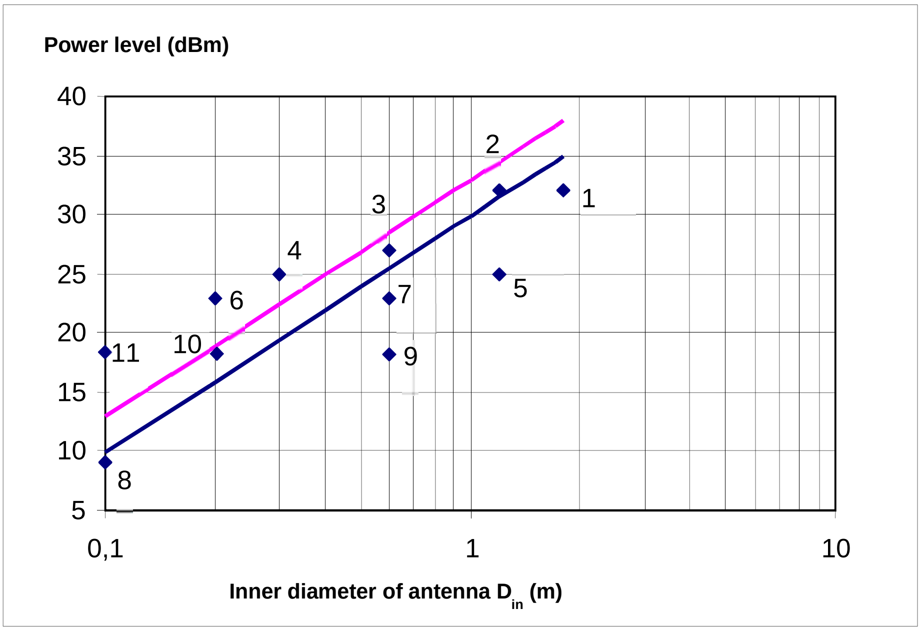


Figure 8.3: Graphical assessment of compliance boundary

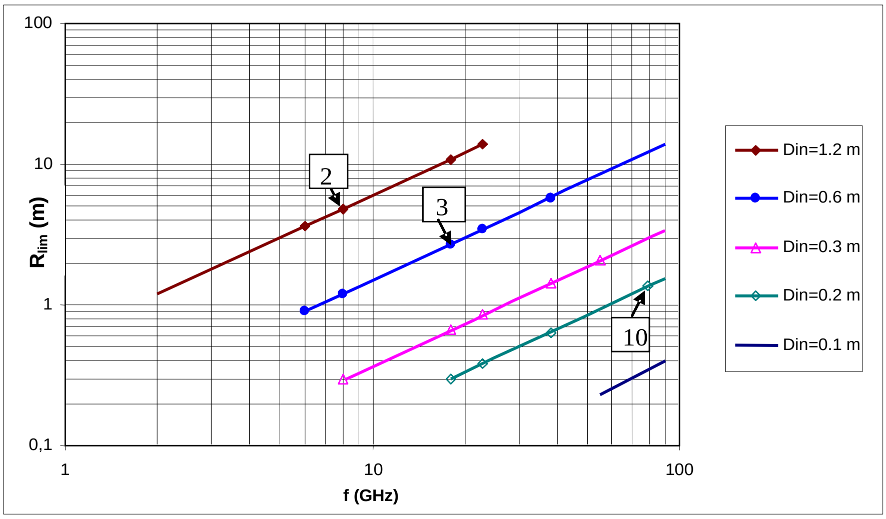


Figure 8.4: Limit distance versus frequency for 0,1 m to 1,2 m antennas

8.4 Examples for equipment with different antenna size

In most cases, fixed radio systems use dedicated or stand-alone antennas of different size/gain for covering various link length range.

In such case it may be useful to draw graphs of CD_{los} versus antenna size with the maximum power (including tolerance) delivered by the equipment.

Figures 8.5, 8.7 and 8.9 show the evaluation of the CD_{los}, versus antenna size, using the true electrical inner D, or real gain G, for three example equipment operating at 8 GHz, 23 GHz and 81 GHz with maximum Pout.

The graphs are calculated from inner D, or real gain G, using conservatively η_A.= 1.

Figures 8.6, 8.8 and 8.10 show the evaluation, for the same above equipment, of the maximum peak power S_{max} in near field for both true electrical inner D and raw outer D (see clauses B.3.2.3 and B.3.2.4). It may be seen that, when S_{max} goes below S_{lim}, the corresponding CD_{los} (in figures 8.5, 8.7 and 8.9) drops to practically 0 (touch compliant).

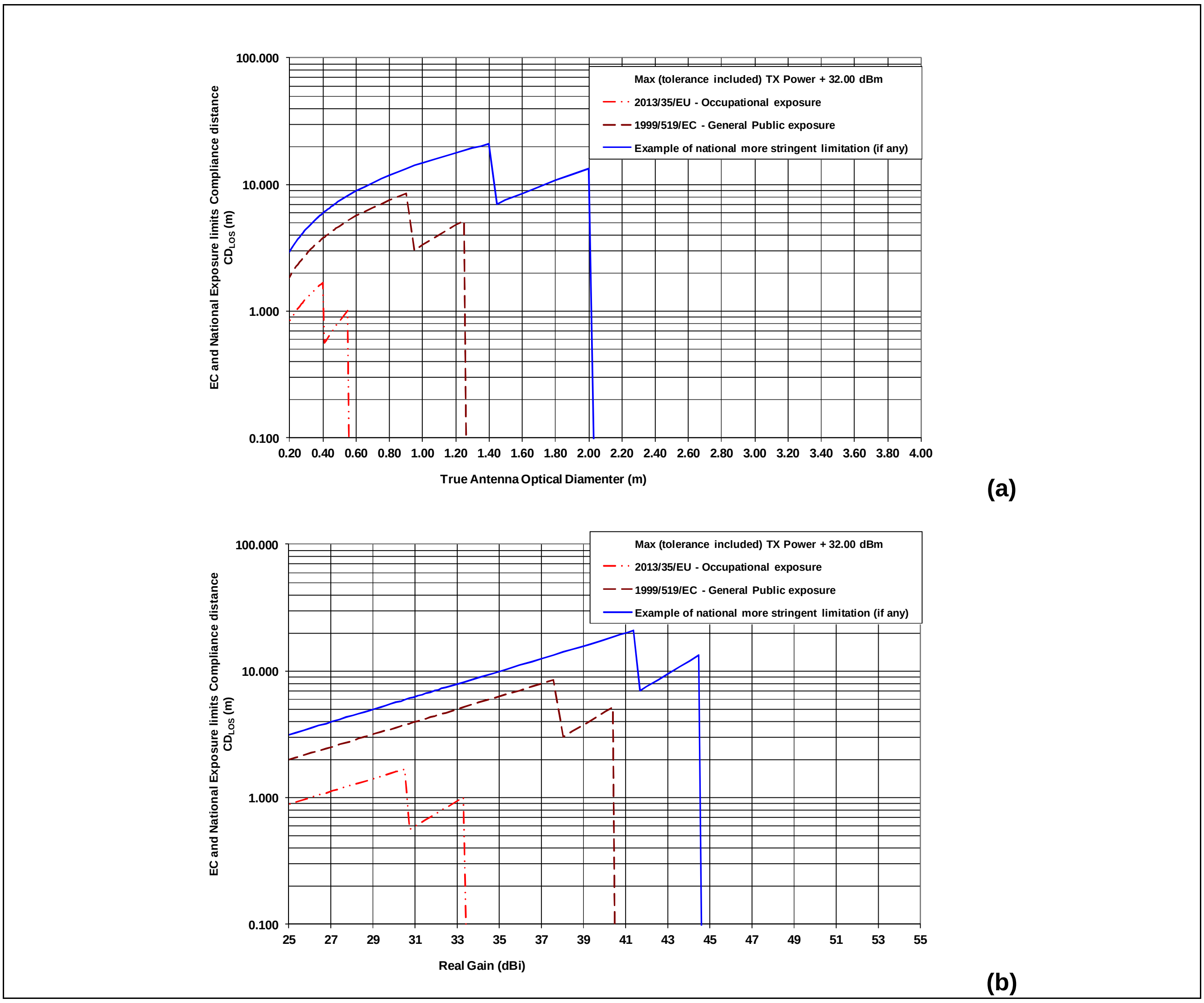


Figure 8.5: CDlos versus inner antenna diameter (a), or real gain (b) for 8 GHz equipment at maximum nominal power

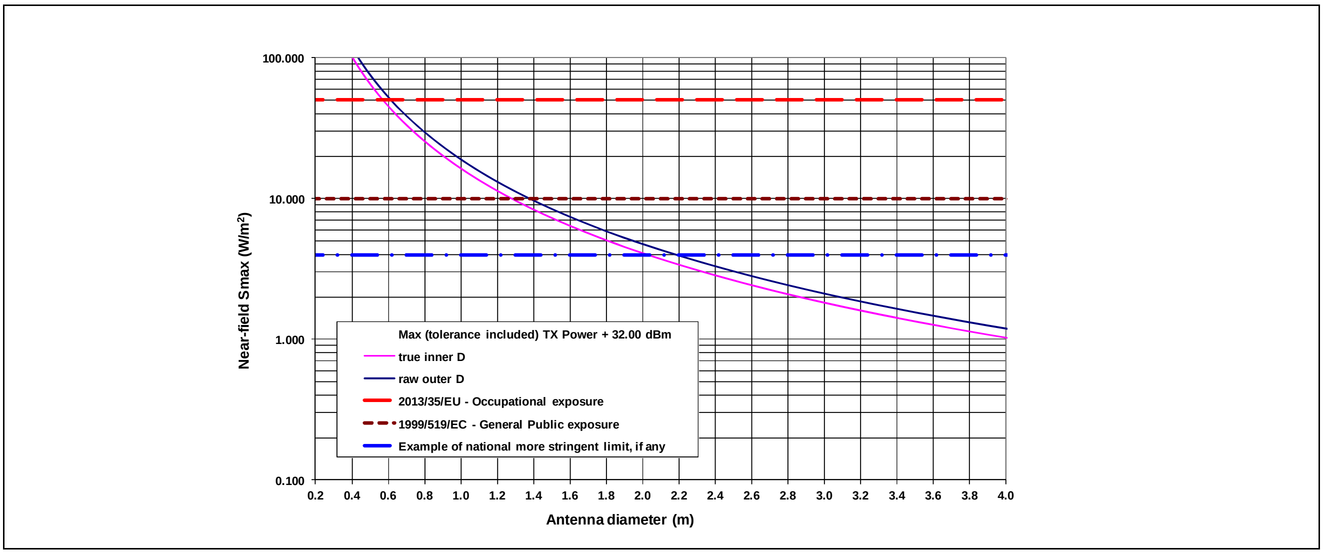


Figure 8.6: Near field Smax (peak value) versus antenna diameter for 8 GHz equipment at maximum nominal power; evaluation with various regulatory limits

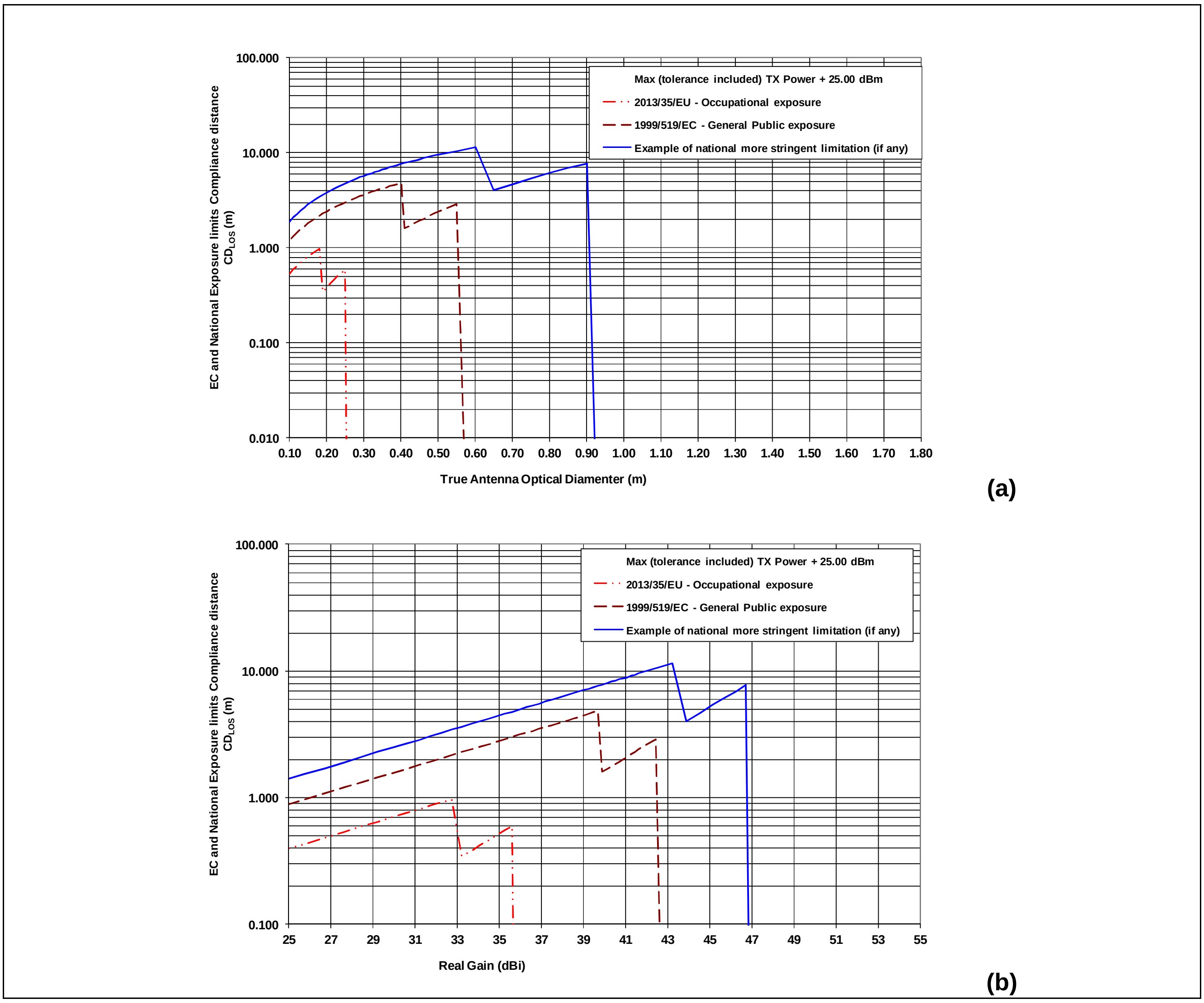


Figure 8.7: CD_{los} versus inner antenna diameter (a), or real gain (b) for 23 GHz equipment at maximum nominal power; evaluation with various regulatory limits

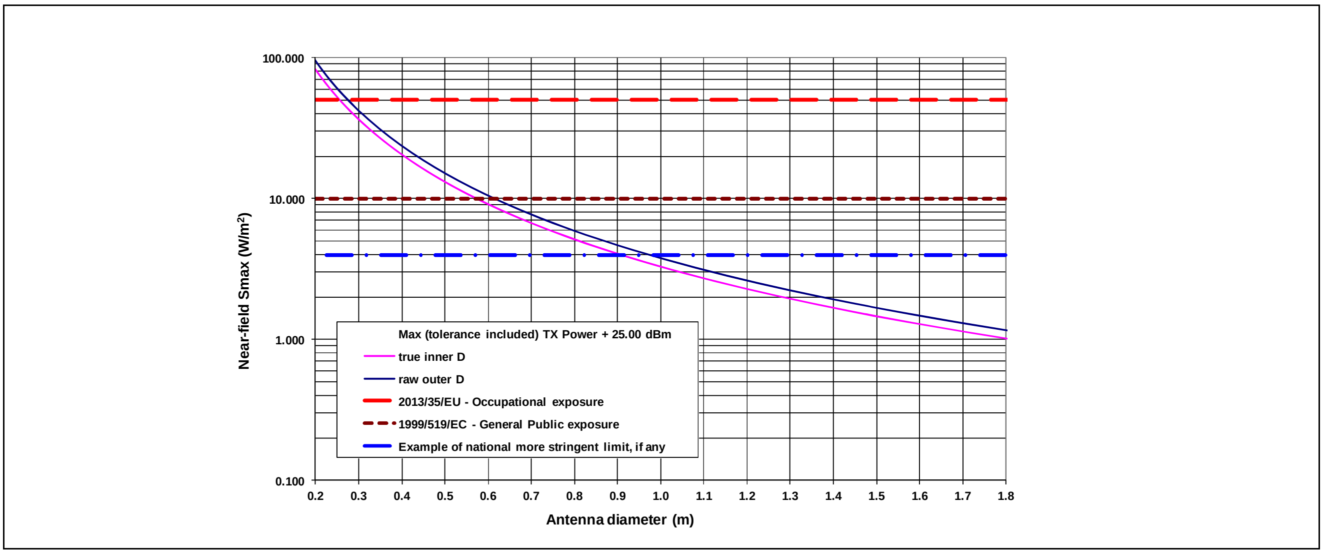


Figure 8.8: Near field Smax (peak value) versus antenna diameter for 23 GHz equipment at maximum nominal power; evaluation with various regulatory limits

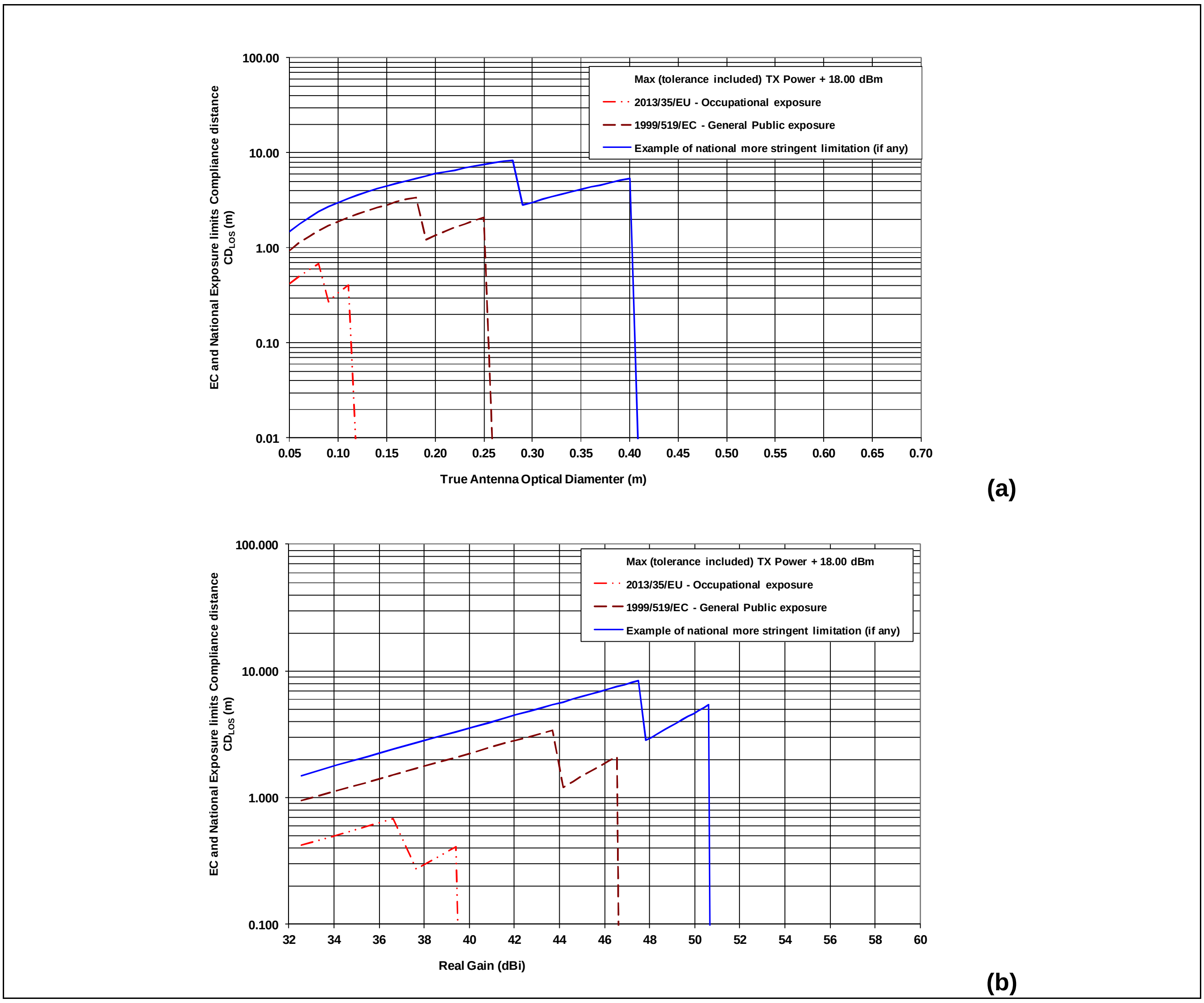


Figure 8.9: CD_{los} versus inner antenna diameter (a), or real gain (b) for 81 GHz equipment at maximum nominal power; evaluation with various regulatory limits

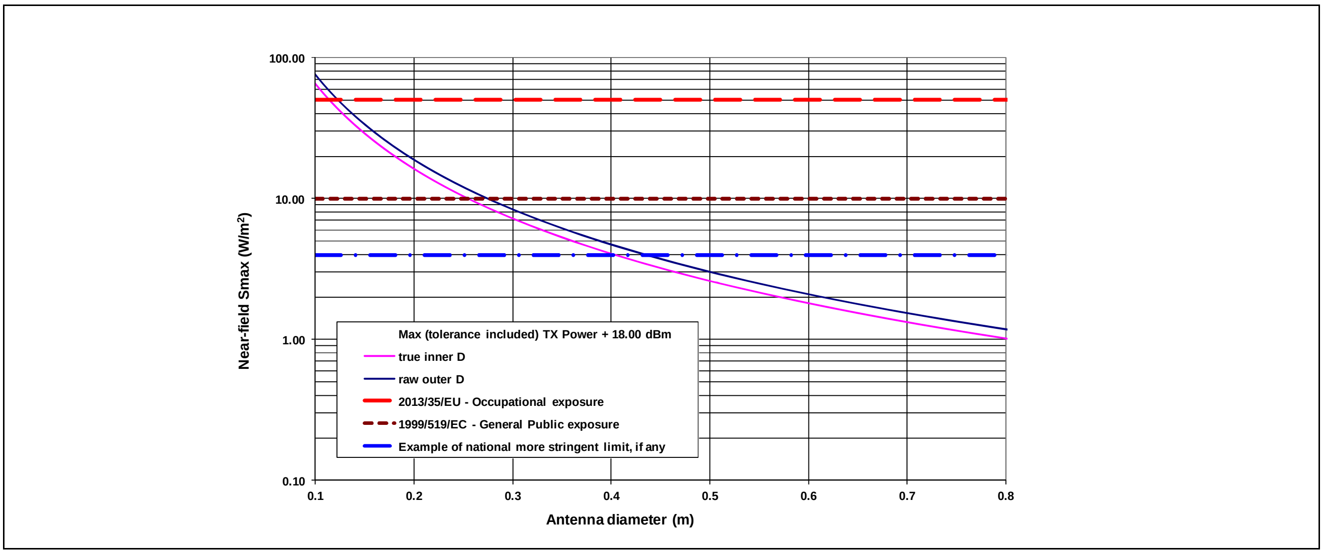


Figure 8.10: Near field Smax (peak value) versus antenna diameter for 81 GHz equipment at maximum nominal power; evaluation with various regulatory limits

Annex A: Power density calculations

A.1 Near-field calculations using the Fresnel transform

A.1.0 Introduction

The near-field high frequency limit field on the axis is expressed via the Fresnel transform (Jull 1981 p.32 [i.15], Bickmore/Hansen 1959 [i.17] and Hansen 1976 [i.16]). For finite frequencies the result is a lower power density. The full Maxwell solution is found in e.g. Balanis [i.14]. According to Hansen-Libelo 1992 [i.13] 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 [i.13] and Jull Edvard J. [i.15]. The Fresnel transform is an approximation in two respects, namely:

- high frequency D >> λ;
- 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 should be alternatively regarded.

A.1.2 Scaling factors

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

$$r = xR_{ff} \tag{A.1}$$

where:

$$R_{ff} = \frac{2D^2}{\lambda} \tag{A.2}$$

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

$$S_n = \frac{S}{P / D^2} \tag{A.3}$$

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 $\frac{D}{\lambda} >> 1$

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

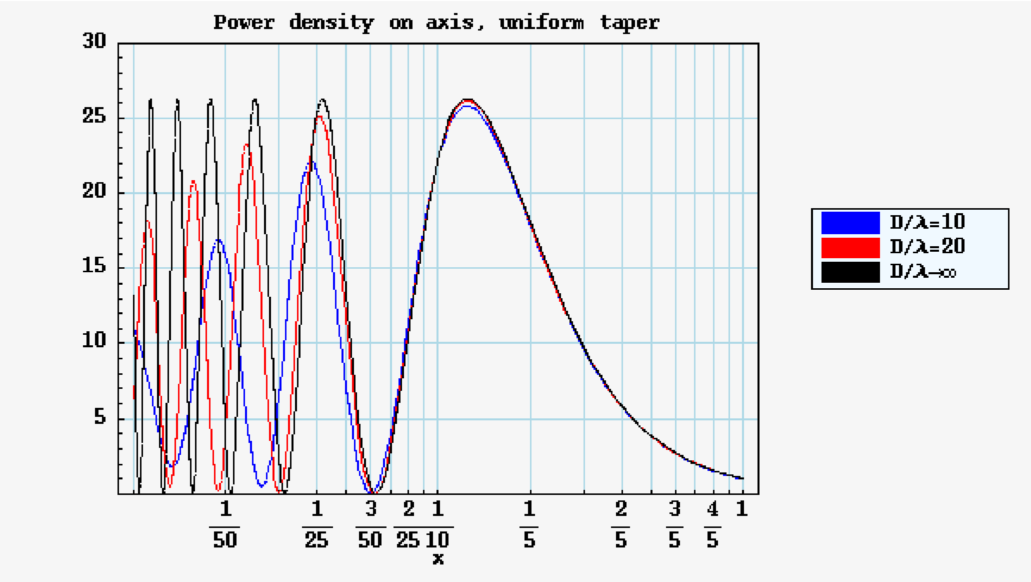
E_a is the electric field distribution over the antenna aperture. The constant is evaluated knowing the power density at normalized distance $x = 1$ given by equation (A.4).

A.1.4 Results

A.1.4.0 General trend

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



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

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

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

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

Note the normalization to unity at x = 1 following Bickmore and Hansen [i.17]. Moreover, the Fresnel zones are manifest and distinct with boundaries (the zeros or local minima of equation (A4)) at:

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

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.

$$E(r) = a + (1 - a)(1 - (r / a)^2)^N \tag{A.9}$$

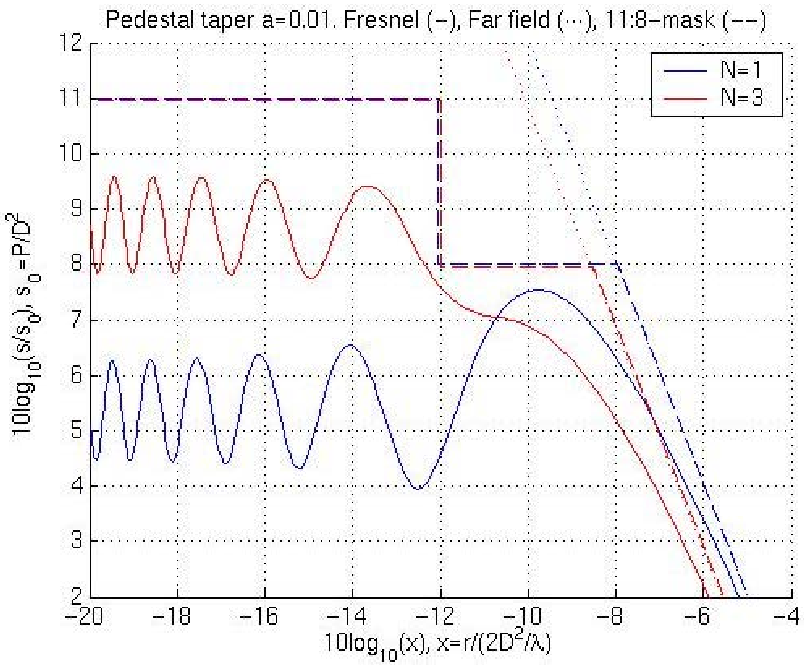
and the circular Taylor taper [i.16] and figure A.3.

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

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

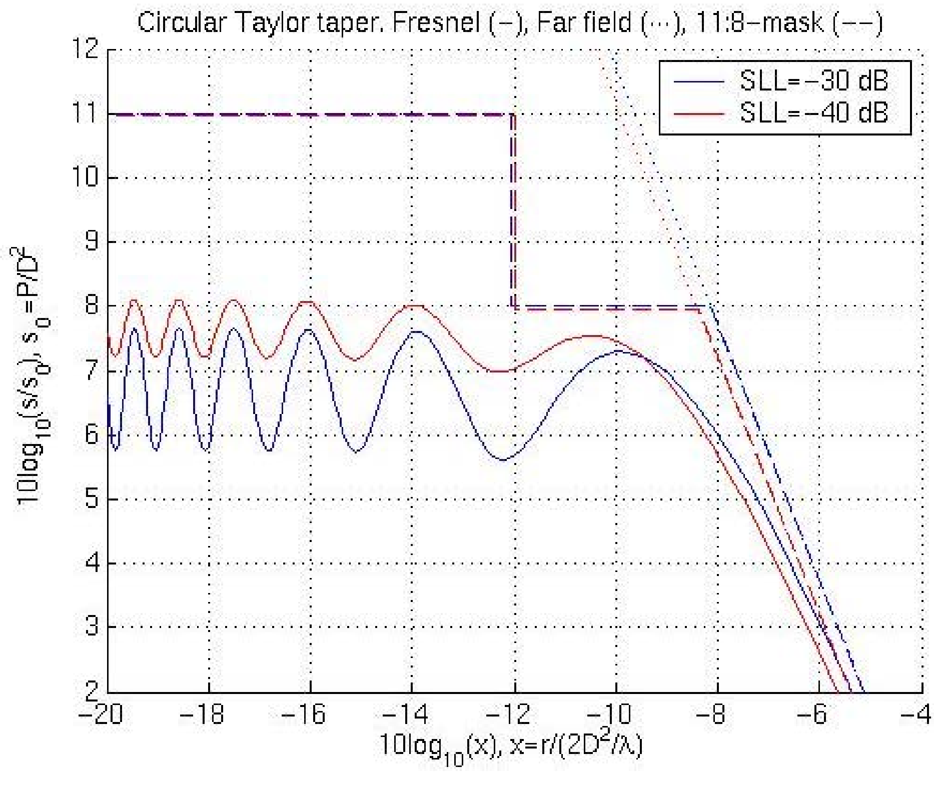
$$E(r) = 1 - (r / a)^2 \tag{A.11}$$

for which an analytic expression was found by Bickmore and Hansen [i.17].



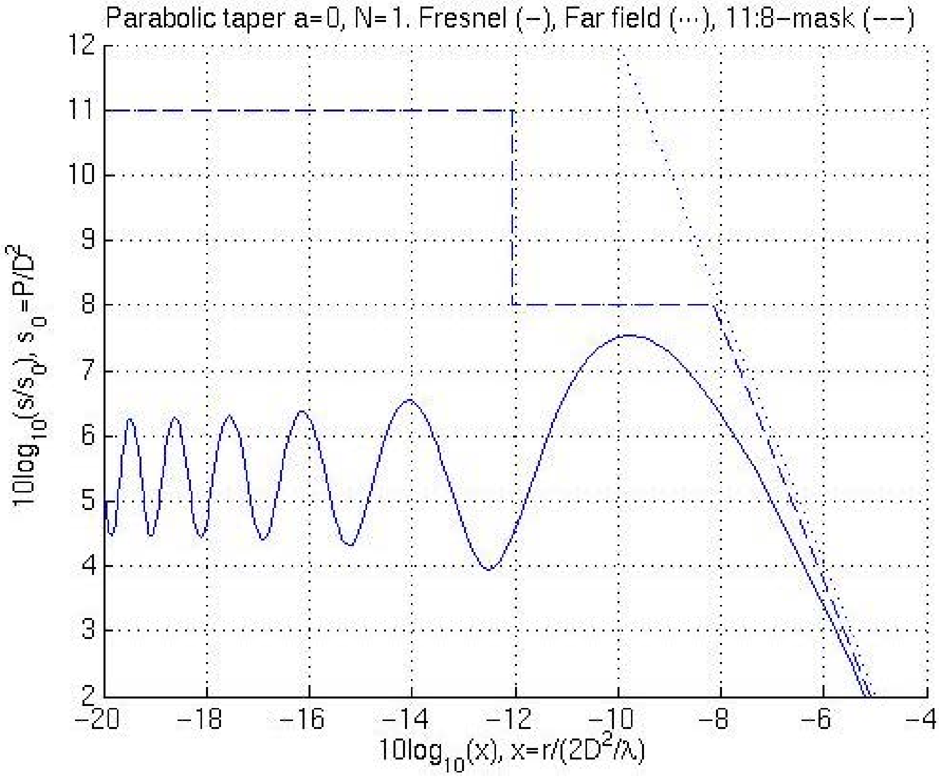
NOTE: The mask is clearly above the chosen test cases. The corresponding aperture efficiencies are 0,82 (N=1) and 0,62 (N=3), of which 0,62 or slightly lower is what is typically find in real products.

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 decrease 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

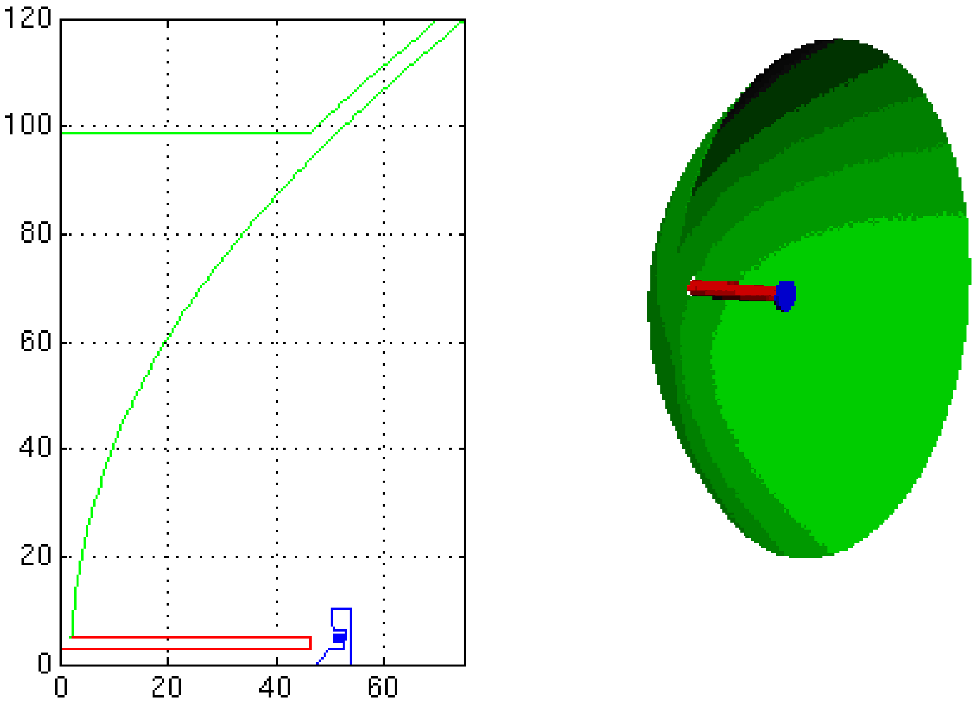
B.1 Simulations and measurements of a 0,24 m 38 GHz antenna

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) a Method-of-Moments solver was used, and for the reflector the high-frequency approximation Physical Optics 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.

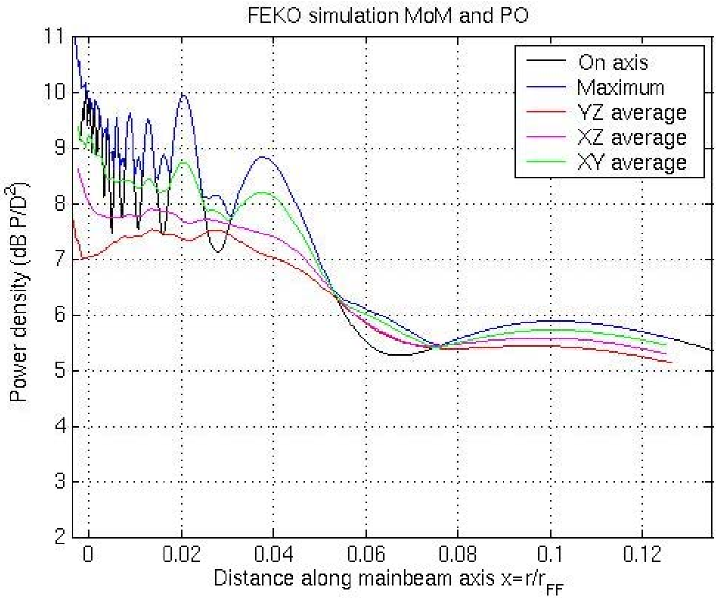
NOTE: FEKO™ a full wave, method of moments (MoM) based, computer code for the analysis of electromagnetic problems developed by EM Software & Systems-SA (Pty) Ltd.



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

Figure B.1: Layout of the 38 GHz 24 cm axis-symmetric parabolic reflector antenna

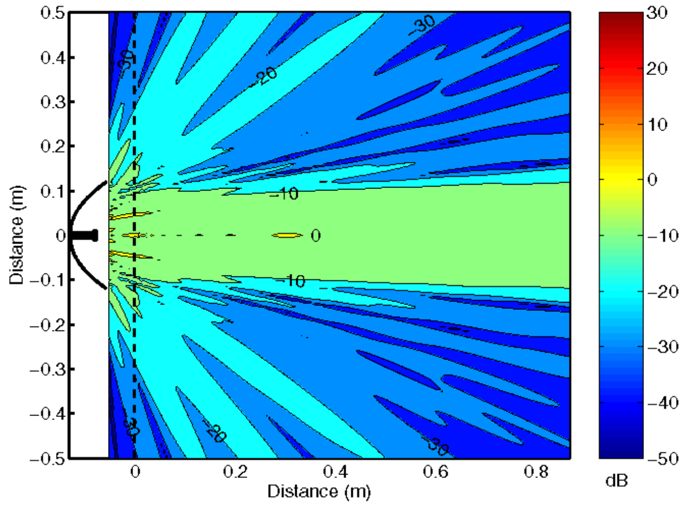
B.1.1.2 On-axis results



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.2: FEKO™ simulation MoM and Physical Optics

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.3: Cross section of the power density distribution

B.1.2 Measurements

B.1.2.1 Test setup

Near-field measurements were carried out in an an-echoic chamber. 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 for 15 GHz and WR28 for 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.

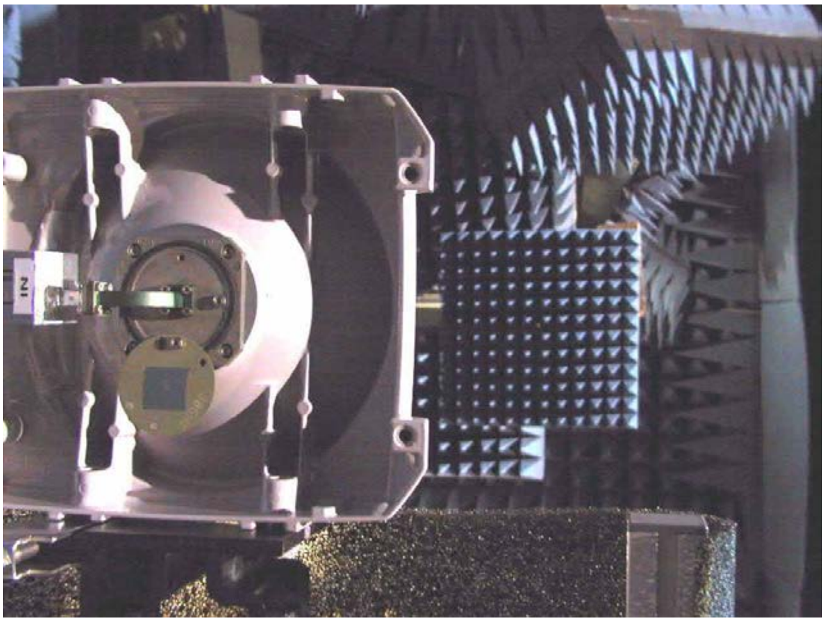


Figure B.4: Rear side of the 38 GHz 24 cm reflector antenna with a rectangular waveguide interface

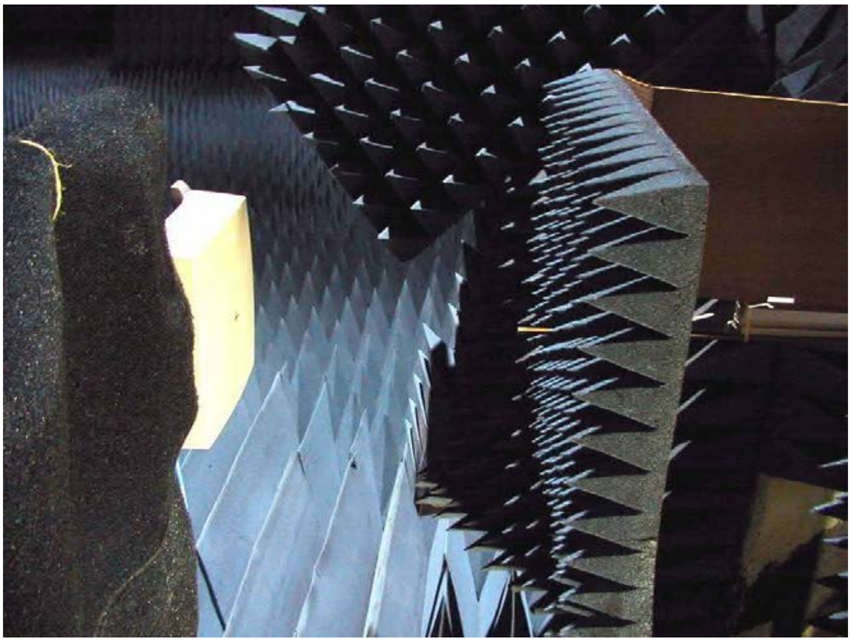
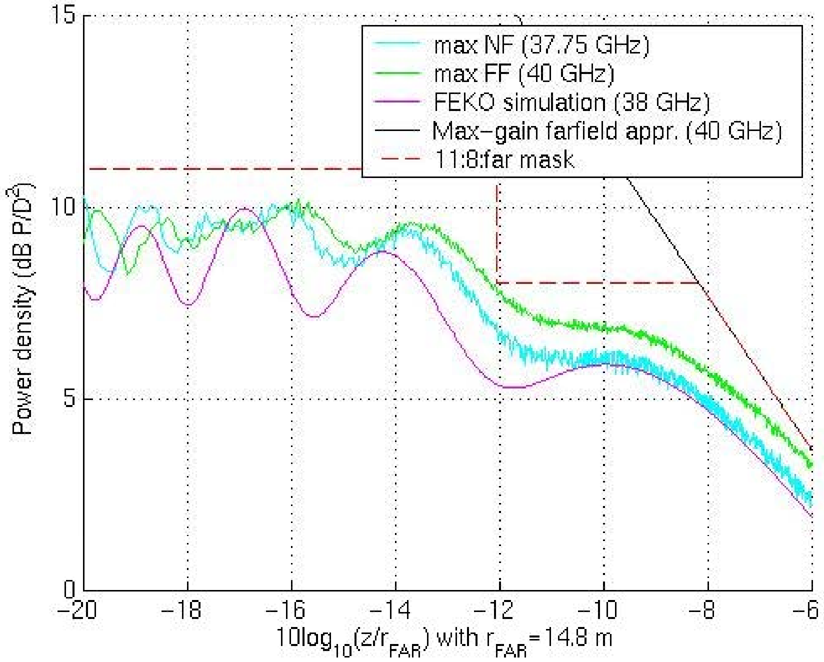


Figure B.5: Antenna to the left and the WR28 rectangular wave guide probe to the right

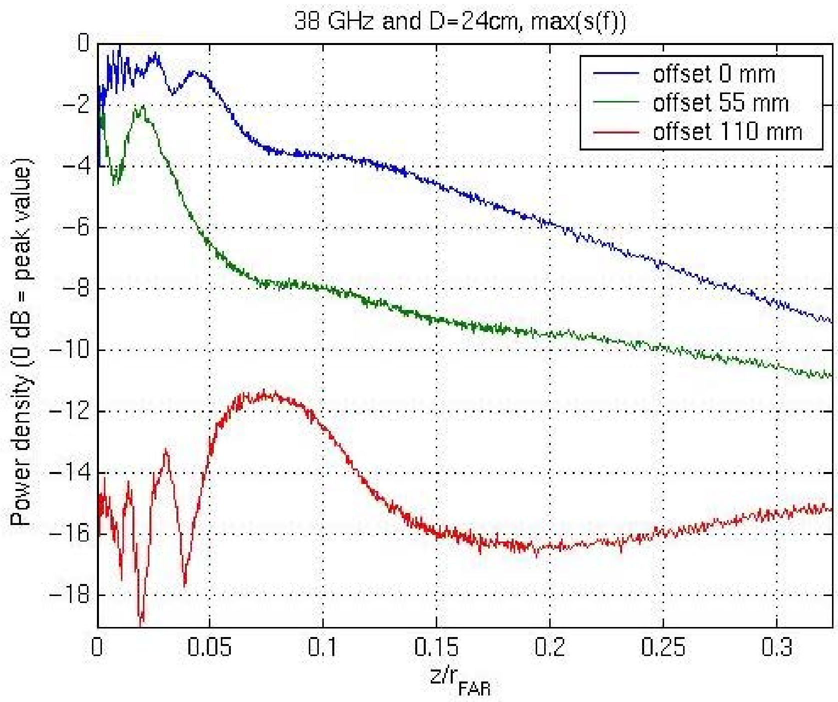
B.1.2.2 On-axis results



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

Figure B.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.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; figure B.8 shows the schematic physical appearance of the antenna.

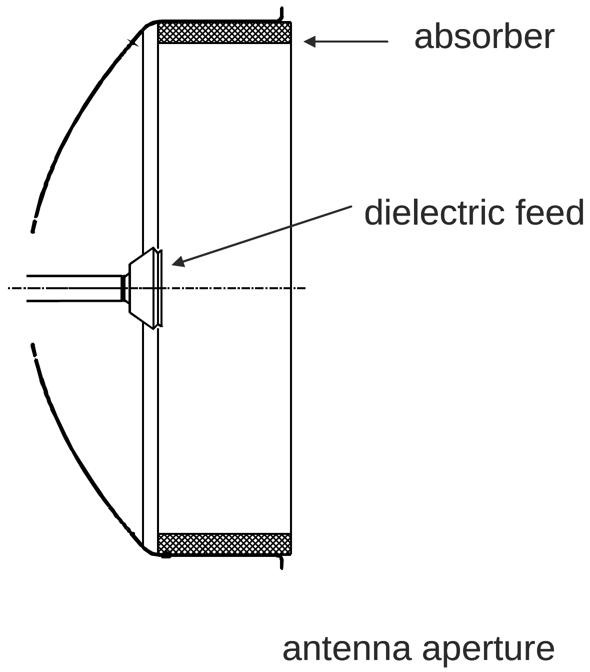


Figure B.8: Antenna schematic picture

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. Figure B.9 shows the test setup.

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 ETSI EG 202 373 [i.18] or CENELEC EN 62232 [i.7].

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

Figure B.9: Test setup

The EM field is measured with an isotropic field probe shown in figure B.10.

Figure B.10: EM Radiation Meter EMR-300

B.2.3 Measurement results

B.2.3.1 Measurement result with absorber

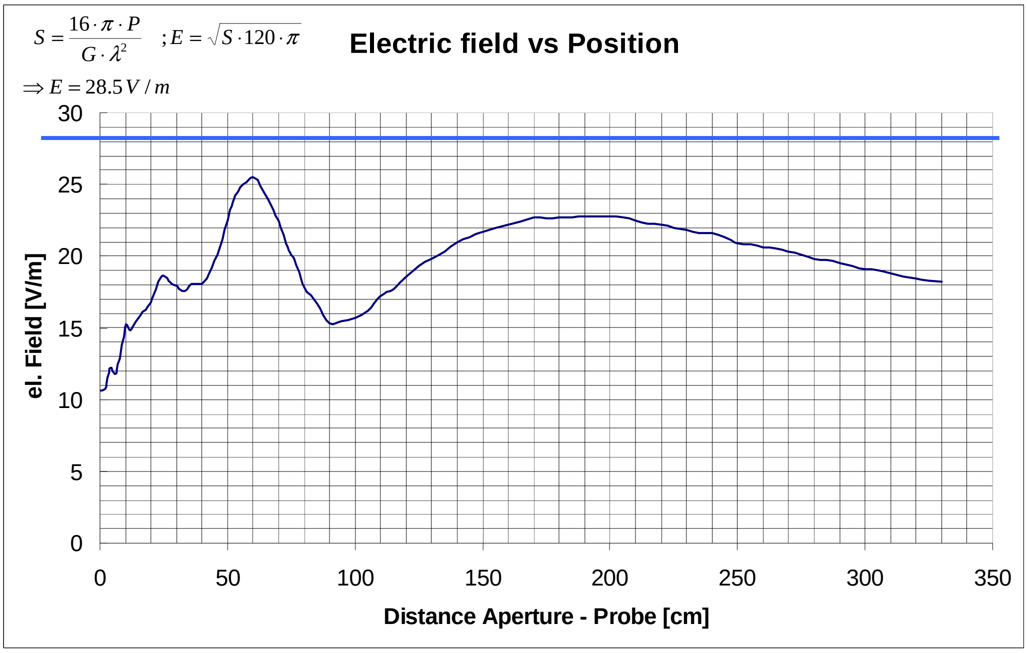


Figure B.11: Electric field vs probe position (with absorber)

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

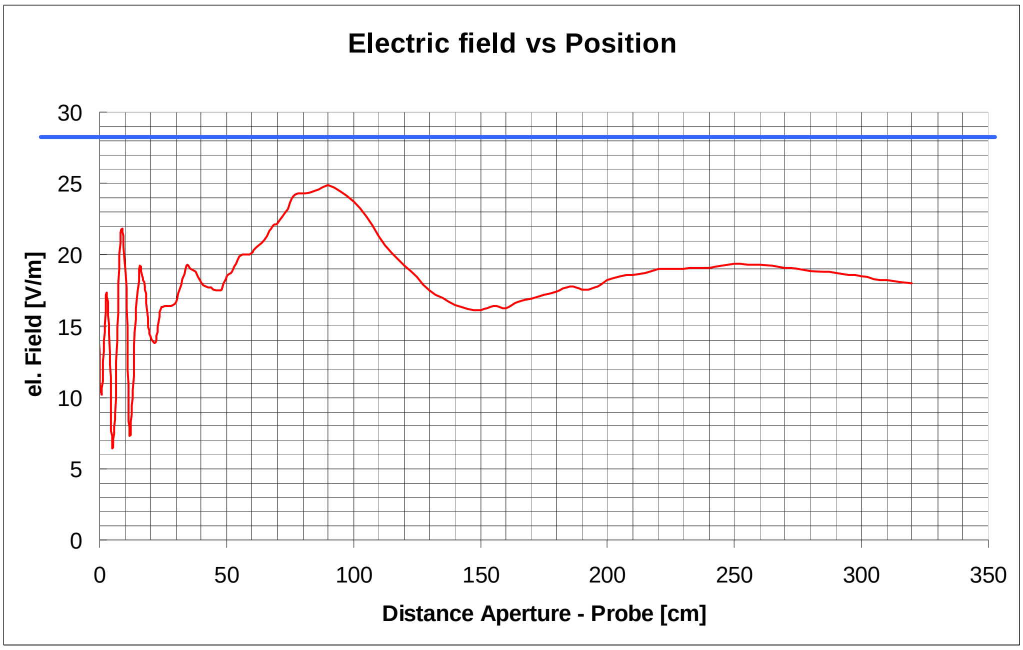


Figure B.12: Electric field vs probe position (without absorber)

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 simulation

Measured electric field strength in front of the antenna aperture - Simulation with FEKO™.

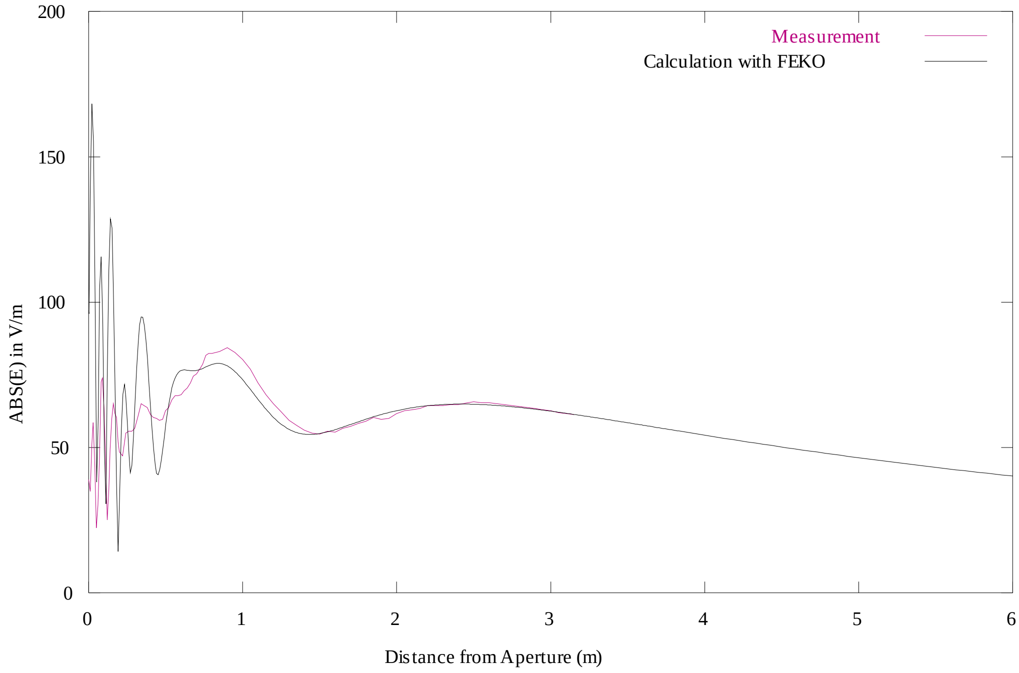


Figure B.13: Electric field vs probe Measured and simulated with FEKO™

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

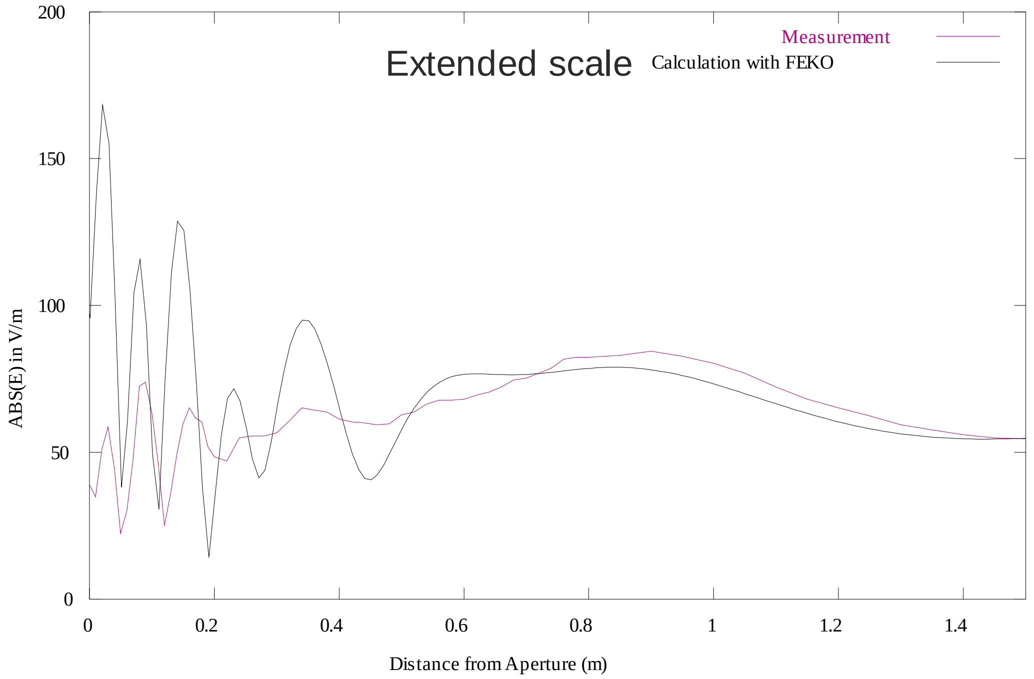


Figure B.14: Electric field vs probe Measured and simulated with FEKO™

Comparison of simulations with MAFIA™ (see note) and FEKO™.

NOTE: MAFIA™ is a simulator SW from CST - Computer Simulation Technology GmbH.

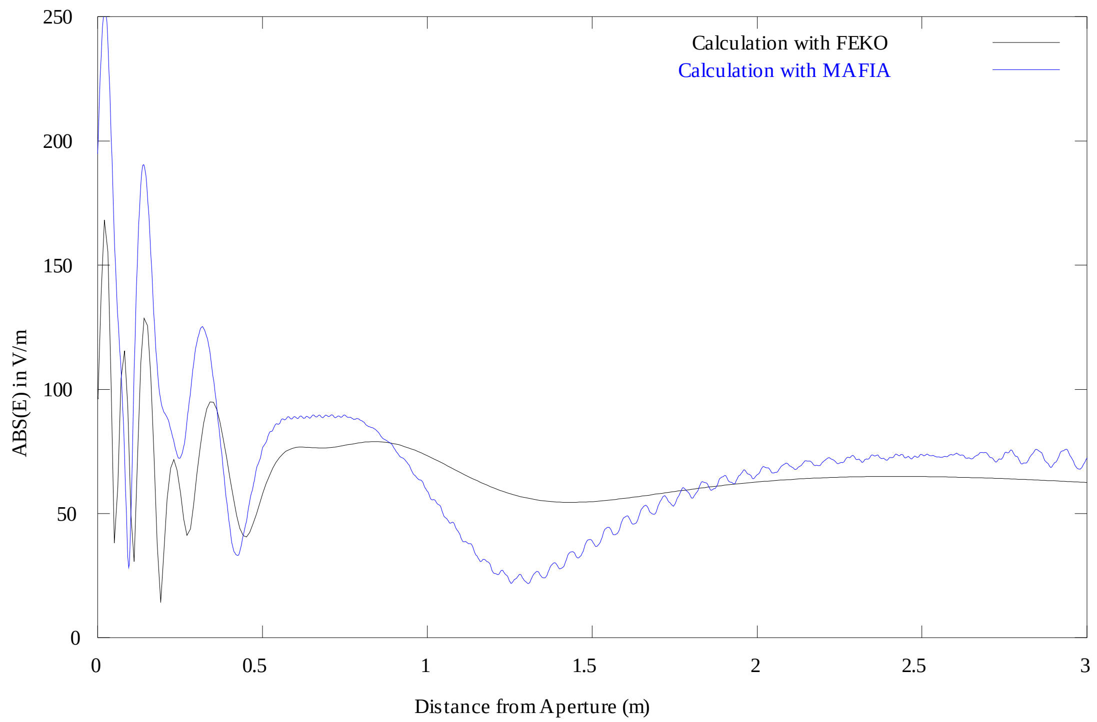


Figure B.15: Electric field vs probe simulation with FEKO™ and MAFIA™ comparison

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 without 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 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.

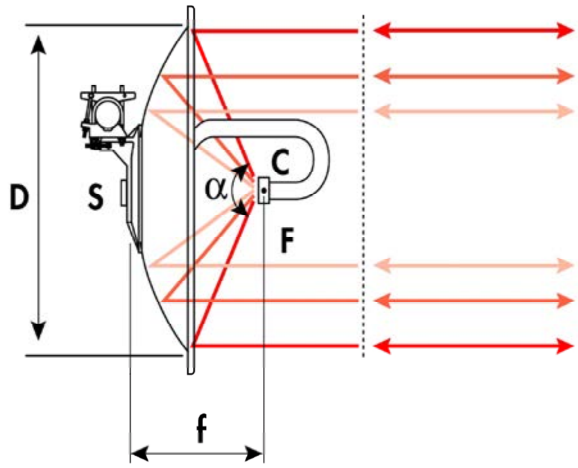
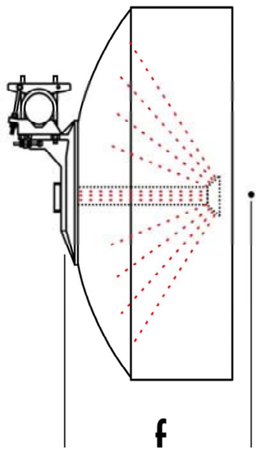


Figure B.16: SU2-W71A

SB1-190A

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



B.17: 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 (figure B.18):
  - Gain: sim. 31,6 dBi / meas. 32,2 dBi (wo shroud);

- Aperture: sim. 4,1° / meas. 4,3°.

- SB1-190A (figure B.19):
  - Gain: sim. 34 dBi / meas. 34,1 dBi (wo shroud);
  - Aperture: sim. 3,3° / meas. 3,4

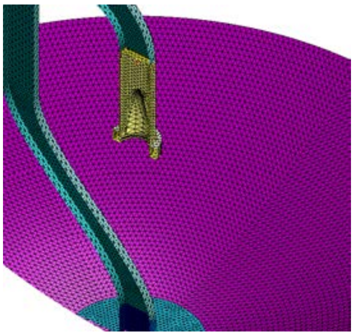


Figure B.18: SU2-W71A - simulated model of radiating source

Figure B.19: SB1-190A - simulated model of radiating source

B.3.1.3 Simulation results

Power density on the axis (SU2-W71A left and SB1-190A right).

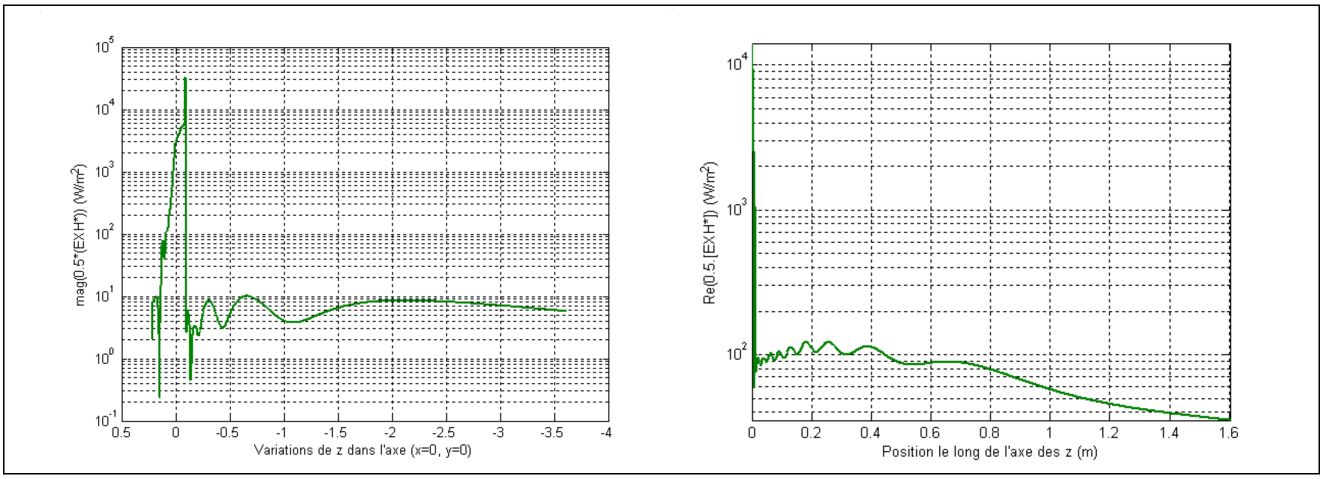


Figure B.20: Simulation results of power density on the main axis (Axial)

Power density on a radial pattern (SU2-W71A left and SB1-190A right).

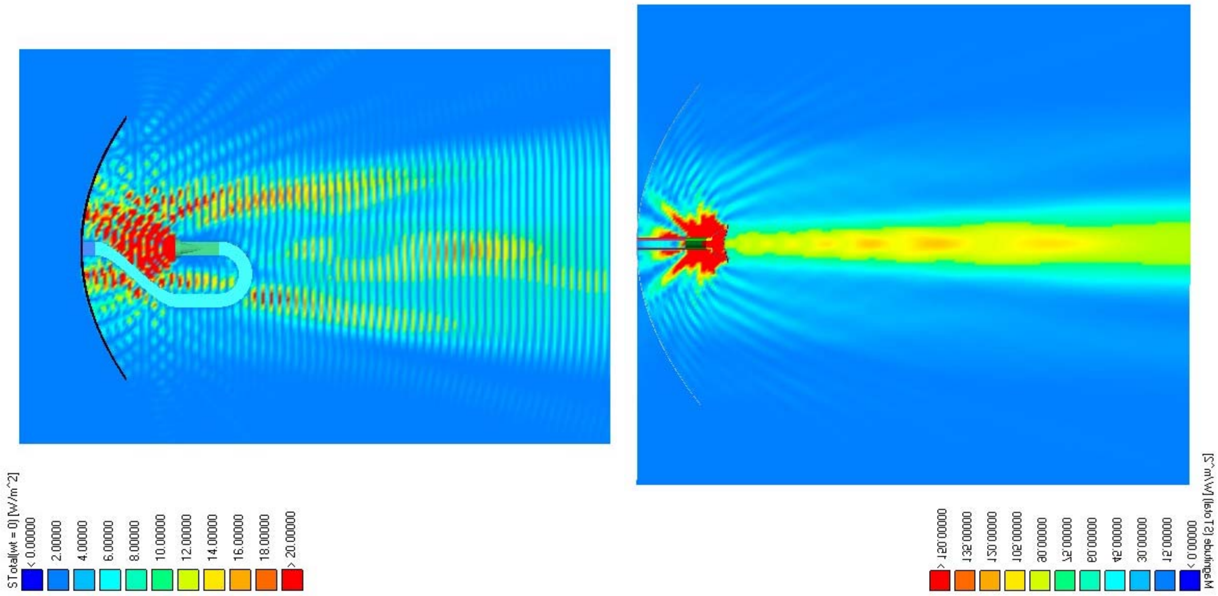


Figure B.21: Simulation results of power density on the main axis (radial pattern)

B.3.1.4 Measurement setup

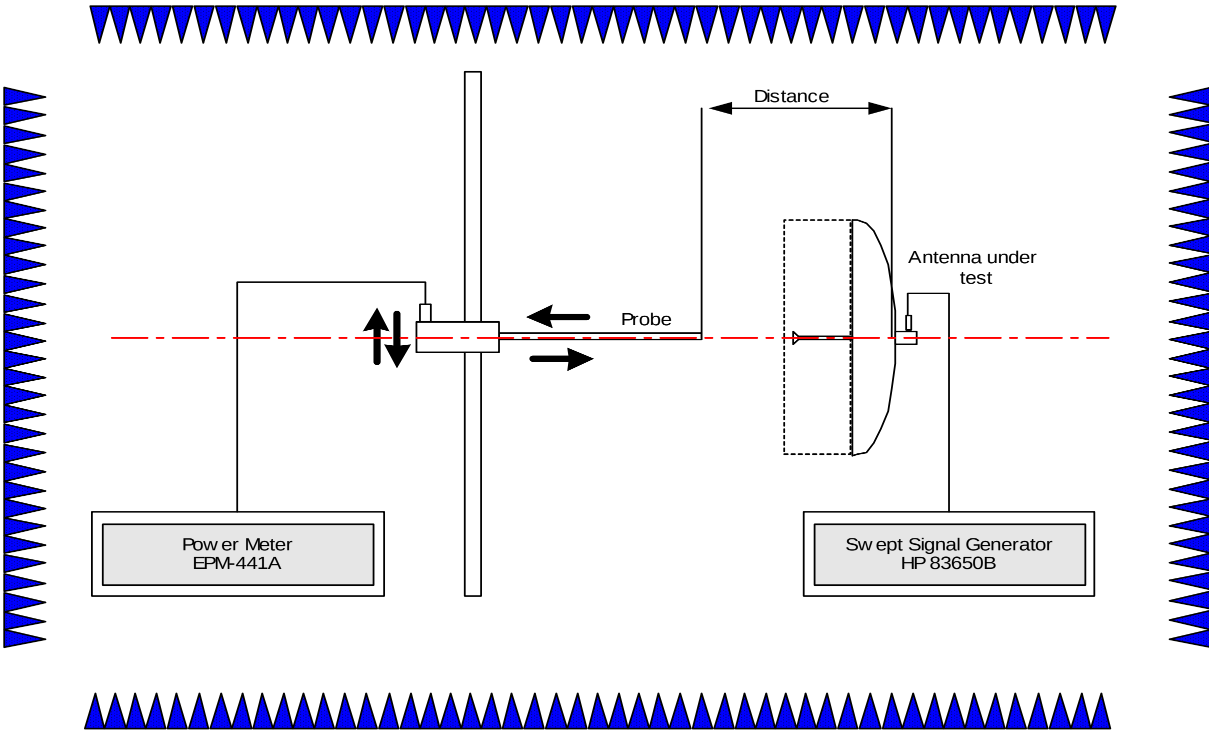


Figure B.22: Measurement setup for power density measurement

NOTE: Probe calibration was performed according to the state of the art, e.g. defined in the relevant standard such as ETSI EG 202 373 [i.18] or CENELEC EN 62232 [i.7].

B.3.1.5 Measurement results

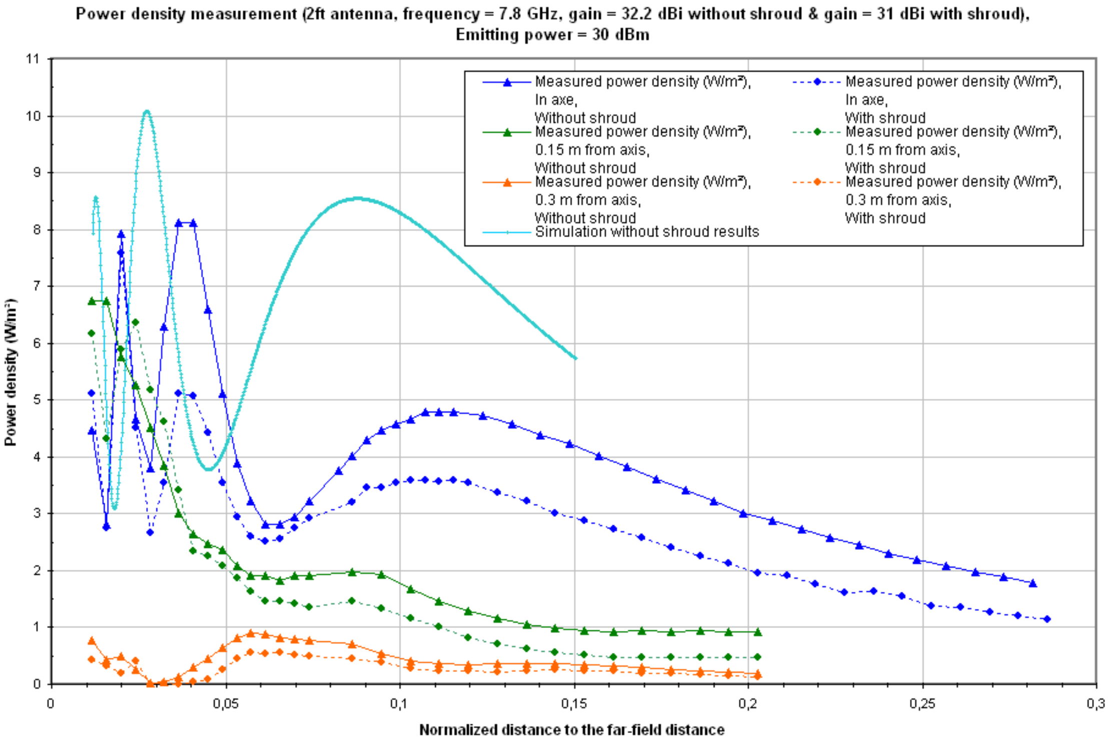


Figure B.23: Measurement results for antenna model SU2-W71A

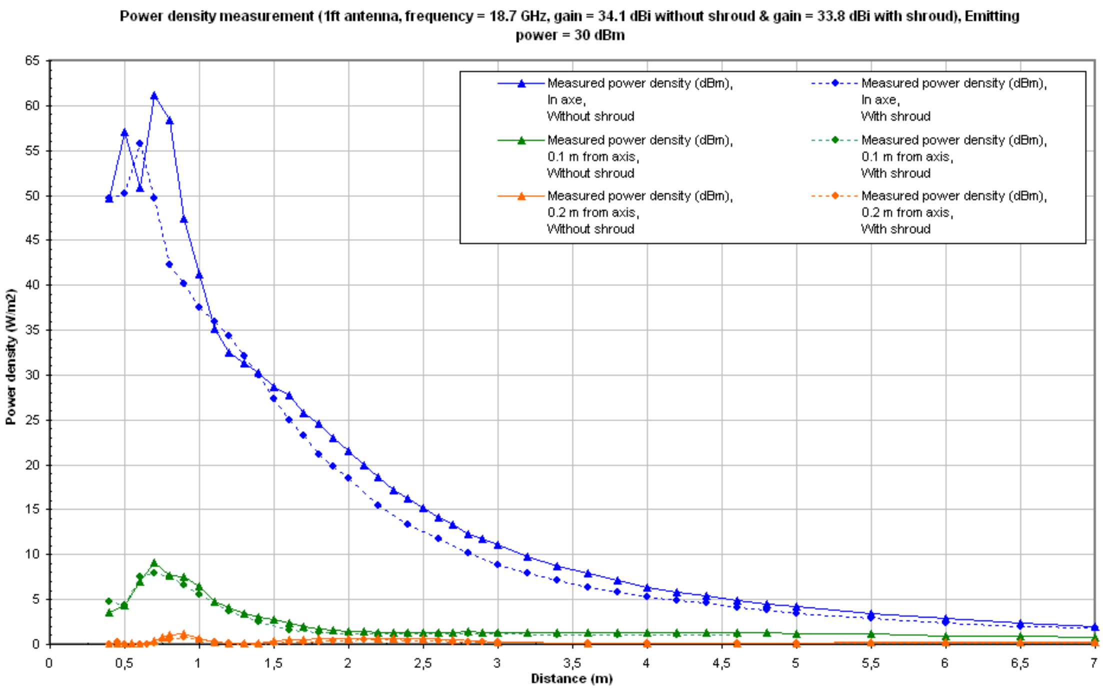


Figure B.24: Measurement results for antenna model SB1-190A

B.3.1.6 Evaluation of the factor F

According to figures B.23 and B.24, $S \leq \frac{FP}{A}$ where F takes the following values:

SU2-W71A:

- F (meas., without shroud) = 2,9.
- F (meas., with shroud)(see note) = 2,8.
- F (sim., without shroud, max) = 3.
- F (sim., without shroud, 20 m^2) = 2,9.

SB1-190A:

- F (meas., without shroud) = 6,9.
- F (meas., with shroud)(see note) = 6,4.
- F (sim., without shroud, max) = 11,2.
- F (sim., without 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 recommendations 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

B.3.2.0 Introduction

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.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.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	27,3
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.25).

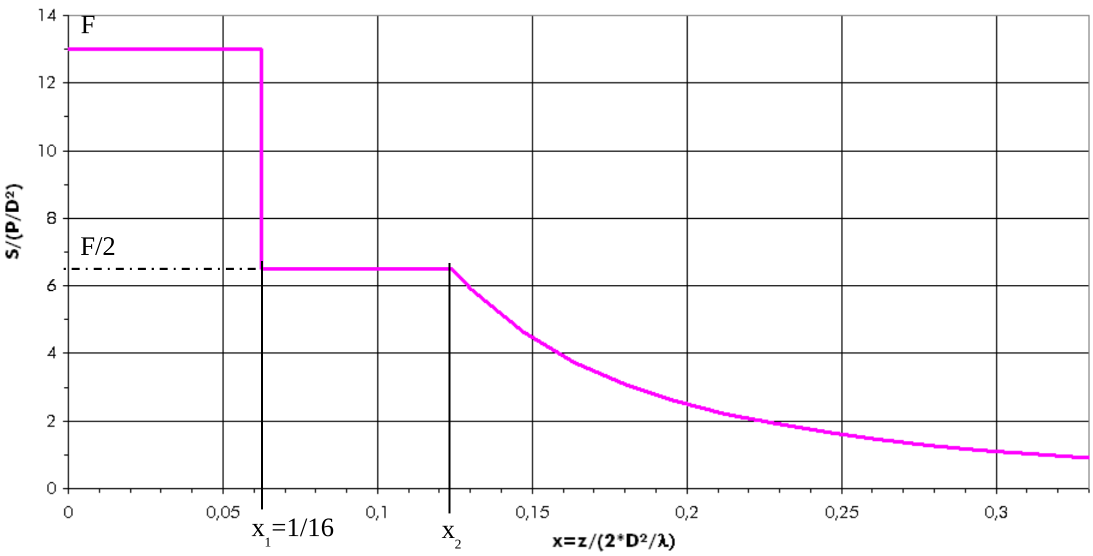


Figure B.25: Proposed envelope template for power density upper bound

Where:

- D is the inner diameter of the antenna.
- $R_{ff} = \frac{2D^2}{\lambda}$.
- x_1 corresponds to the first zero for a uniform taper using Fresnel transform (see clause A.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.

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

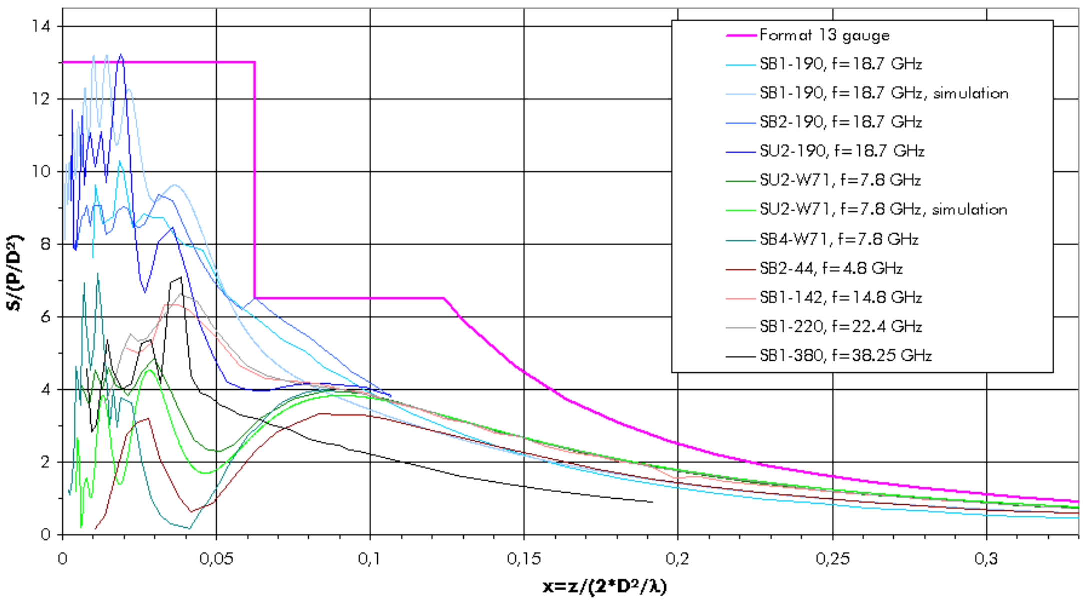


Figure B.26: Power density measurement and simulation results with format F=13 envelope template using inner diameter (aperture)

Both simulations and measurements on all tested antennas (9) are compliant with the proposed 13 format envelope template ($S_{Max} \leq 13\frac{P}{D_{in}^2}$). 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. $S_{Max} \leq 15\frac{P}{D_{out}^2}$).

In figure B.27 are presented the power density measurements results in the main axis with this format 15 envelope template.

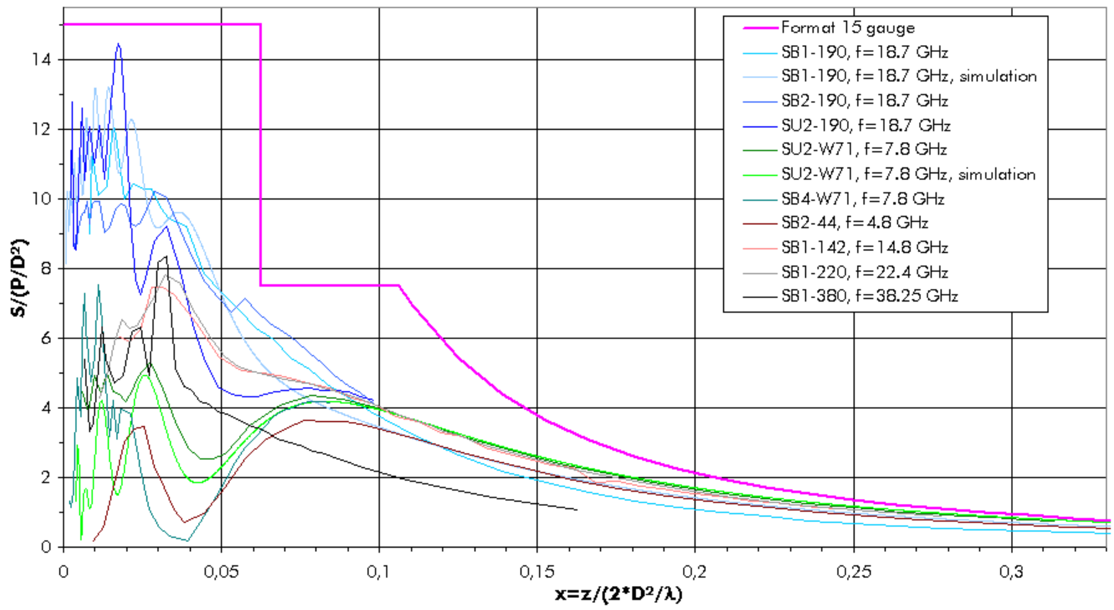


Figure B.27: Power density measurement and simulation results with format F=15 envelope template using outer diameter

B.3.3 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:

$$S_{av} = P/A. \qquad (B.1)$$

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

$$Smax = F \times Sav \qquad (B.2)$$

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.2: 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.3: 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

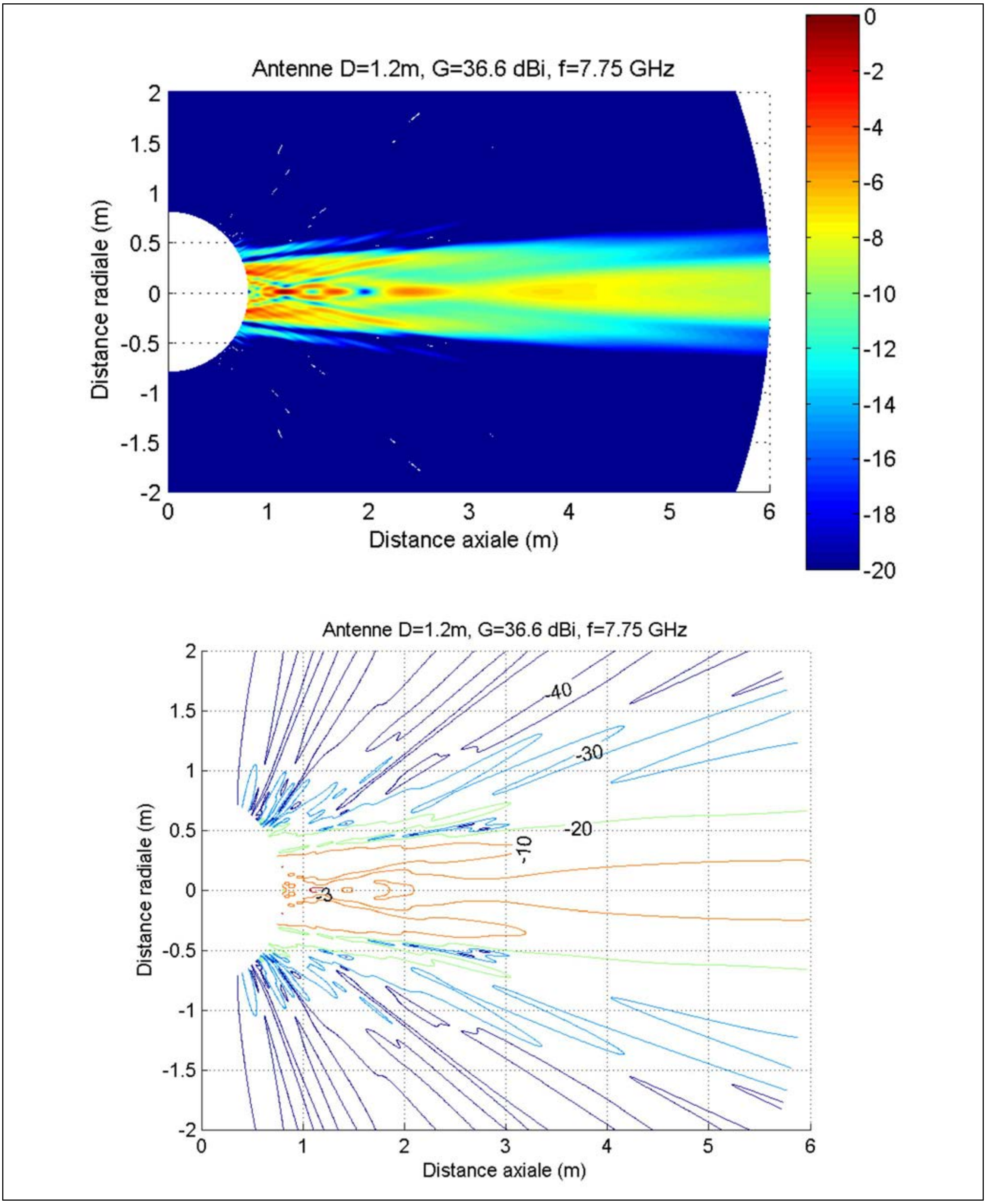
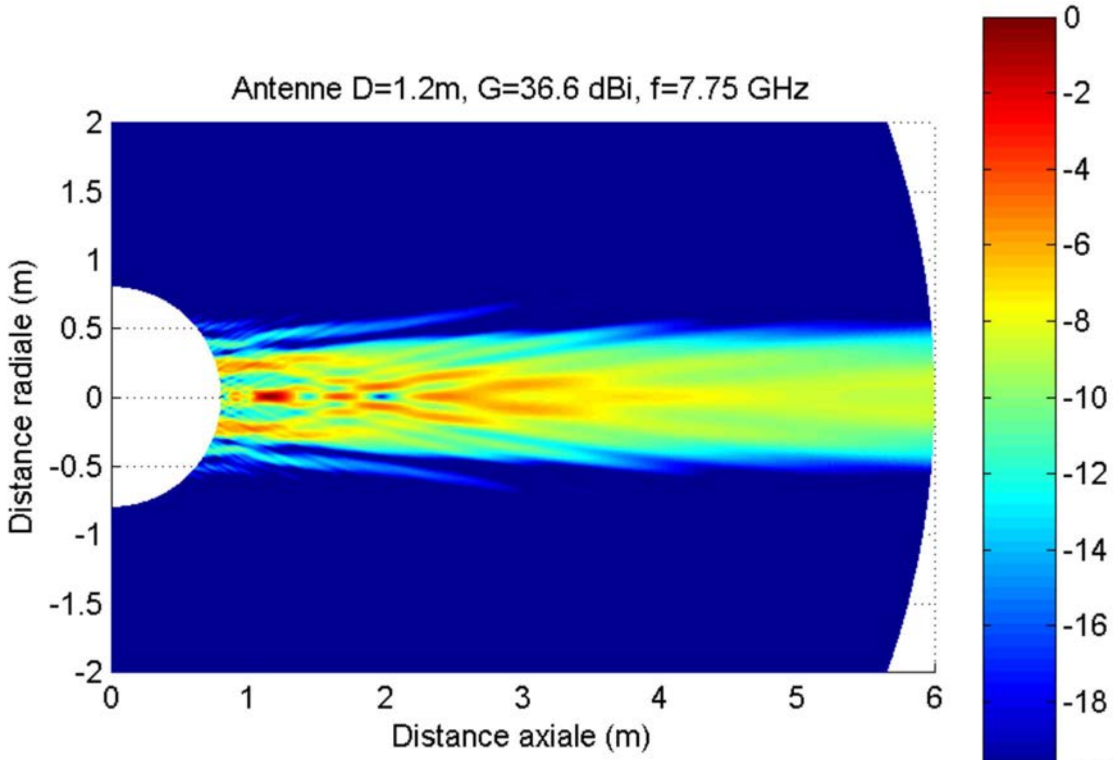


Figure B.28: Cross section of the power density distribution



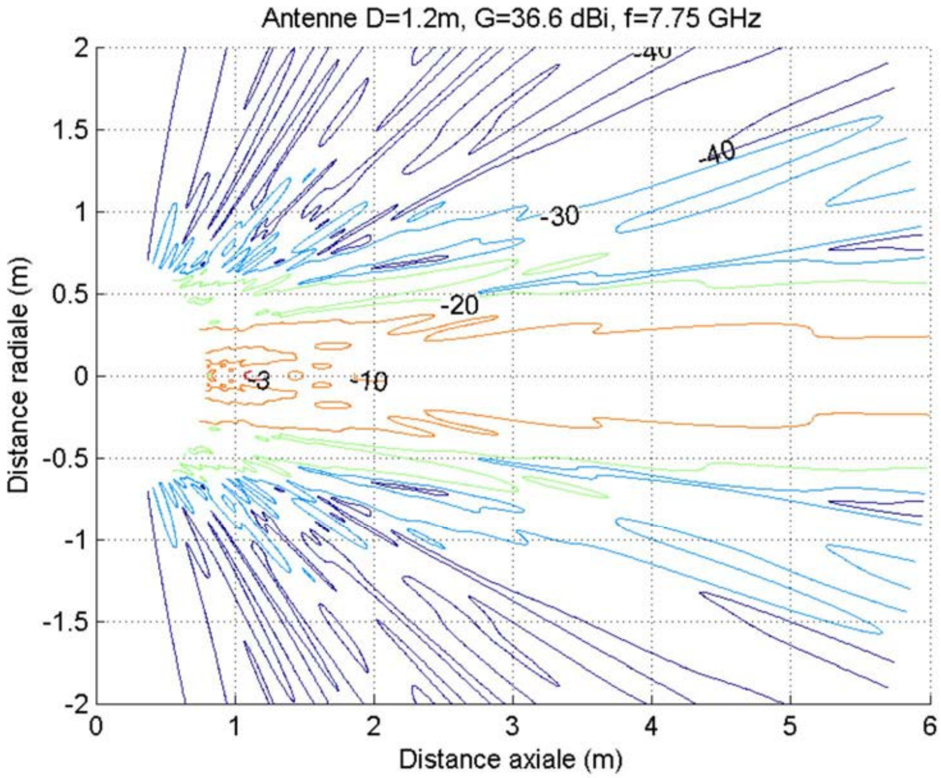


Figure B.29: Cross section of the power density distribution

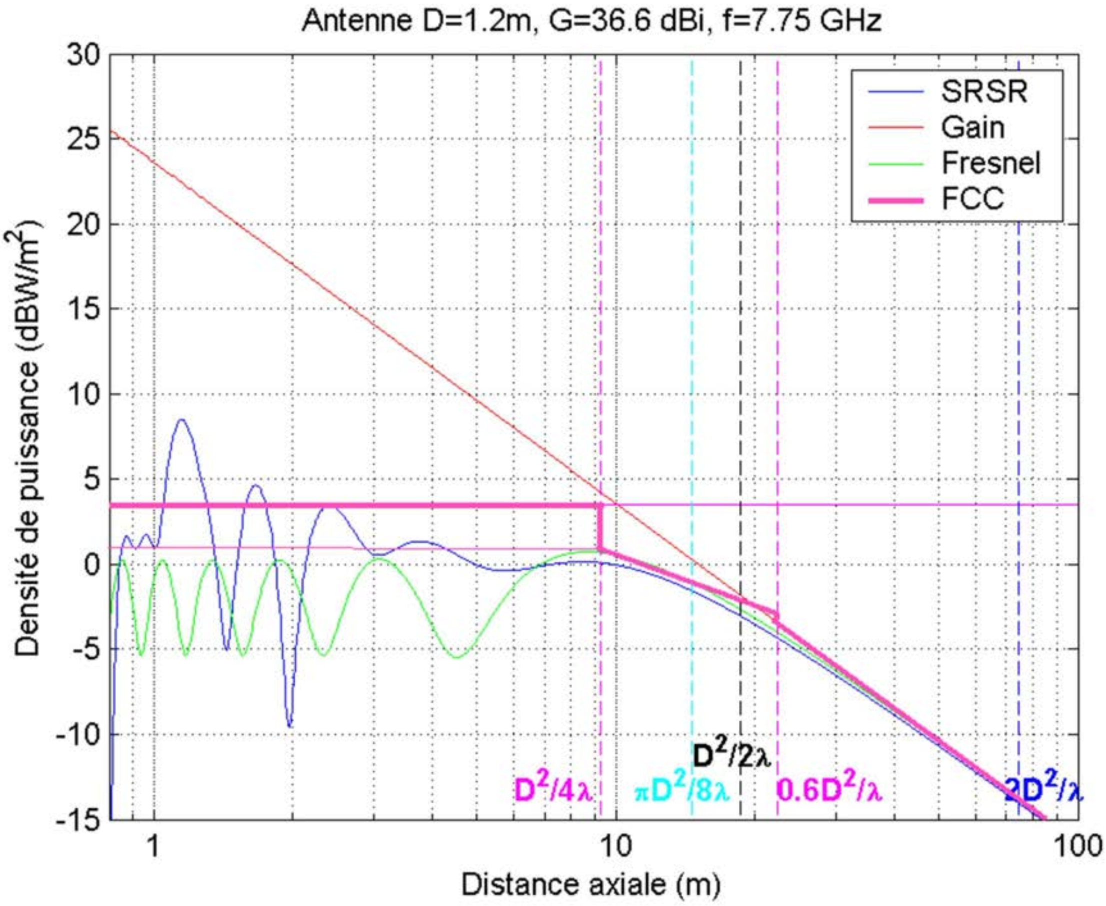


Figure B.30: Power density measurement and simulation results with FCC envelope template

B.4.5 Simulation results 13 GHz

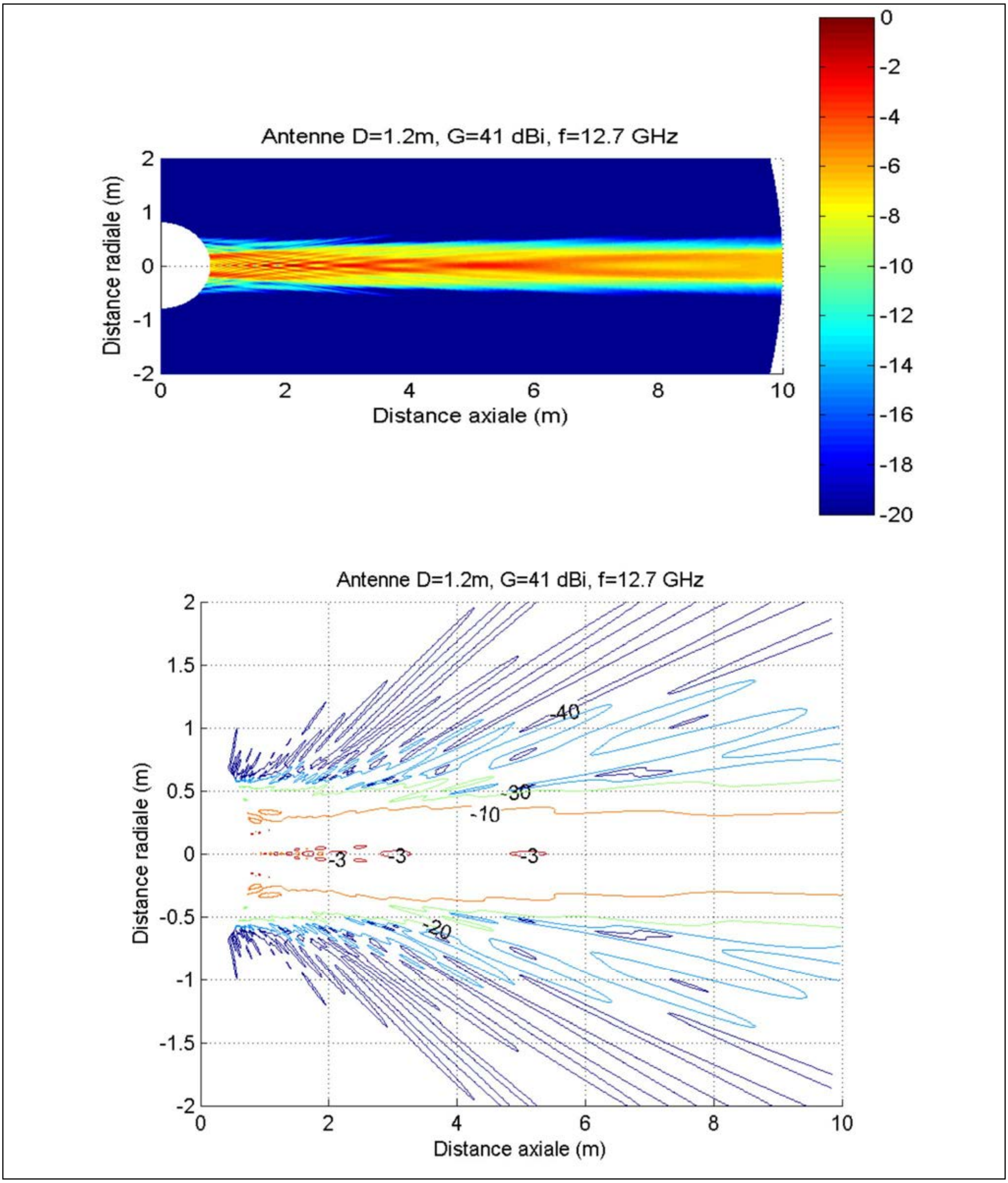


Figure B.31: Cross section of the power density distribution

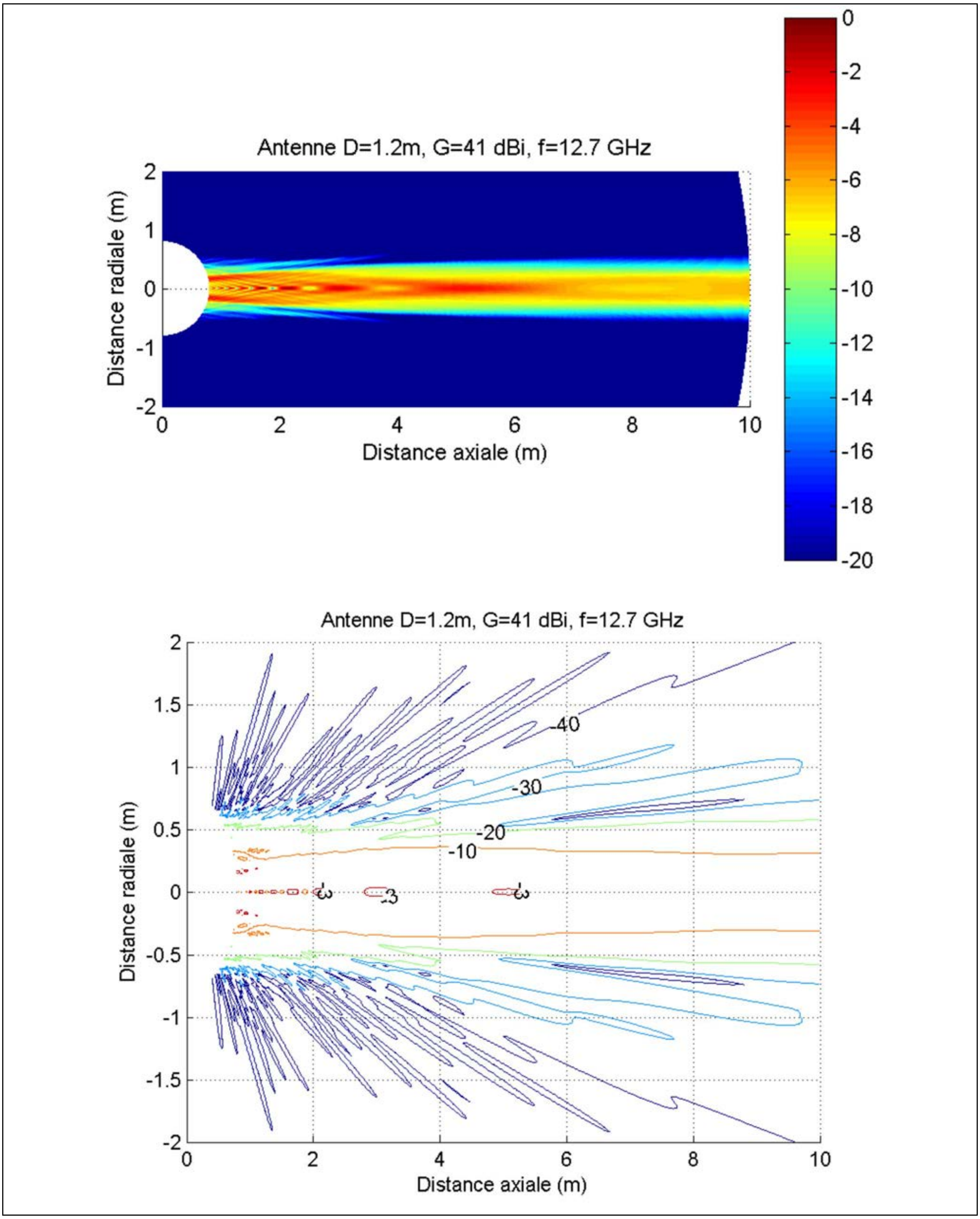


Figure B.32: Cross section of the power density distribution

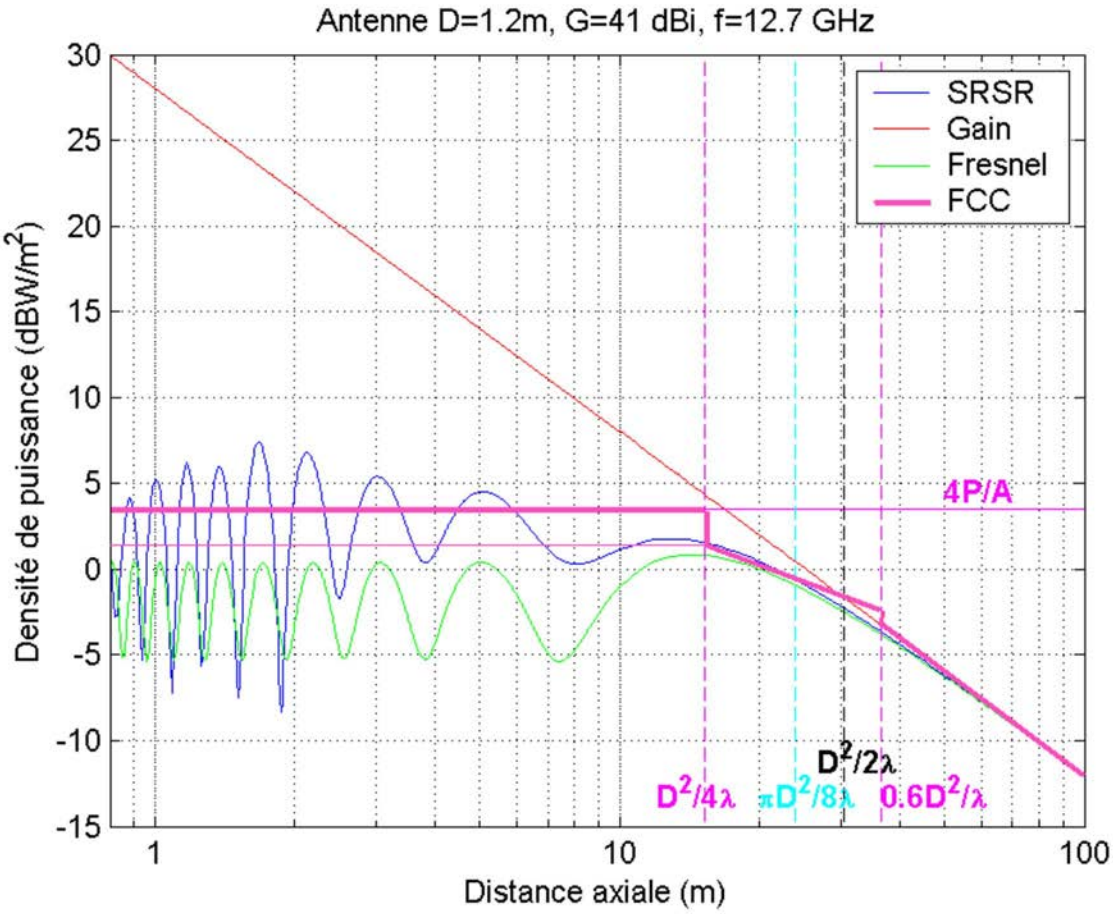


Figure B.33: Power density measurement and simulation results with FCC envelope template

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.34 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.

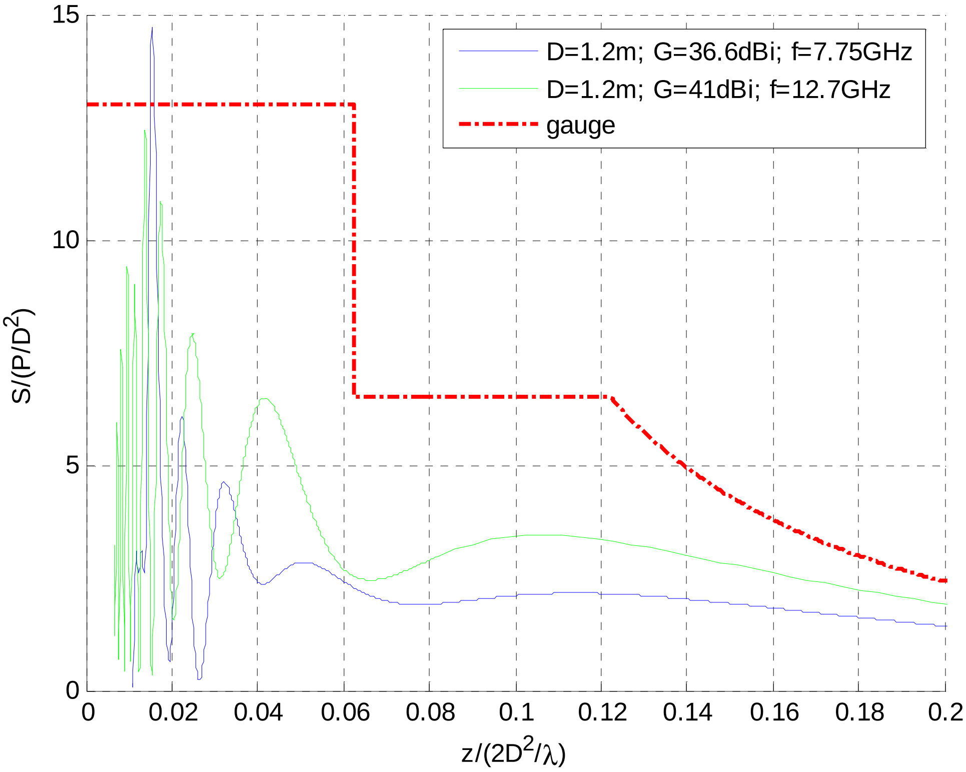


Figure B.34: Comparisons of normalized power density vs. format F=13 envelope template

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.

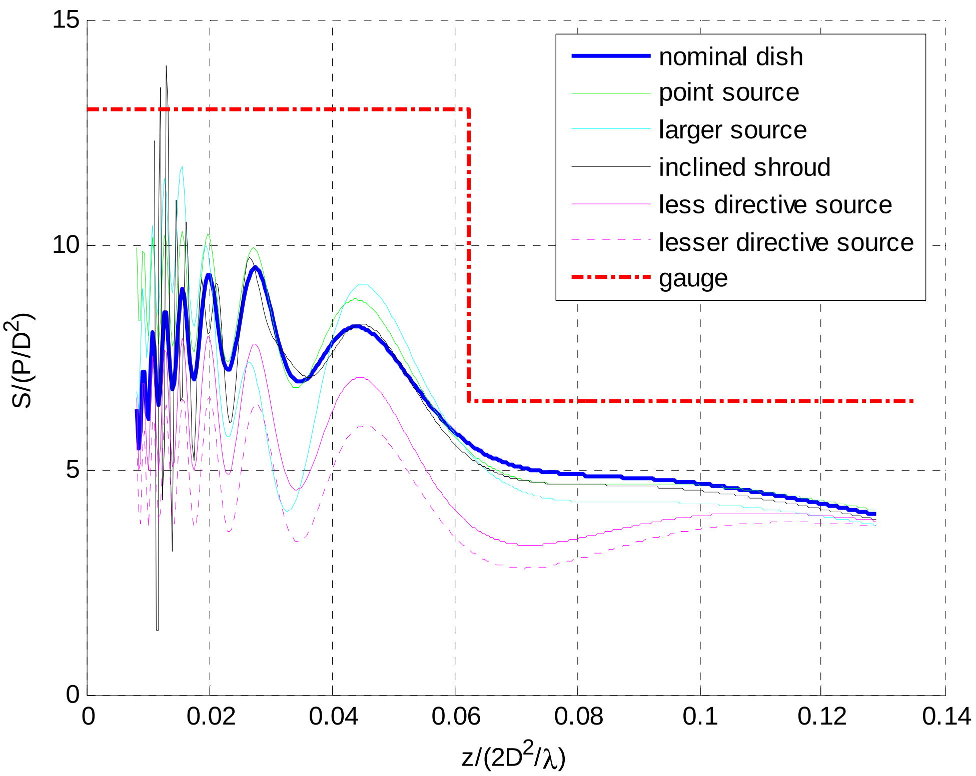


Figure B.35: Comparisons of normalized power density vs. format F=13 envelope template

Figure B.35 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.36 and B.37 show the results at 8 GHz and 13 GHz respectively. The higher is the efficiency, the lower is the power density.

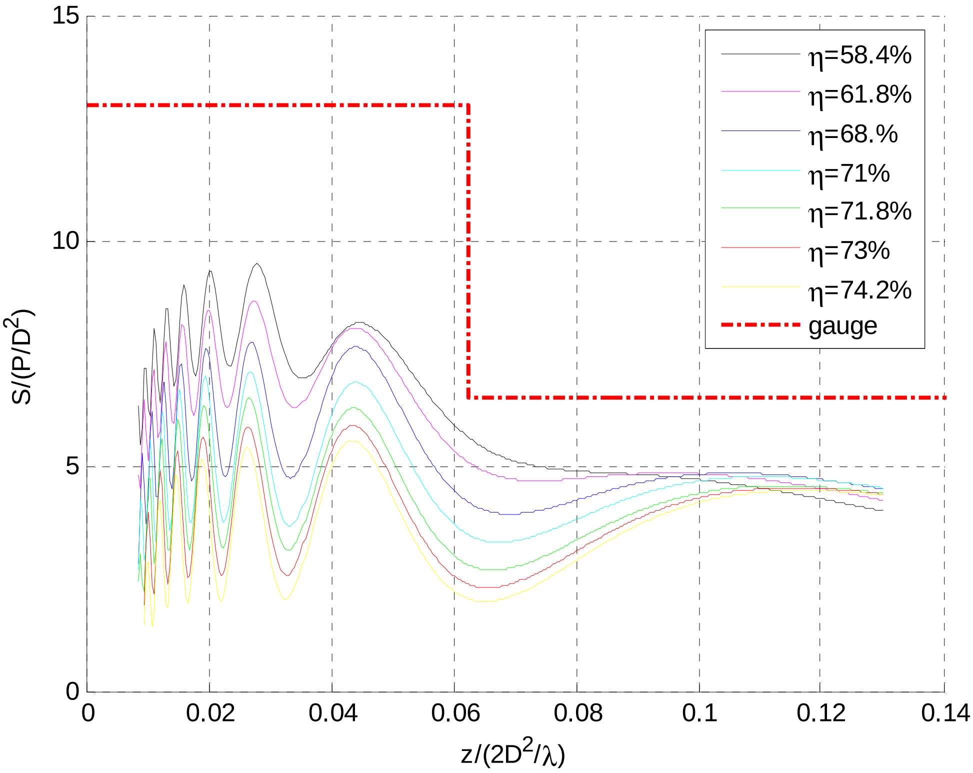


Figure B.36: Normalized power density vs. efficiency (focal distances) and format F=13 envelope template @ 8 GHz

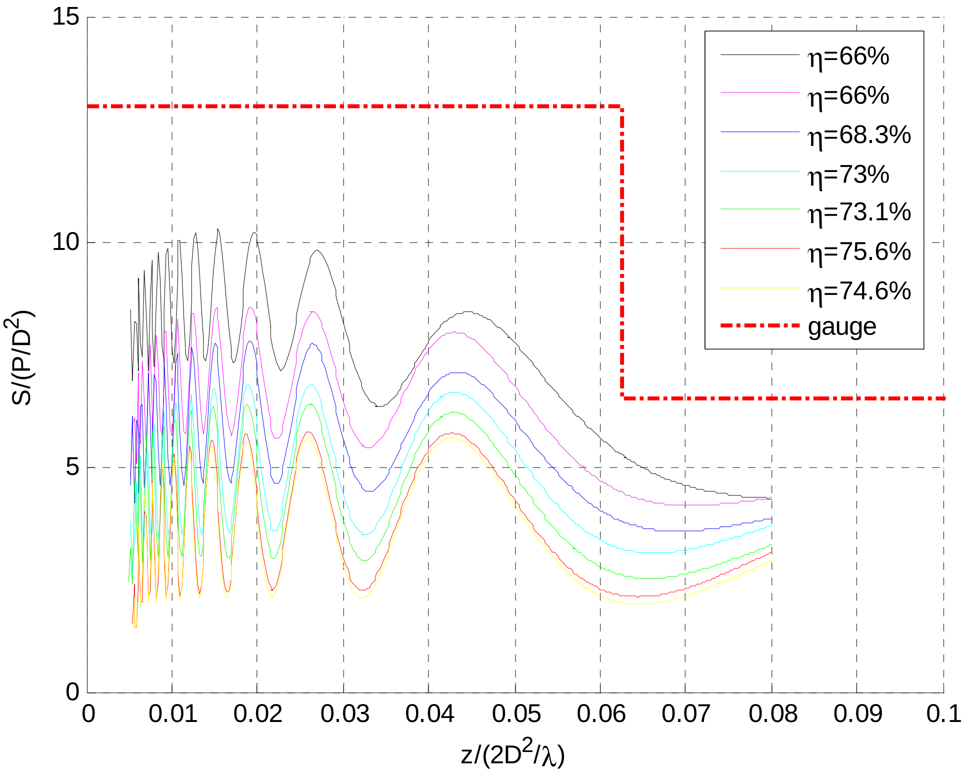


Figure B.37: Normalized power density vs. efficiency (focal distances) and format F=13 envelope template @ 13 GHz

Annex C: Rationale for equivalence of SAR (BR/ELV) to E or S (RL/AL) between 1,3 GHz and 10 GHz

For frequencies of interest in the present document (i.e. above the 1,3 GHz boundary (which covers large majority of the fixed service links stations), in the ICNIRP [i.6], European Recommendation 1999/519/EC [i.2] and European Directive 2013/35/EU [i.3], the BR/ELV are expressed in terms of SAR up to 6 GHz for [i.3] and 10 GHz for [i.6] and [i.2]; In those documents, it is assumed that:

- the exposed body tissues are mainly superficial 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 C.1 showing the energy transfer curve (in red) and the associated skin thickness:

$$SAR_{10g}\left[{}^{W}\!/_{kg}\right] \approx \frac{S_{in}\left[{}^{W}\!/_{m^2}\right]\times 0{,}002\left[m^2\right]}{0{,}01\left[kg\right]} - \frac{S_{out}\left[{}^{W}\!/_{m^2}\right]\times 0{,}002\left[m^2\right]}{0{,}01\left[kg\right]} \qquad \text{(C.1)}$$

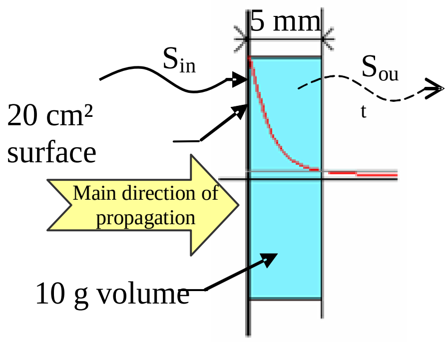


Figure C.1: Illustration of SAR and skin thickness

Consequently, the relation between SAR10g and S can be expressed as follows:

$$SAR_{10g}\left[{}^{W}\!/_{kg}\right] \leq \frac{S_{in}\left[{}^{W}\!/_{m^2}\right]\times 0{,}002\left[m^2\right]}{0{,}01\left[kg\right]} \qquad \text{(C.2)}$$

Consequently, the formula (reported also as equation 5.2 in clause 5.4) is derived:

$$\frac{SAR_{10g}\left[{}^{W}\!/_{kg}\right]\bullet m_0\left[kg\right]}{A_0\left[m^2\right]} \leq S\left[W/m^2\right] \qquad \text{(C.3)}$$

Where:

A_0 is the reference area 20 cm² used for spatial averaging,

m_0 is the reference mass 10 g for spatial averaging.

Annex D: Bibliography

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History

Document history		
V1.1.1	August 2006	Publication
V2.1.0	September 2018	Publication