PUBLICLY
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SPECIFICATION

Pre-Standard

IEC
PAS 62431

First edition
2005-07

Measurement methods for reflectivity
of electromagnetic wave absorbers
in millimetre wave frequency

Publication numbering

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Measurement methods for reflectivity of electromagnetic wave absorbers in millimetre wave frequency

Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

PRICE CODE   **X**

For price, see current catalogue

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION
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MEASUREMENT METHODS FOR REFLECTIVITY OF ELECTROMAGNETIC WAVE ABSORBERS IN MILLIMETRE WAVE FREQUENCY

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The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document
Draft PAS	**Report on voting**
46F/26/NP	46F/29/RVN

Following publication of this PAS, which is a pre-standard publication, the technical committee or subcommittee concerned will transform it into an International Standard.

This PAS shall remain valid for an initial maximum period of three years starting from 2005-07. The validity may be extended for a single three-year period, following which it shall be revised to become another type of normative document or shall be withdrawn.

MEASUREMENT METHODS FOR REFLECTIVITY
OF ELECTROMAGNETIC WAVE ABSORBERS
IN MILLIMETRE WAVE FREQUENCY

1   Scope

This PAS specifies the measurement methods for the reflectivity of electromagnetic wave absorbers (EMA) for the normal incident, oblique incident and each polarized wave in the frequency range from 30 GHz to 300 GHz. In addition, these methods are also equally effective for the reflectivity measurement of other materials.

This PAS is applicable not only to those EMA which are widely used as the counter-measures against communication faults, radio interference etc., but also to those used in an anechoic chamber in some cases. EMAs may be any kind of material and may have any arbitrary shape, configuration, or layered structure as indicated below.

Material: Conductive material, dielectric material, magnetic material
Shape: Planar, pyramidal-type, wedge-type, etc.
Layer structure: Single layer, multi layers, and graded-index material

This PAS may give the measurement method of reflectivity applicable to various EMAs or materials. However, it may not be applicable to all EMAs.

This PAS may be supplemented with additional methods if necessary so that a future demand may be fulfilled.

The PAS specifies the measurement methods for the reflectivity of EMA in the millimetre-wave range:

– measurement frequency range: 30 GHz to 300 GHz

– reflectivity: 0 to –50 dB

– incident angle: 0° to 80°.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

IEEE 1128, IEEE *Recommended Practice for EMA evaluation in the range from 30 MHz to 5 GHz*

3 Terms, definitions and acronyms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions of IEEE 1128, as well as the following apply.

3.1.1
ambient level
value of radiation power or noise which exists when no measurement is being carried out at the experiment site

3.1.2
dynamic range
difference in decibels between the receiving level from a reference metal plate and the receiving level measured when the metal plate is removed

3.1.3
directional gain
ratio of the radiated power density in a particular direction to the average power density that would be radiated in all directions

3.1.4
dielectric lens
electromagnetic wave lens that is composed of dielectric material, usually mounted in front of a pyramidal or conical horn

3.1.5
electromagnetic wave absorber
material ingredient which absorbs the electromagnetic wave energy and dissipates it thermally

3.1.6
focused beam
focused electromagnetic wave converged by the dielectric lens mounted in front of the horn antenna. The focused beam diameter is a few times the wavelength or more at the beam waist, which depends on the focal distance of the lens

3.1.7
Fraunhofer region
The region where the angular radiation pattern of an aperture antenna is nearly independent of the distance.

3.1.8
Fresnel region
region where the angular radiation pattern of an aperture antenna depends on the distance except for the extremely near region from the aperture

3.1.9
free-space method
measurement method that employs a single or a pair of horn antennas where the specimen and the antennas are put in free space

3.1.10
horn antenna
aperture antenna where impedance matching is taken gradually from the waveguide aperture to free space

3.1.11
normal incidence
incident electromagnetic wave striking normally to the specimen surface. The reflectivity in normal incidence is usually measured in the configuration where the incident angle of a transmit antenna and that of a receive antenna are within 0∼5° with respect to the normal direction of the specimen surface

3.1.12
oblique incidence
incident electromagnetic wave striking to the specimen surface at an oblique angle. The reflectivity in oblique incidence is usually measured with a transmit and a receive antenna set up so that the incident and reflected angle of the EM wave may be equal

3.1.13
parallel beam
EM wave, which has a nearly flat phase front on the surface normal to the antenna axis, and which is formed using a dielectric lens set up in the front of a horn antenna

3.1.14
monostatic measurement
measurement where the incident and reflected waves follow the same direction which lie at an arbitrary angle with respect to normal to the specimen surface

3.1.15
bistatic measurement
measurement where the incident and reflection angle is equal

3.1.16
beam waist
portion at which the diameter of the focused beam becomes minimum when the electromagnetic wave radiated from a transmit antenna is converged using a dielectric lens

3.1.17
focal point
centre of beam waist when the electromagnetic waves are converged using a dielectric lens

3.1.18
focal distance
distance between the centre of the dielectric lens and the focal point

3.1.19
reflectivity
reflectivity is expressed by

$$\text{reflectivity} = 20 \log_{10} \left| \frac{V_s}{V_m} \right| \text{ [dB]},$$

where V_s is the reflected EM wave voltage received by the receive antenna when the specimen is irradiated by the EM wave, and V_m is the voltage of the EM wave reflected from a metal plate with equal size and with the same projection shape as normal to specimen surface
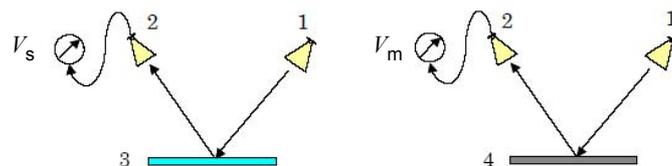
Key
1 Tx antenna
2 Rx antenna
3 EMA
4 Metal plate

Figure 1 – Definition of reflectivity

3.1.20
reference metal plate
metal plate with the same shape and equal surface projected area as normal to the specimen

3.1.21
transverse electromagnetic wave
EM wave in which both the electric and magnetic fields are perpendicular to the plane of incidence when an EM wave is incident normally to the specimen surface

3.1.22
transverse electric wave
EM wave in which the electric field is perpendicular to the plane of incidence when the EM wave is incident to the specimen surface at an oblique angle

3.1.23
transverse magnetic wave
EM wave in which the magnetic field is perpendicular to the plane of incidence when the EM wave is incident to the specimen surface at an oblique angle

3.1.24
time-domain function
VNA generally has a function to transform the measured frequency domain data to time evolution data using Fourier transform because the VNA can measure both the amplitude and phase of EM wave. Therefore, the reflected wave only from the specimen can be extracted by applying a suitable time gating to the time evolution output signal and inverse Fourier transform

3.2 Acronyms

Acronyms	
EMA	Electromagnetic wave absorber
NWA	Network analyser
VNA	Vector network analyser
TEM	Transverse electromagnetic
TE	Transverse electric
TM	Transverse magnetic

4 Specimen

4.1 Specimen specification

It is recommended that the specimen have a flat surface and rigid structure having a dimension equal to, or larger than 15 λ where λ is the wavelength of the EM wave at the lowest frequency in the measurement frequency range. However, the detailed specifications are given in each type of the two measurement methods described below.

4.2 Reference metal plate

4.2.1 Material and thickness

Aluminium, copper, stainless steel etc., which has a thickness of 1 mm to 2 mm, is preferred.

4.2.2 Surface roughness

The surface roughness of a reference metal plate should be less than $\lambda/10$, although less than $\lambda/20$ is preferred, where λ is the wavelength that corresponds to the maximum frequency in

the measurement frequencies range. For example, if the maximum frequency is 300 GHz, then λ is 1 mm, and the preferable roughness becomes 0,05 mm.

4.2.3 Flatness

It is recommended that the flatness be less than 0,5 mm for a reference metal plate with size 1 m $\times$ 1 m.

4.2.4 Size and shape

Reference metal plate should have the same size and same projection shape normal to the specimen surface. However, it is desirable to use the size specified by each method described below. Care should be taken in selecting the size of the reference metal plate because the reflection and scattering characteristics may depend on its size due to the Fresnel refraction. The dependence of the reflection and scattering characteristics on the size in the case of the horn antenna method is illustrated in Annex A.

4.3 Reference specimen for calibration

A reference specimen for calibration should be silica-glass plate or sapphire single-crystal (001) plate with uniform thickness and smooth surface roughness. Relative permittivity should be known in advance. When the dielectric material is selected, it is necessary to measure the reflectivity of the specimen without putting anything on the backward surface of the reference specimen. The reference specimen should be fixed by foamed plastics, which have a relative permittivity, of near to 1, and EM waves do not reflect as in free space. It is recommended that the accuracy of the measurement system be measured by comparing the measured reflectivity with the theoretical one. The reflectivity of a silica-glass plate or sapphire plate measured in the millimetre wave range is given in Annex B.

5 Specimen holder

A specimen holder may be different from any type of measurement method mentioned below. The specimen holder should possess functions of adjusting azimuth and elevation.

6 Measurement equipment

Correct usage of the measurement equipment is very important in order to obtain the exact results. The measurement of the reflectivity of EMA shall be performed using either a VNA or scalar network analyser. When there are discrepancies in the measured results, it is necessary to make calibration of the measurement system using a reference specimen. The necessary equipment should be selected according to the type of measurement methods used, as shown in below.

6.1 Network analyser

6.1.1 Vector network analyser

The VNA is recommended because it can measure both the amplitude and phase and time domain function.

6.1.2 Scalar network analyser

The scalar network analyser can only measure the amplitude, and does not have time-domain function, which is mainly used for relatively low accuracy measurement.

6.2 Antenna

6.2.1 Horn antenna

Both a commercial as well as an in-built horn antenna can be used for the reflectivity measurement of EMA except in special cases. However, The commercial horn antenna is recommended in order to obtain the required measurement accuracy, which has an accurate gain, VSWR, and size. The commercial coaxial-waveguide transducer is also recommended where the VSWR or sizes are verified in each frequency band. The specifications of some commercial horn antennas are shown in Annex C.

6.2.2 Lens antenna

Not only a dielectric lens antenna but also a metal-plate lens antenna or Luneberg lens antenna can be used for the reflectivity measurement of EMA in this PAS. Either a commercially available or an in-built product can also be applicable. However, the use of a commercial antenna, in which the antenna gain, VSWR, and sizes are specified, will be recommended in order to realize the required measurement accuracy. The specifications of commercial horn antennas and dielectric lenses are illustrated in Annex C.

6.3 Amplifier

An amplifier is generally used in order to get sufficient dynamic range of the measurement system. The warming-up of the amplifier is required, and the temperature should be kept as constant as possible because the total gain of the amplifier will vary due to the temperature drift as described in Clause 7.

7 Measurement condition

7.1 Temperature and environment

The measurement should be carried out in the atmosphere from 860 hPa to 1 060 hPa, and in the room from 5 °C to 35 °C, and relative humidity from 45 % to 85 %. If the operation temperature and humidity range of the measurement equipment are narrower than the above range, the specifications of the measurement equipment should be followed. It is desirable to control the measurement temperature within ±3 °C in order to suppress the influence of the temperature drift of measurement equipment to a minimum. The measurement temperature of the specimen should be selected to be 20 °C, 23 °C or 25 °C. In the case of high humidity, relative humidity should be maintained at either 50 % or 65 % in measurement.

7.2 Calibration temperature of measurement equipment

If the temperature at which measurement equipment is calibrated is within ±3 °C around the measurement temperature, measurement errors can be minimized. However, if the measurement temperature exceeds the range of ±3 °C, then it is recommended to carry out the calibration again.

7.3 Warming-up of measurement equipments

The warming-up time must be kept, typically 15-45 min, written in the specifications of the measurement equipment or systems. Moreover, the warming-up time should be taken to be longest in all of the measurement equipments.

7.4 Electromagnetic environment

When the EM wave power density in the measurement environment exceeds the public regulation, and when the EM environment is judged to be not so good, the measurement should be carried out in an anechoic room. When the directional gain of an antenna is large, however, an anechoic chamber may not necessarily be required.

7.5 Calibration of measurement equipment

The equipment shall be calibrated according to the standard established by the manufacturers, or according to ISO/IEC 17025, or other corresponding standard. The items to be calibrated include frequency, voltage, and attenuation, which depend on the measurement accuracy or uncertainty of the measurement equipment.

7.6 Cable calibration

Degradation in the transmission characteristics of cables shall be checked when the cables are connected direct without the intervention of an EMA or free space.

8 Calibration of measurement system and measurement conditions

8.1 Calibration of measurement system

Calibration of the measurement system shall be carried out according to the recommended methods by NWA. Typical calibration methods are shown in Annex D.

8.2 Measurement conditions

8.2.1 Dynamic range

Both the receive levels with and without the reference metal plate shall be measured firstly when the measurement system is set up. The dynamic range is defined as the difference of these measured values in decibels. Annex E illustrates the relation between the dynamic range and the measurement error. If the dynamic range of the measurement system is 40 dB and the reflectivity of the specimen is –20dB, respectively, an error bar lies from –0,92 dB to +0,83 dB with respect to –20 dB.

8.2.2 Setting up of the network analyser for keeping adequate dynamic range

The dynamic range of the measurement system can be increased by modifying the IF band or by utilizing the averaging function, etc. of NWA when the dynamic range does not exceed a necessary value. The dynamic range increases by use of the isolation calibration of VNA, as shown in Annex F.

9 Horn-antenna method

9.1 Measurement system

9.1.1 Configuration of the measurement system

Figure 2 shows a block diagram of the measurement system. The arrangement of the transmitting and receiving antennas, and the block diagram of the measurement system in the horn-antenna method are illustrated below for normal and oblique incidence measurement. In the measuring transmission coefficient S_{21}, a pair of antennas is used whereas only one antenna is used for measuring the reflection coefficient S_{11} in normal incidence.

In the case of oblique incidence, the transmitting antenna should be arranged in such a way that the central axis makes the same angle to the normal direction of the specimen surface with that of the receive antenna. Here, if S_{21} is measured using two horn antennas in normal incidence, then the vertical alignment of the transmit and receive antennas should be fixed within 5°. The measurement equipment including a NWA were given in Clause 6.
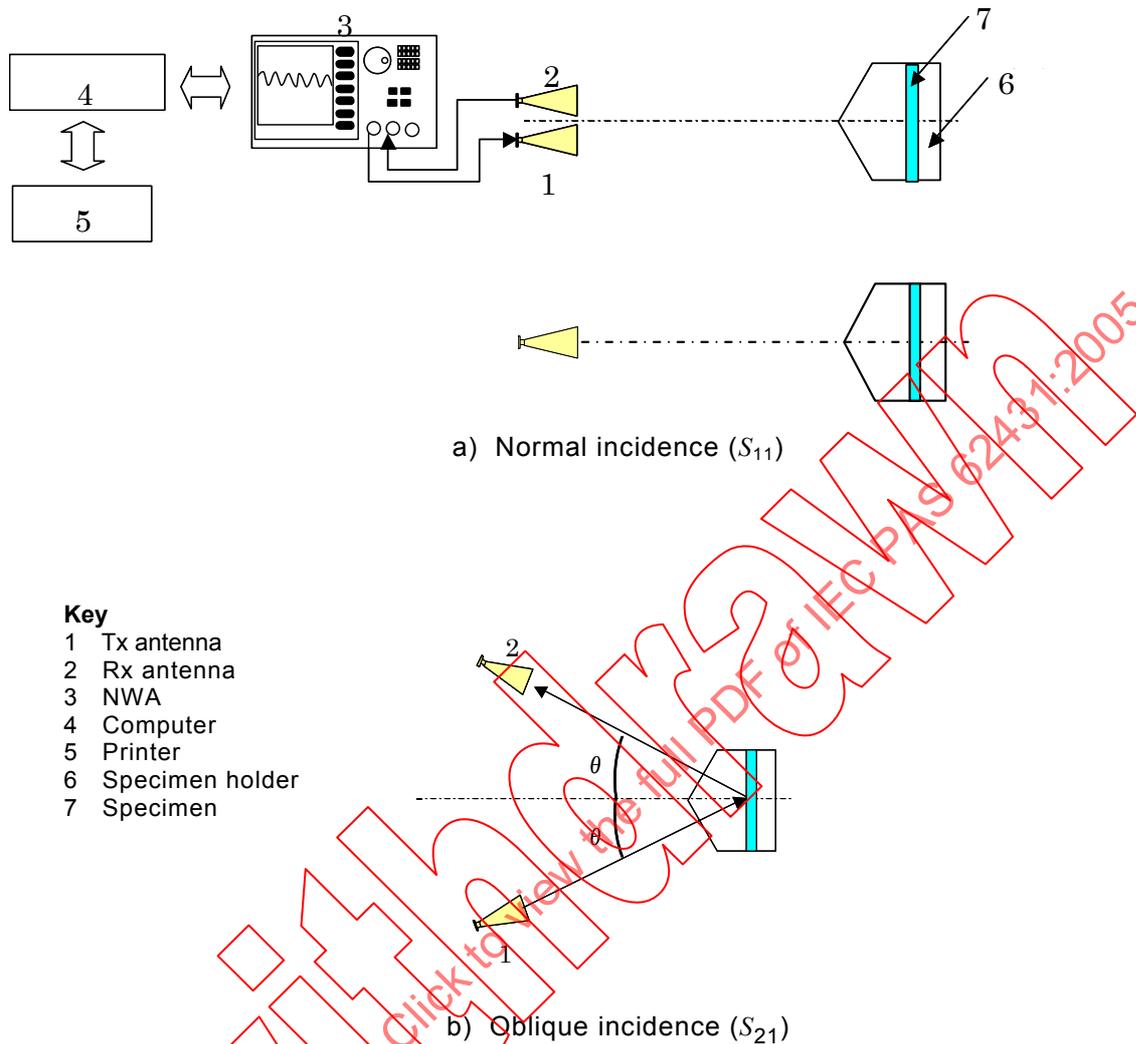
a) Normal incidence (S_{11})

Key
1 Tx antenna
2 Rx antenna
3 NWA
4 Computer
5 Printer
6 Specimen holder
7 Specimen

b) Oblique incidence (S_{21})

Figure 2 – Configuration of the measurement system

9.1.2 Horn antenna

Both a commercial as well as an in-built horn antenna can be used for the reflectivity measurement of EMA except in special cases. Before the measurement of reflectivity it is necessary to calculate the directional gain of the horn antenna to determine the distance from the antenna to the specimen. Annex G calculates the directional gain of the horn antenna. Further, the directional gain, VSWR and sizes must be checked from the catalogue when a commercial horn antenna is used.

9.1.3 Specimen holder

9.1.3.1 Material and shape

a) Material

The reflection from the specimen holder can be minimized by making use of foamed polystyrene a with high a foaming ratio as a specimen holder because foamed plastics have very low relative permittivity (near 1). Annex H shows the relative permittivity of foamed polystyrene as a function of foaming ratio.

b) Shape

The shape in normal projection to the specimen surface and area of a specimen holder which mounts the specimen should be equal to those of the specimen in order to suppress the reflection of the EM wave from the specimen holder. The uncovered portion of the specimen holder should be covered by a pyramidal-type wave absorber, and the shape of the uncovered portion should have a wedge form, as Illustrated in Figure 3.
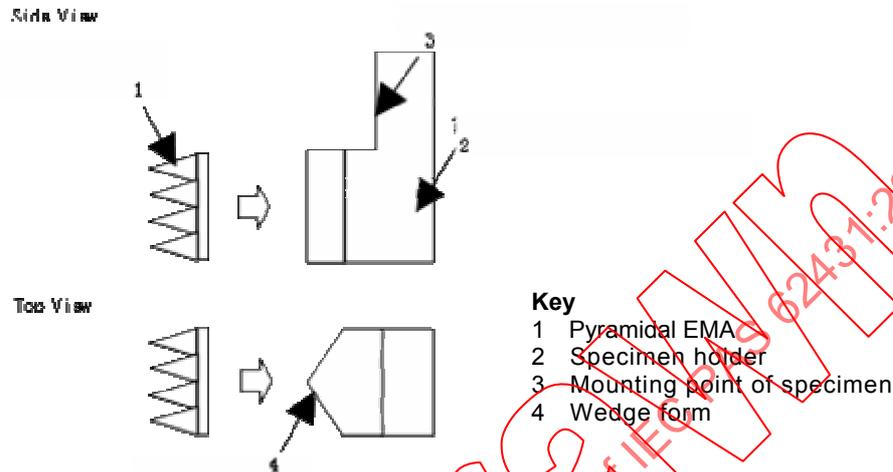

Key
1   Pyramidal EMA
2   Specimen holder
3   Mounting point of specimen
4   Wedge form

Figure 3 – Mounting method of specimen

9.1.3.2 Azimuth and elevation angle adjustment function

Figure 4 shows the elevation angle adjustment as well as the lifting and descending mechanism. An azimuth table under the specimen holder, which has the mechanism adjusting elevation and azimuth angle, should be installed in order to enable the accurate installation of the specimen with respect to the transmit antenna. The accuracy of elevation and directional angle should be about 0,1°.

Key
1   Specimen holder
2   Azimuth angle adjustment function
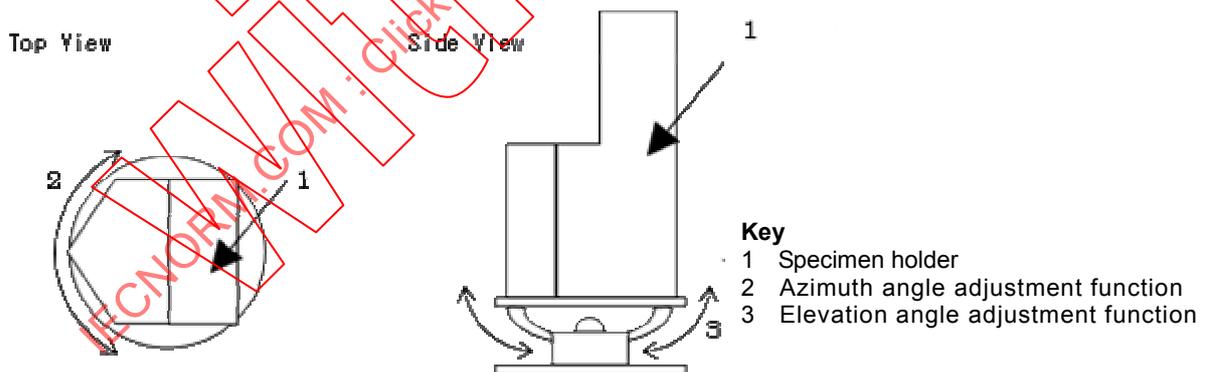3   Elevation angle adjustment function

Figure 4 – Mechanism for adjusting azimuth and elevation

9.1.4 Mounting of the specimen

Either double-sided adhesion tape, simple paste or thin cellophane tape is used to fix the reference metal plate and specimen to the specimen holder.

9.1.5 Antenna stand

Attention should be paid to cover up a tripod portion by a pyramidal-type wave absorber although the quality of the material of the tripod stand which mounts a transmitting antenna does not need to be made from rosin or wood.

9.2 Measurement conditions

9.2.1 Measurement environment

The measurement should not necessarily be performed in an anechoic chamber, which depends on the directional gain of the antenna. However, there shall be no obstacle in the direction of the main beam of the horn antenna. If the obstacle cannot be removed, a screen of pyramidal-type wave absorbers shall be installed on the path of the EM wave. When the oblique incidence characteristic is measured, the floor and roof, etc. should also be covered with pyramidal-type EMA because the reflected EM wave from them has the same path length as that from the specimen in many cases.

9.2.2 Measuring distance

When the EM waves are radiated from the rectangular aperture of a horn antenna, the distance, R which separates the Fresnel region from the Fraunhofer region, the boundary between the two may be arbitrarily taken to be at Eq. (1), where D is an effective maximum dimension of the antenna aperture, and λ is the wavelength. The directional gain, G_d of the horn antenna is represented by Equation (2). From Equations (1) and (2), the range of R representing the Fraunhofer region can be expressed by Equation (3) using G_d.

$$R \geq 2D^2 / \lambda \qquad (1)$$
$$G_d = 4\pi D^2 / \lambda^2 \qquad (2)$$
$$R \geq G_d \lambda / 2\pi \qquad (3)$$

It is desirable to keep the distance between the specimen and the antennas greater than the right-hand side of Equation (3), which depends on the measurement frequency. Annex I shows the relation of the directional gain of the antenna and measuring distance.

9.2.3 Size of specimen

The size of the specimen should be larger than $10\lambda \times 10\lambda$ for the reflectivity measurement using the horn-antenna method, where λ is the maximum wave length in the measurement frequency range. If the size of the specimen is smaller than $10\lambda \times 10\lambda$, a quite accurate adjustment of azimuth and elevation angles should be done.

9.3 Measurement procedures

Measurement is carried out according to the following steps after installation of measurement equipment, based upon the conditions described in Clause 7.

9.3.1 Adjustment of measurement system

a) Set up the transmitting antenna and specimen holder according to each measurement condition, i.e. normal or oblique incidence, distance between specimen and antennas, etc.

b) Set up the transmit antenna in such a way that its height will be at the centre of the specimen, and adjust the horn antenna so that the aperture may be perpendicular to the horizontal plane using a spirit level.

c) Set up the reference metal plate on the specimen holder, and adjust the elevation angle so that the reference metal plate is perpendicular to the horizontal plane using a spirit level.

d) Set up the position and normal direction of the reference metal plate so that the receiving level of the scattered EM wave may become maximum by rotating the metal plate through ±10° of the directional angle using an azimuth turntable.

e) Check the dynamic range of the measurement system. Measure the receiving level of the reference metal plate at the measurement frequency range. Remove the reference metal plate and measure the receive level. Calculate the dynamic range and the difference of the two levels in decibels. Carry out the isolation calibration according to 8.2.2 when the desired dynamic range is not obtained.

9.3.2 Measurement using scalar network analyser

a) Set up the reference metal plate on the specimen holder, and measure the receiving level, R_{metal} (dB).

b) Replace the reference metal plate by specimen on the specimen holder, and measure the receiving level, $R_{absorber}$ [dB].

c) Calculate the reflectivity of the specimen by subtracting the receiving level R_{metal} [dB] from receiving level, $R_{absorber}$ [dB].

9.3.3 Measurement using vector network analyser

a) Set up the reference metal plate on the specimen holder. Measure the vector quantities of the receiving level, $\dot{\Gamma}_{metal}$.

b) Remove the reference metal plate from the specimen holder, and measure the receiving level, $\dot{\Gamma}_{residual}$ without the specimen.

c) Mount the specimen on the specimen holder, and measure the vector quantities of the receiving level, $\dot{\Gamma}_{absorber}$.

d) Remove the specimen from the specimen holder, and measure the vector quantities of the receiving level, $\dot{\Gamma}_{residual}$.

e) Subtract the vector quantities of the receiving levels, $\dot{\Gamma}_{residual}$ from $\dot{\Gamma}_{metal}$, and subtract the undesired waves other than those reflected directly from EMA.

f) Transform the vector quantities into the time-domain data from the frequency domain data, and apply time gating for the main response from EMA only.

g) After the time gating is applied, transform the responses into the frequency domain receiving level, R_{metal} (dB) of the reference metal plate.

h) Subtract the vector quantities of receiving level, $\dot{\Gamma}_{residual}$, from the vector quantities of the receiving level, $\dot{\Gamma}_{absorber}$ of the reference metal plate, and subtract the undesired waves.

i) Transform the vector quantities obtained into the time domain from the frequency-domain data, and apply time gating for the main response only.

j) After the time gating is applied, these responses are retransformed to the frequency domain data, receiving level, $R_{absorber}$ (dB) of the specimen.

k) Calculate the reflectivity of specimen by subtracting the receiving level, R_{metal} (dB) of the reference metal plate from the receiving level, $R_{absorber}$ (dB) of specimen.

10 Dielectric lens antenna method – Focused beam type -

10.1 Outline

A method which uses the focused beam type horn antenna has the following characteristics.

— Large measurement space may not necessarily be required because the focused EM wave has a beam waist of several wavelength and has nearly flat phase-front on the focal plane.

— Sufficient dynamic range can be easily obtained because the EM wave does not spread over into the surroundings.

— The measurement cannot necessarily be carried out in an anechoic chamber in the case where the large dynamic range is not required because the scattered EM waves in the surroundings cannot easily become a receiving antenna.

10.2 Measurement system

10.2.1 Transmitting and receiving antennas

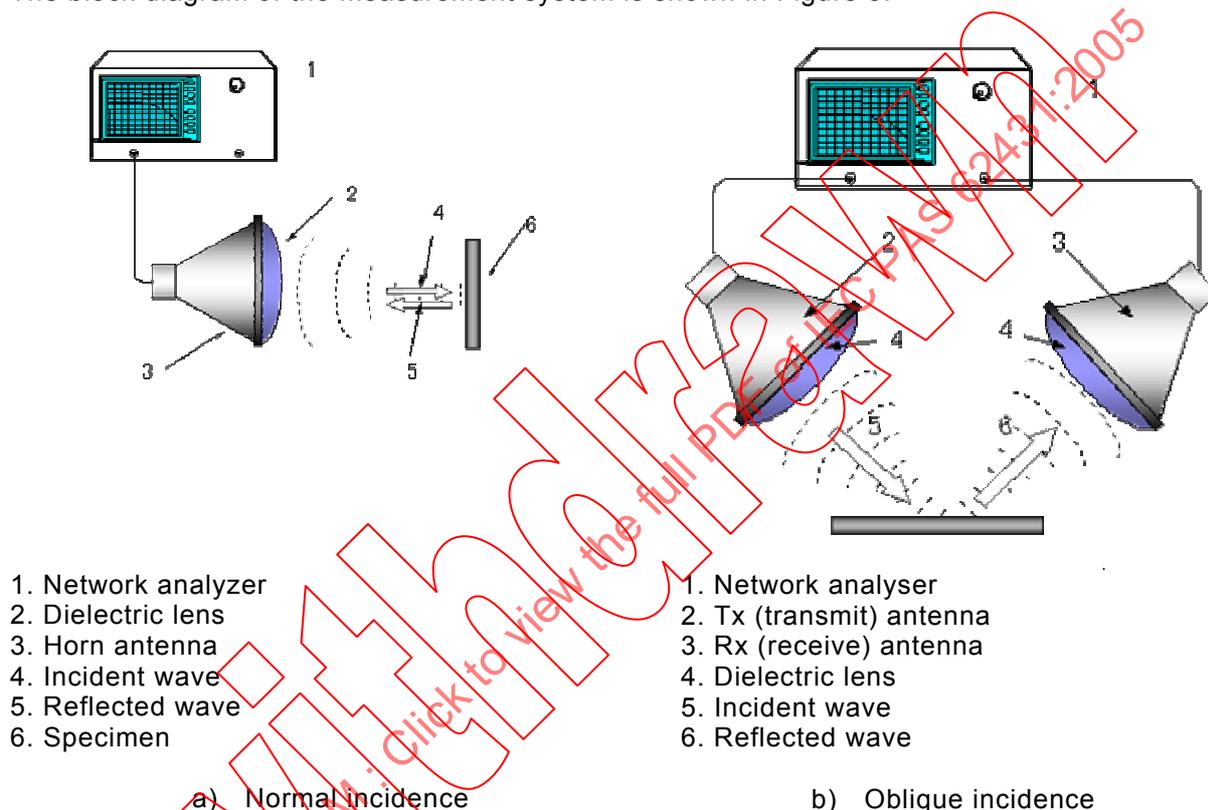The block diagram of the measurement system is shown in Figure 5.

1. Network analyzer
2. Dielectric lens
3. Horn antenna
4. Incident wave
5. Reflected wave
6. Specimen

1. Network analyser
2. Tx (transmit) antenna
3. Rx (receive) antenna
4. Dielectric lens
5. Incident wave
6. Reflected wave

a)   Normal incidence   b)   Oblique incidence

Figure 5 – Block diagram of measurement system

10.2.2 Focused beam horn antenna

10.2.2.1 Antenna structure

Figure 6 shows a structure of an antenna with a dielectric lens used in the focused beam method which is composed of a coaxial-waveguide transducer, mode conversion feed, which converts a linearly-polarized EM wave to a circularly polarized one, circular horns, and convex-type dielectric lens. The EM waves radiated from the antenna gradually converge at the focus, where the minimum beam waist of the EM wave becomes several wavelengths. The focal length is determined by both curvature of a convex-type dielectric lens and relative permittivity of the lens material. The amplitude of the EM wave at beam waist changes as Gaussian as a function of the radial distance away from the central axis of the lens, which is at its maximum at the centre of the focus. The phase at the focus does not depend so strongly on the radial distance because both the path (electric length) that is transmitted through the centre of the lens and the path (electric length) that is transmitted through the peripheral part of the lens are nearly equal. Some specifications of a commercial dielectric lens antenna, such as diameter, focal length, and lens material etc., are shown in Clause C.2.
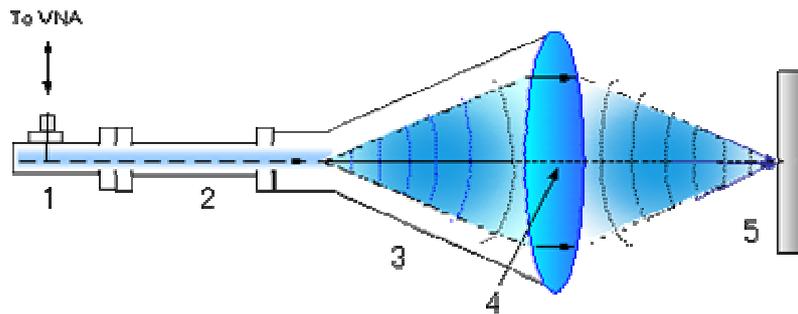
Key
1 Coaxial-waveguide transducer
2 Mode converter
3 Horn antenna
4 Dielectric lens
5 Specimen

Figure 6 – Structure of a dielectric lens antenna

10.2.2.2 Measurement range

A different coaxial-waveguide transducer and a different rectangular-circular mode conversion feed must be prepared for a different frequency band in Figure 6.

10.2.2.3 Antenna positioner

An antenna positioner shall be prepared for accurate measurement of the oblique incidence, which enables to move the transmitting and receiving antennas along the central axis and to measure the moved distance accurately. Moreover, an antenna holder should have a function so that the incident angle of the EM wave may be varied with respect to the normal direction of the specimen surface.

10.2.3 Specimen size

Each length of the specimen sides should be at least larger than 3 times the diameter of the largest beam waist at the lowest frequency of the measuring frequency range.

10.2.4 Reference metal plate size

The reference metal plate should have the same area and shape in normal projection as the specimen surface.

10.2.5 Specimen holder

10.2.5.1 Material and size

A specimen holder is illustrated in Figure 7. The specimen holder is made with resinous material, polycarbonate plastics, which has relatively low permittivity near 1 and does not reflect EM waves so strongly at the holder surface. The specimen holder should have a rigid structure without any swing or vibration.

In the case of normal incidence, the size should be larger than 3 times the beam waist, and it is preferable as large as possible. Therefore, the structure, which can set a large or small specimen at the same time, is preferred. In the case of oblique incidence angle θ, the size of the specimen holder is made larger than in normal incidence because the irradiated specimen surface area becomes larger than in normal incidence by $1/\cos\theta$.
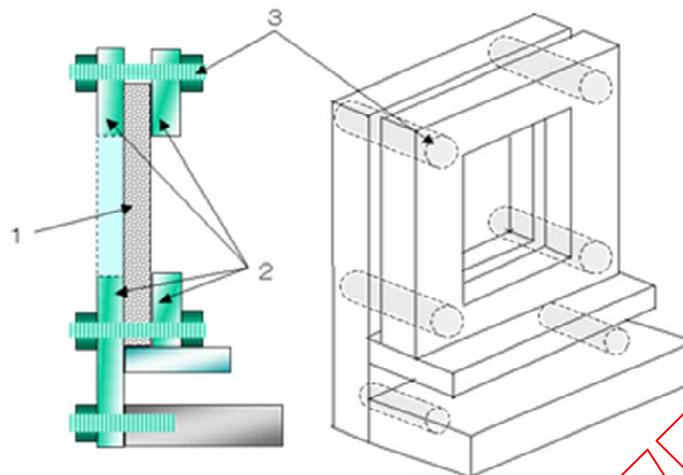
Key
1 Specimen
2 Poly-carbonate frame
3 Poly-carbonate screw and nut

Figure 7 – Structure of specimen holder

10.2.5.2 Adjustment of azimuth and elevation angle

To installation the specimen accurately, a specimen holder should have a function to manipulate the elevation and azimuth angles. Azimuth and elevation angles are adjusted to the most appropriate values so that the receiving level may become maximum after a reference metal plate is put instead of the specimen.

10.2.6 Method of fixing the specimen and the reference metal plate

The 4 sides of the specimen or the reference metal plate should be tightly fixed on the specimen holder so that bending may not occur.

10.3 Measurement procedures

Measurement procedures, which resemble the horn antenna method are summarized as follows.

a) Set the distance between the specimen holder at the focal point of a dielectric lens antenna. Refer to Annex J.

b) Put the reference metal plate on the specimen holder.

c) Perform calibration of the network analyser

d) Put the reference metal plate again on the specimen holder, measure the reflection level, and confirm whether the measured total reflection level is 0 dB or not.

e) Make Fourier transformation of the reflected EM wave raw data to the time-domain data, set up an optimal time gating, i.e. bandpass filter on a time axis, where the reflected response from the reference metal plate is centred. See Annex K.

f) Perform the inverse Fourier transformation of the gated time-domain response. See Annex K.

g) Replace the reference metal plate by the specimen, measure the reflection levels of specimen at several points on the specimen because the focused beam diameter is only about 3λ to 5λ, and normalize the reflection level by that from the reference metal plate. Finally the measured values are averaged over the several measured values as shown in Annex L.

h) In oblique incidence, repeat from step d) to step g) after varying the incident angle between transmit and receive antennas.

11 Dielectric lens method – Parallel beam method

11.1 Principle

11.1.1 Outline

In the parallel beam method, the EM wave radiated from the transmitting antenna, is deflected to be parallel beam using a dielectric EM wave lens. The transmitted wave incidents on the specimen, and the reflected EM wave level is measured using a horn antenna after being transmitted through dielectric lens.

This method has the following characteristics.

— Large measurement room is not usually required because the spherical equi-phase front of the EM wave from a horn antenna can be converted to quasi-plane phase front near the focal point.

— An anechoic chamber is not always necessary because enough dynamic range is generally achieved since the scattered EM waves into the surrounding cannot easily invade the receiving ports.

— In oblique incidence, it is possible to make measurement at large incident angle because EM wave beam is quasi-paralleled by dielectric lens.

11.1.2 Parallel EM wave beam formed using a EM wave lens

The wavelength of the millimeter wave, several mm, is generally far smaller than the distance between the antenna and the specimen, an EM wave lens can be realized similarly to an optical lens based upon the ray theory. There exist a dielectric lens, a metal plate lens, etc., as typical EM wave lenses. Figure 8 shows the effect of using dielectric lens. The secondary phase error on the specimen surface can be compensated, and EM wave has planer equi-phase front (hereafter called parallel beam) and with high energy density can be obtained if a dielectric lens is put in front of a horn antenna. If a dielectric lens is used, side-lobes are suppressed due to the low radiation power on the end portion of a dielectric lens.

The horn antenna with a dielectric lens has the following characteristics.

a) Side lobes can be suppressed when there is no obstacle on the forward direction between a horn antenna and a dielectric lens.

b) Reflections from a lens can be easily reduced by using anti-reflection coating on the lens surface.

a) Construction   b) Equi-phase plane
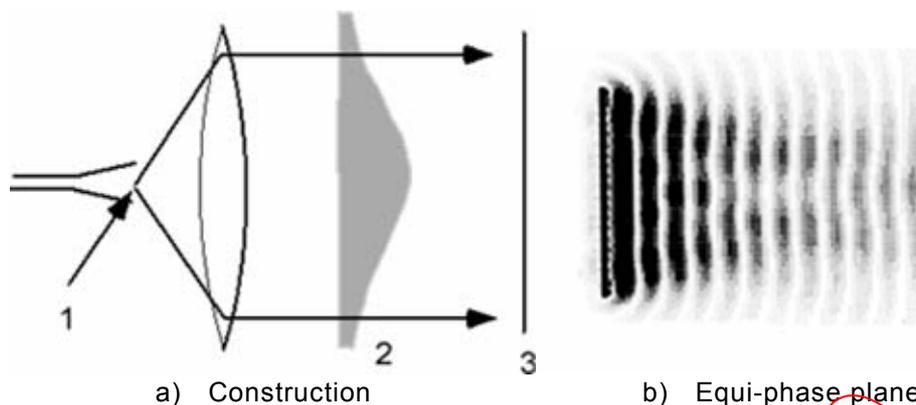
Key
1 radiation source of EM wave
2 field distribution
3 equi-phase plane pattern

Figure 8 – EM wave propagation using a horn antenna and a dielectric lens

11.2 Measurement system

11.2.1 Composition of measurement system

An example of a measurement system is shown in Figure 9. The specimen is kept normal to the plane of incidence. A specimen holder has a structure applicable to the measurement for oblique incidence. The directions of both antennas are adjusted such that incident and reflection angle may be equal by maximizing the reflection level of the receiving antenna.
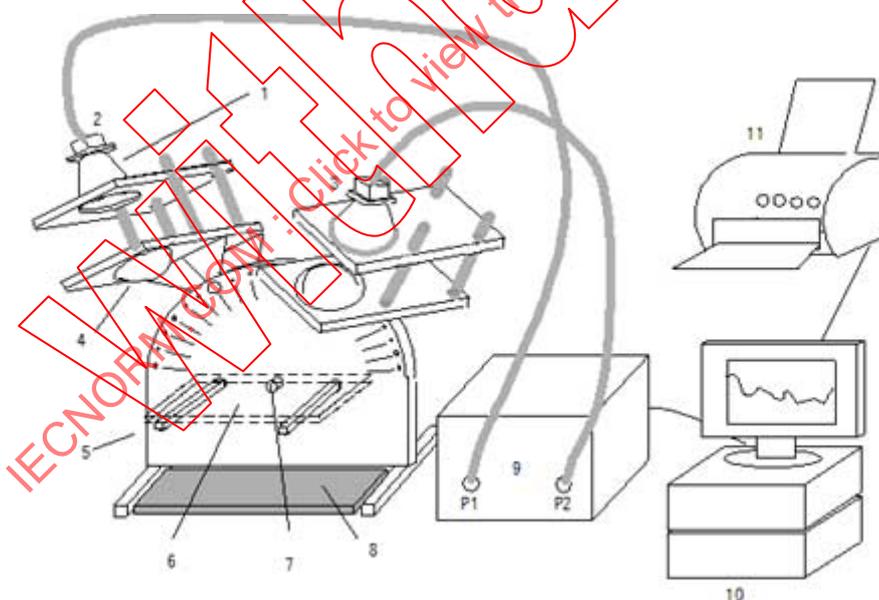
Key

1	Horn antenna	7	Rotary shaft
2	Transmitting antenna	8	EM absorber
3	Receiving antenna	9	Network analyser
4	Dielectric lens	10	Personal computer
5	Specimen holder	11	Printer
6	Specimen		

Figure 9 – Block diagram of the measurement system

11.2.1.1 Normal incidence

Figure 10 shows the block diagram of a measurement system for normal incidence. One dielectric lens and an antenna are used. Transmission, and reflection coefficient, S_{21} and S_{11} are measured using a network analyser. In order to remove the multiple reflections, a VNA is used which has the time-domain function in order to extract the reflected wave of the required gating time. See Annex K
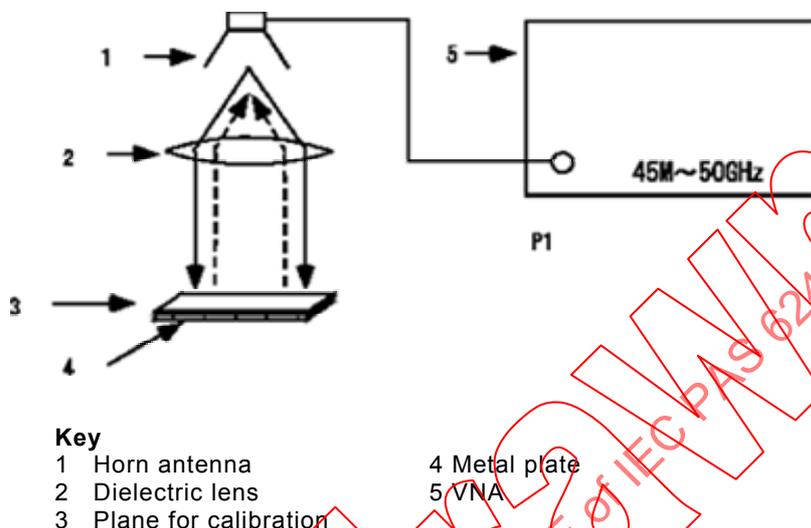

Key

1 Horn antenna   4 Metal plate
2 Dielectric lens   5 VNA
3 Plane for calibration

Figure 10 – A measurement system for normal incidence

11.2.1.2 Oblique incidence

Figure 11 shows the block diagram of a measurement system for oblique incidence. Transmission coefficient, S_{21} is measured by using each dielectric lens in a transmitting and receiving antenna, respectively. In the case of oblique incidence, the spurious EM wave is decreased due to the scattering of the EM wave of multiple reflections etc. Therefore, usually time-domain and gating functions of VNA are not necessary. For this reason, a SNA can also be used. In high-accuracy measurement, however, the reflected wave shall be extracted only from the specimen using the time domain and gating functions of VNA. See Annex K.
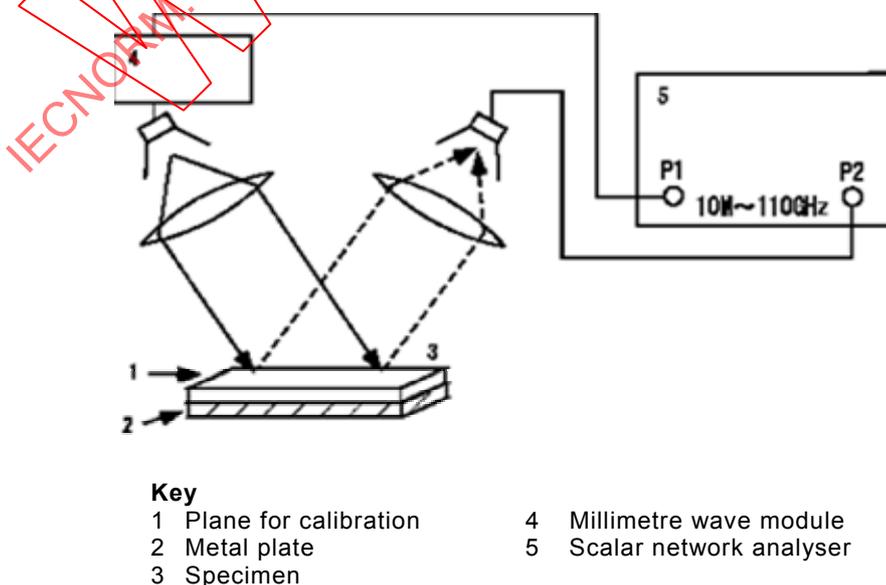

Key

1 Plane for calibration   4   Millimetre wave module
2 Metal plate   5   Scalar network analyser
3 Specimen

Figure 11 – Measurement system for oblique incidence.

For an incident angle larger than 70°, not the correctly reflected wave from the specimen but the direct coupling between the transmitting and receiving antenna occurs. In this case, a shielding plate of an EM absorber should be used as shown in Figure12. The calibration of the system should be performed including isolation. See Annex F.
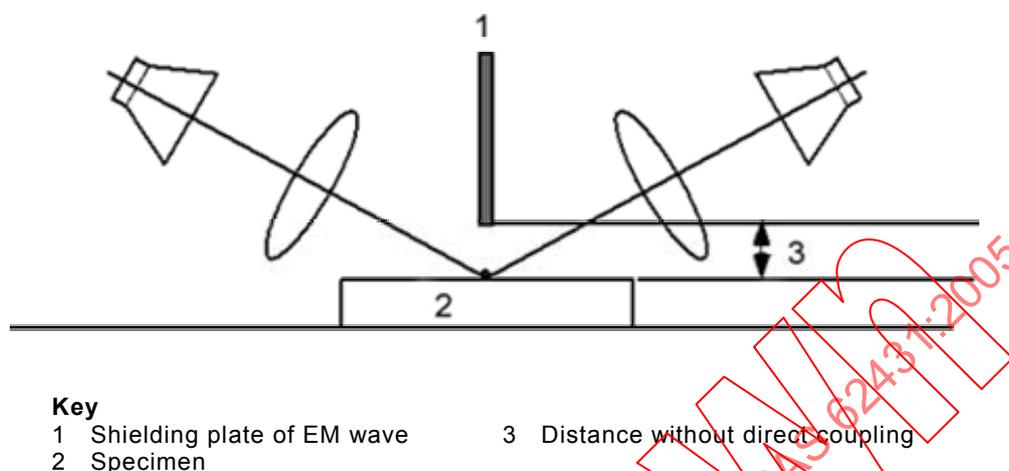

Key
1 Shielding plate of EM wave   3 Distance without direct coupling
2 Specimen

Figure 12 – Position of a shielding plate

11.2.2 Dielectric lens antenna

a) Diameter of dielectric lens and surface roughness

  – The diameter of the lens is more than 10 times that of the wavelength.

  – Surface roughness must be less than 1/16 of the wavelength. Measurement procedures are similar to those of the horn-antenna method.

b) Horn antenna

  – A horn antenna is set so that the imaginary source point of the antenna comes to the focal point of a dielectric lens. The position of the imaginary source is illustrated in Annex M.

c) Distance between specimen and dielectric lens

  – The distance between a specimen and a lens is taken from 2,5 to 5 times the diameter of the dielectric lens in order to avoid the near-field region of the EM waves at the dielectric lens. A designing method for dielectric lens antenna is illustrated in Annex M.

11.3 Specimen

11.3.1 General

In the case of dielectric lens, the transmitted wave is not plane wave, and equi-phase front is not planar but is curved if it is away from the central axis, which leads to a decrease in the magnitude of reflectivity. If the maximum phase difference of the EM wave within the specimen surface is less than 22.5°, i.e. 1/16 of the wavelength, the decrease in reflectivity is usually less than –10 dB. The error may be small for a larger specimen.

11.3.2 Reference metal plate

Each side of the reference metal plate should be greater than the diameter of the dielectric lens. Aluminium or copper is made use of as a metal plate with equal diameter.

11.3.3 Size of specimen

Each side of a specimen must be larger than 0,3 times the diameter of the dielectric lens. In the case of oblique incidence, it is desirable to take a larger distance of path between the incident and reflected wave for a large incident angle. In order to remove the undesired reflections, EM wave absorbers are often put on the back side of the reference metal plate and specimen.

11.4 Measurement procedures

11.4.1 Normal incidence using a VNA

Prepare a coaxial cable (CABLE-1) which connects the port, P1 of the VNA, and the horn antenna. The connect coaxial cable (CABLE-2) to the port, P1 of VNA, and connect the other end of the cable to the horn antenna.

Put the reference metal plate on the surface of the specimen, each side of which is larger than the diameter of the dielectric lens, and carry out response calibration using short only. Nextly, optimize the gate time. Rotate and adjust the specimen mount in such a way that reflection from the metal plate is maximum, and measure the reflectivity of the reference metal plate, A [dB].

Put the specimen so that the upper surface will come to the same position of the reference plane, and measure the reflectivity of specimen, B [dB]. Calculate the reflectivity by B – A [dB].

NOTE   One horn antenna is used in the rigorous measurement of normal incidence. However, the measurement of oblique incidence by making the incident angle as small as about 5° can be usually assumed to be normal incidence.

11.4.2 Oblique Incidence

11.4.2.1 Measurement using a VNA

Adjust the spatial direction of an antenna properly according as the polarization of TE or TM waves.

Prepare a coaxial cable (CABLE-2) in order to connect the port, P1 of VNA, and the transmitting antenna, and another coaxial cable (CABLE-3) in order to connect the port, P2 of VNA, and the receiving antenna. Connect these cables to the ports, P1 and P2, respectively, and carry out short-, open-, and match-calibration at the other ends terminated with 50 Ω.

Set the transmit and receiving antennas so that the incident and reflection angles are equal, respectively, and connect coaxial cables to each horn antenna. Put the reference metal plate on the same height of the specimen surface, and perform through calibration. Note that each side of the metal plate must be greater than the diameter of the dielectric lens.

Optimize the gating time and width for measuring the reflectivity from the reference metal plate. Rotate the specimen mount in such a way that reflection from the reference metal plate is maximum, and measure the reflection from the reference metal plate, A [dB].

Put the specimen so that its upper surface will come to the same height of the reference plane, and measure the reflection, B [dB]. See Annex K.

Calculate the reflectivity by B – A [dB].

11.4.2.2 Measurement using a scalar network analyser

a) Adjust the spatial direction of an antenna according to the polarization for the TE wave or the TM wave.

b) Connect a coaxial cable (CABLE-2) to the port, P1 of SNA, and to the transmitting antenna, and another coaxial cable (CABLE-3) to the port, P2 of SNA, and to the receiving antenna.

c) Fix the transmitting and receiving antennas so that the incident and reflection angles may be equal. Connect coaxial cables to each horn antenna. Put the reference metal plate on the sample holder so that its height is at the same height of specimen surface. Set the NWA to transmission measurement state. Note that each side of the reference metal plate must be larger than the diameter of dielectric lens.

d) Adjust the specimen holder so that the reflected signal level of the EM wave from the reference metal plate is maximum. Calibrate the NWA.

e) Put the specimen on the specimen holder so that the upper surface will come to the same height as that of the previous reference metal plate. Measure the reflectivity of the specimen, B [dB].

12 Test report

12.1 Content

A test report should be written, in order to include the experimental results properly in written form where the experimental conditions are indicated by the following terms.

12.2 Specimen

In a test report, enter also the product type of the specimen and the name, if possible. Product type may include material, shape, composition of layers, etc. Include the dimension of the specimen.

12.3 Measurement data

The measurement results of the reflectivity of a specimen should be expressed in table or graph form. Moreover, the measurement result of a dynamic range shall also be specified. Refer to Figure 13.

12.4 List of test equipment

It is necessary to list the test equipment used in the test report. It is also desirable to mention the manufacturer's model and latest calibration date.

12.5 Unit

The reflectivity of the specimen is expressed in dB. The unit of frequency is in GHz.

12.6 Measurement method

Describe the measurement method of the reflectivity of the specimen and the measurement procedures.

12.7 Measurement condition

Describe the measurement environment of reflectivity of the specimen. Also mention the environment—whether it is an anechoic chamber or an indoor environment. Moreover, the set-up conditions (frequency range, number of points, averaging, etc.) of a NWA should also be indicated.
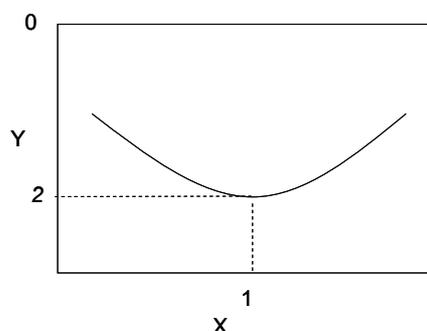
X: Frequency [GHz]
Y: Attenuation [dB]
1: Matching frequency [GHz]
2: Reflectivity [dB]

Figure 12 – Items to be mentioned in a test report

Annex A
(informative)

Reflection and scattering from metal plate – Horn antenna method

A.1   Reflection characteristics

Figure A.1 shows the reflectivity of metal plates versus distance from the antenna for several plate sizes at 40 GHz. Figure A.2 shows the reflectivity when the plates are positioned at 2 m from the transmitting and the receiving antennas. The reflectivity is defined as the received level of EM waves by the receiving antenna transmitted by a transmitting antenna through a direct path of 2 m. The reflectivity of several sizes of metal plates was measured. The curve, which was fitted to the measured data, was calculated using Kirchhoff's and Huygens' diffraction theory. The relation of the reflectivity of the reference metal plate with the distance from the transmit antenna can be well explained by Kirchhoff's and Huygens' diffraction theory. Exact reflectivity data could not be obtained sufficiently when the specimen size is smaller than $\sqrt{(\pi)}\sqrt{(d_1 d_2 \lambda/(2(d_1 + d_2)))}$ even if the sides of the metal plate are longer than the free-space wavelength λ. Therefore, the measurement distance, i.e. the distance between the transmitting and the receiving antennas, should be carefully selected.
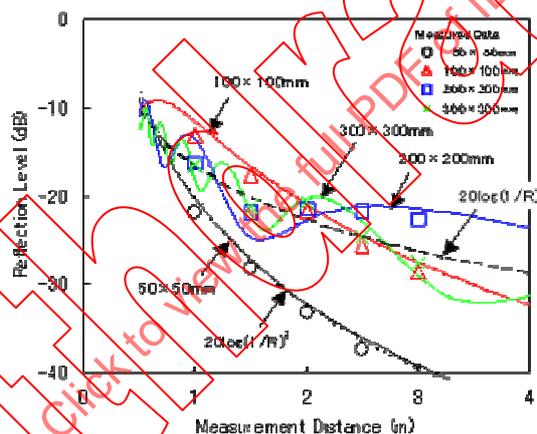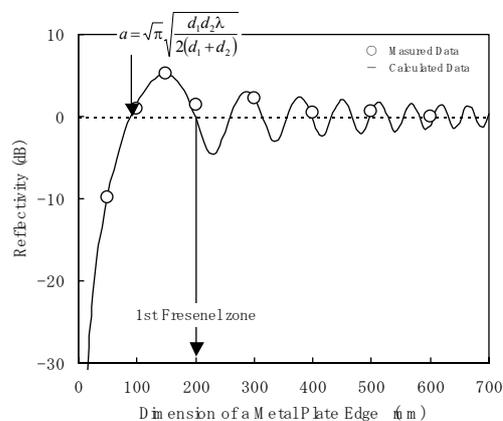

Figure A.1 – Reflection from the reference metal plate versus measurement distance between the antenna and the metal plate


NOTE   The measurement distance is 2 m.

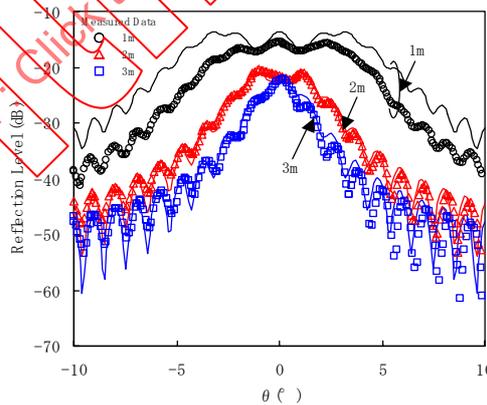**Figure A.2 – Reflectivity of reference metal plate versus size**

A.2   Scattering characteristics $\theta \fallingdotseq 0°$

The reflectivity of the EM wave from the metal plates with various sizes is shown in Figure A.3 when the distance between the antennas and a metal plate is set to be 2 m. The dependence of the measurement distance upon reflectivity of a metal plate with a cross-section of 200 mm × 200 mm is shown in Figure A.4. The incident angle θ of the EM wave, where the maximum reflectivity is obtained, depends upon the reference metal plate size and the distance from the antennas. Nearly flat reflectivity curve at around $\theta \fallingdotseq 0°$ was obtained when the metal plate size is large or the distance between the metal plate and the antennas is short. This flat angular dependence is not desirable because the exact direction of the incident or transmitted EM wave cannot be determined simply from maximizing the measured signal level of the network analyser.
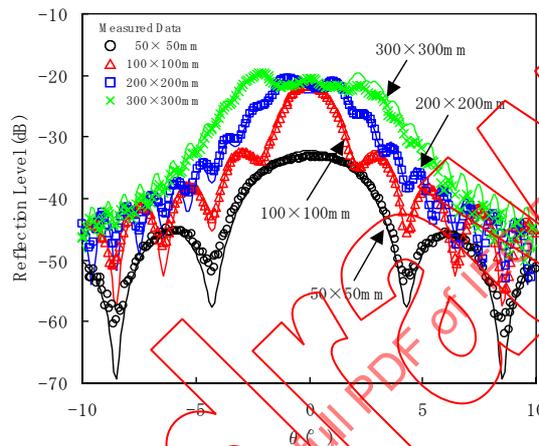
NOTE   The distance between the plate and the antenna is 2 m.

Figure A.3 – Reflectivity of reference metal plate at 40 GHz

NOTE   The distance between the plate and the antenna is 2 m.

Figure A.4 – Reflectivity of reference metal plate with cross-section of 200 mm × 200 mm at 40 GHz.

Annex B
(informative)

Reflectivity of reference specimens using the horn-antenna method

Figure B.1 shows the reflectivity from a quartz-glass plate with a cross-section of 200 mm × 200 mm for the measurement distance of 1 m, 2 m, and 3 m, respectively, in the frequency range from 33 GHz to 95 GHz, when a metal plate behind it is removed. The experimental data are plotted with circles, rectangles, and squares, and a solid curve is calculated theoretically using the complex relative permittivity of the quartz, 3,80-j0, which is determined by the S-parameter method. All these measurement data and the theoretical curve are in good agreement not only at the matching frequency but also at other frequencies. The difference between the measured and calculated results outside the matching frequency is from ±0,5 dB to ±1 dB. Figure B.2 shows the reflectivity from a sapphire single crystal (001) plate with cross-section of 75 mm × 75 mm plate for the measurement distance 1 m, 2 m, and 3 m, respectively, in the frequency range from 50 GHz to 110 GHz, when a metal plate behind it is removed. The solid curve is calculated theoretically using the relative permittivity of the sapphire single crystal, 9,40, which was measured by the S-parameter method in free space. The results measured were in good agreement with the theoretical curve not only at the frequency with maximum absorption obtained but also at the other frequencies. The difference between the measured and calculated results is from ±0,5 dB to ±1 dB.
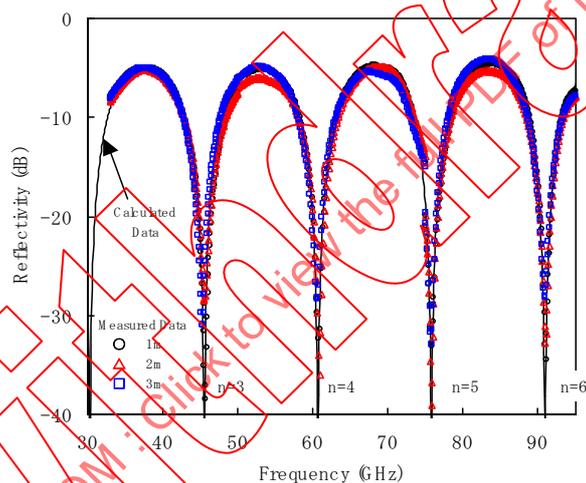
**Figure B.1 – Reflectivity of a 200 mm × 200 mm silica-glass plate
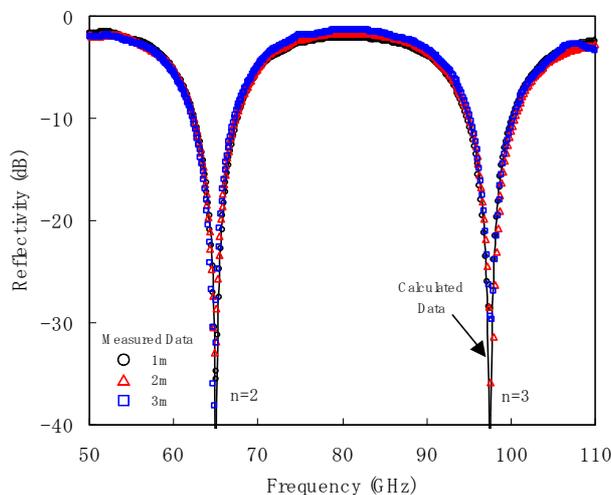in millimetre wave frequency**

**Figure B.2 – Reflectivity of a 75mm × 75 mm sapphire crystal (001) plate
in millimetre wave frequency**

Annex C
(Informative)

Specifications of commercially available antennas

C.1   Horn antennas

Figure C.1 shows the structure and dimensions of commercially available pyramidal horn antennas for several frequency bands.
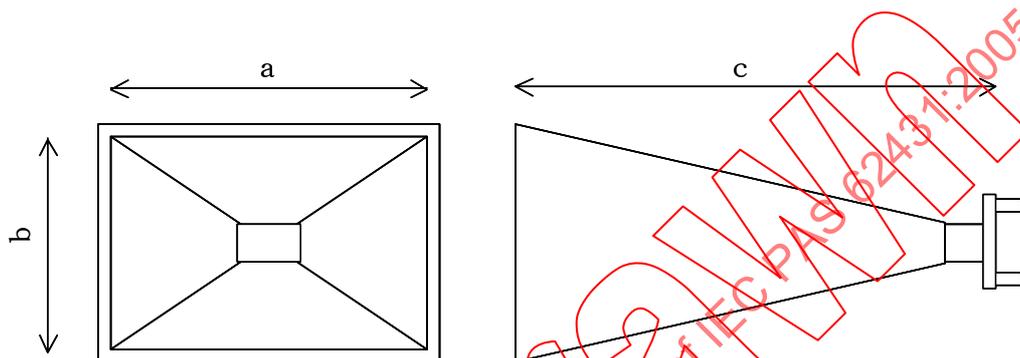
Figure C.1 – Representative specifications of a horn antenna

Tables C.1, C.2, and C.3 show the specifications of antennas with antenna gain of 24 mm, 20 mm, and 25 mm, respectively.

TableC.1 – Antenna gain 24 dB (Example A)

Frequency	Waveguide	a mm	b mm	c mm
33～50 GHz	WR-23	103,378	41,910	55,118
40～60 GHz	WR-24	88,392	35,179	46,253
50～75 GHz	WR-25	70,485	27,686	36,424
60～90 GHz	WR-26	59,639	22,809	30,023
75～110 GHz	WR-27	49,225	18,694	24,613
90～140 GHz	WR-28	39,649	14,961	19,685
110～170 GHz	WR-29	32,131	12,167	16,002
140～220 GHz	WR-30	26,314	9,550	12,548
170～260 GHz	WR-31	21,171	8,052	10,592
220～325 GHz	WR-32	17,958	6,350	8,357

Table C.2 – Antenna gain 20 dB (Example B)

Frequency	Waveguide	a mm	b mm	c mm
33～50,1 GHz	WR-23	68	20	28
39,7～59,7 GHz	WR-24	54,5	18	23
49,9～75,8 GHz	WR-25	45,5	13	19
60,5～92 GHz	WR-26	38,5	11	15
73,8～112 GHz	WR-27	32,5	9	13
92,3～140 GHz	WR-28	27,5	8	10
114～173 GHz	WR-29	24,5	6,5	8,5
145～220 GHz	WR-30	21	5	7
217～325 GHz	WR-32	12	5	6

Table C.3 – Antenna Gain 25 dB (Example C)

Frequency	Waveguide	a mm	b mm	c mm
30～50 GHz	WR-22	129,5	48,5	58,4
40～60 GHz	WR-24	102,9	35,1	46,0
50～75 GHz	WR-25	99,1	36,3	43,7
60～90 GHz	WR-26	81,3	30,8	37,1
75～110 GHz	WR-27	71,1	25,9	30,7
90～140 GHz	WR-28	53,3	21,3	25,4
110～170 GHz	WR-29	43,9	17,8	21,1
140～220 GHz	WR-30	31,8	16,3	13,7

C.2 Antennas consisting of dielectric lens.

Table C.4 shows specifications for several kinds of horn antennas with dielectric lenses.

Table C4 – Some specifications of antennas with dielectric lenses

Number	Diameter mm	Focal Distance mm	Material	Type
A	305	305	Polyethylene	Focused-beam
B	175	175	PTFE	〃
C	175	275	〃	〃
D	120	—	〃	Parallel-beam

Annex D
(informative)

Calibration using network analyzer

D.1 Type of calibration

The types of calibration of NWA are classified as mentioned below.

D.1.1 In case of normal incidence

a) S_{11} response and isolation calibration

b) S_{11} 1-port calibration (short-offset short-load calibration)

c) TRL 2-port calibration (thru (or through)-reflect-line calibration)

D.1.2 In case of oblique incidence

a) S_{21} response calibration

b) S_{21} response and Isolation calibration

D.2 Calibration procedures

The calibration procedures and steps are summarized as follows.

D.2.1 S_{21} response calibration

a) Place a specimen and a reference metal plate on the specimen holder.

b) Obtain the complex reflection coefficient (response calibration).

c) Express the ratio of the reflection of the specimen with that from the reference metal plate which is prepared as a reference standard for total reflection.

D.2.2 S_{11} and S_{21} response and isolation calibration

a) Place a specimen and a reference metal plate on the specimen holder.

b) Measure complex reflection coefficient (short calibration).

c) Move the receive antenna or the specimen holder by the distance $\lambda/4$, where λ is the free-space wavelength at the central frequency in the measurement range. Very accurate positioning is required for the calibration.

d) Measure the complex reflection coefficient (offset short calibration).

D.2.3 S_{11} port calibration (short-offset short-load calibration)

a) Place a specimen and a reference metal plate on the specimen holder.

b) Measure complex reflection coefficient (short calibration).

c) Move the receive antenna or the specimen holder by the distance $\lambda/4$, where λ is the free-space wavelength at the central frequency in the measurement range. Very accurate positioning is required for the calibration.

d) Measure the complex reflection coefficient (offset short calibration).

e) Return the antenna or the specimen holder to its original position and remove the reference metal plate. Remove as many reflection objects as possible behind the pecimen holder.

f) Measure the complex reflection coefficient (load calibration).

g) Calculate the error parameters of 1-port model.

h) Measure the specimen and compensate the error of the measured value.

D.2.4   TRL 2-port calibration

In order to perform TRL calibration, a VNA, a pair of antennas, and an antenna positioner is prepared as shown in Figure D.1.

a) Place the port-1 antenna, specimen holder, and port-2 antenna as shown in Figure D.2. Adjust the two antennas to be in confocal position.

b) Move the port-2 antenna away from the reference position by a quarter wavelength at the central frequency in the measurement range. Take off a specimen or a reference metal plate. Perform line calibration.

c) Place the reference metal plate on the specimen holder. Move the port-2 antenna away from the reference position just by the thickness of metal plate. Perform reflection calibration.

d) Return back the port-2 antenna to the initial reference position and take off the specimen or the reference metal plate. Perform thru (through) calibration.
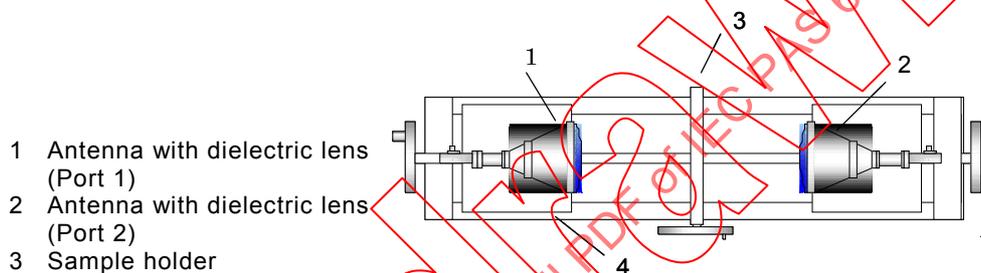

1 Antenna with dielectric lens (Port 1)
2 Antenna with dielectric lens (Port 2)
3 Sample holder

Figure D.1 – Precision antenna positioner configuration

The reflectivity of the specimen is obtained by measuring only S_{11}, where only the port-1 antenna is used. In the actual measurement, it is desirable to isolate the port-2 antenna from the port-1 antenna, by covering the port-2 antenna using EM wave absorber. In the millimetre wave frequency, a quarter wavelength at the central frequency becomes smaller than the thickness of the reference metal plate. It is better to perform reflection measurement first, the Line calibration secondly, and thru calibration at the end.
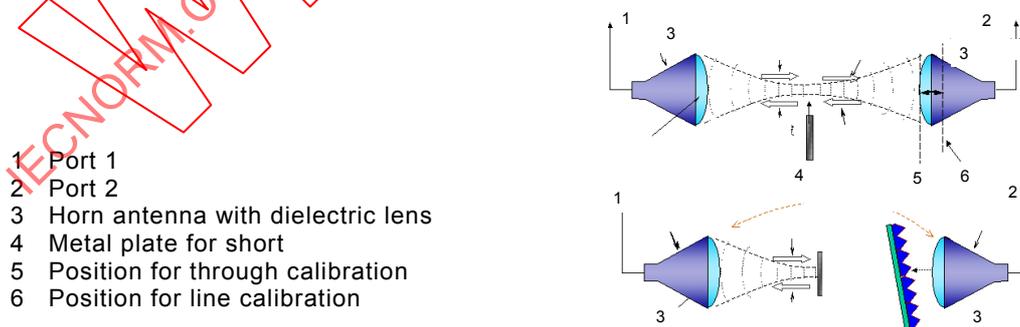

1 Port 1
2 Port 2
3 Horn antenna with dielectric lens
4 Metal plate for short
5 Position for through calibration
6 Position for line calibration

Figure D.2 – Measurement and TRL calibration of transmission line

Annex E
(informative)

Dynamic range and measurement errors

Dynamic range is defined as the difference in dB between the receiving level from the reference metal plate and the level which is measured after removing the metal plate. Figure E.1 shows the dynamic range and measurement error. The receiving level is between –80 dB and –70 dB when the metal plate is removed. In the millimetre-wave range, the dynamic range lies between 40 dB and 50 dB when the size of the reference metal plate is larger than $10\,\lambda \times 10\,\lambda$, and the distance between the metal plate and the antenna is from 1 m to 3 m. The measured reflectivity may range from –20 dB –0,92 dB to –20 dB +0,83 dB when the reflectivity is measured for an EM wave absorber with reflectivity of –20 dB and the dynamic range of the system is 40 dB.
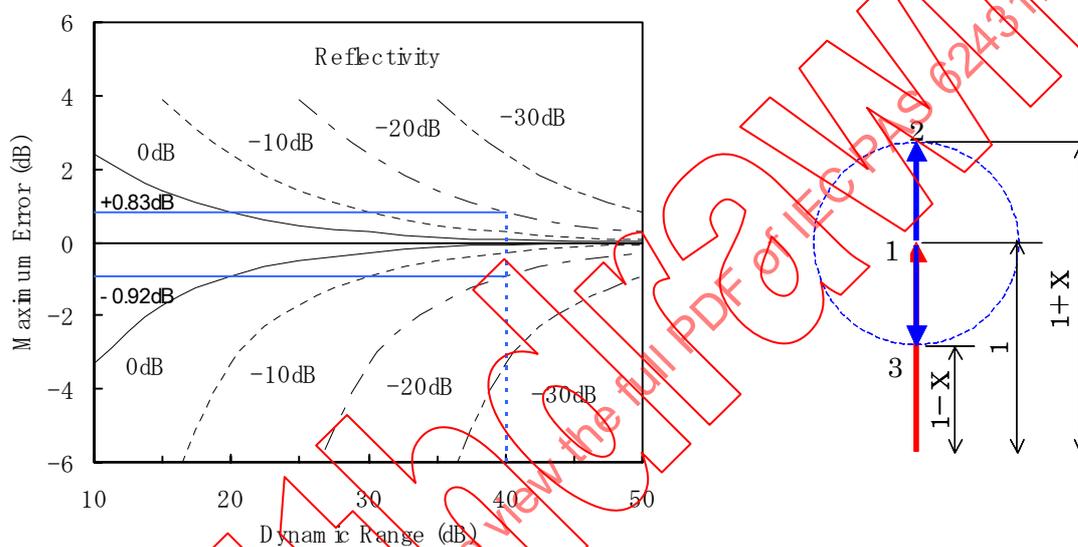
Key

1 True value
2 Maximum measured value with measurement error
3 Minimum measured value with measurement error

Figure E.1 – Dynamic range and measurement error of reflectivity

Annex F
(informative)

Enlargement of dynamic range – Calibration by isolation

In a horn-antenna method, the receiving level consists not only of the reflected signal from a specimen, but also of the undesired signals due to such as the direct wave from a transmit antenna, reflected waves from the specimen holder, and those from the other circumferential objects as shown in Figure F.1.
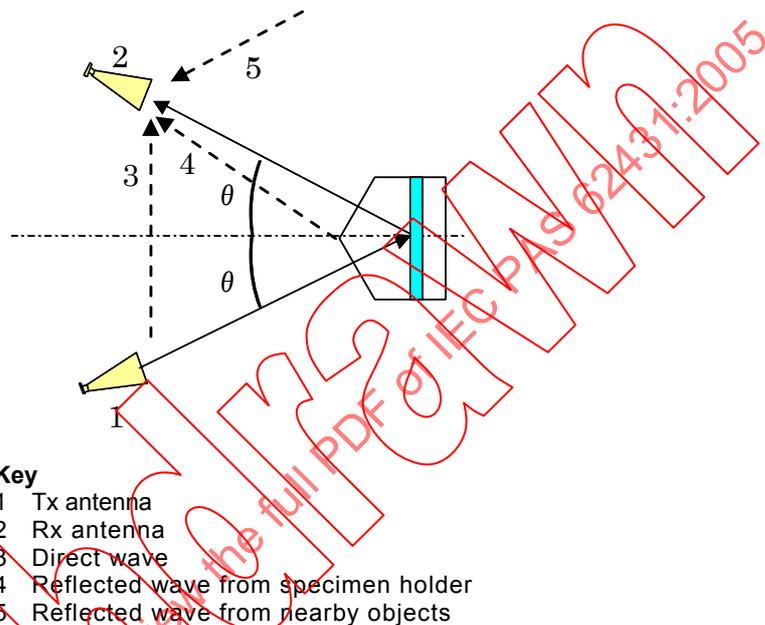

Key
1 Tx antenna
2 Rx antenna
3 Direct wave
4 Reflected wave from specimen holder
5 Reflected wave from nearby objects

Figure F.1 – Reflected waves incorporated in measurement

Only the reflected waves from the specimen can be extracted from the spurious signals mathematically using the time domain technique.

The relation between V_measure, V_absorber, and V_residual is defined as

$$V_\text{measure} = V_\text{absorber} + V_\text{residual}$$

$$V_\text{measure} = V_\text{absorber} - V_\text{residual}$$

$$V_\text{measure} = V_\text{d} + V_\text{h} + V_\text{a}$$

where V_measure is the measured voltage, V_residual, and V_absorber are the voltages in the case of no specimen and of only specimen, respectively, and V_d, V_h, V_a are direct wave voltage, reflected wave voltage from specimen holder, and that from nearby objects, respectively. V_absorber can be obtained simply by subtracting V_residual from V_measure. The reflected signal purely from the specimen is obtained after removing the spurious signals, i.e. after transforming V_measure to a time-domain signal using such as time-domain function of VNA, proper gating for the time-ddmain signal, and transformation into the frequency domain again.

Annex G
(informative)

Example of method of calculation of directional gain of horn antenna

The radiation pattern of EM wave from the aperture of the horn antenna can be understood by the fact that the EM field in the waveguide, which is connected to the horn, spread into the antenna. Then the antenna gain can be determined as follows:

For Example A in Annex C

$$G_{\mathrm{d}} = \frac{4\pi\,cb}{\lambda^2}g = \frac{32 \times 5{,}5118 \times 4{,}191}{0.909091^2 \times \pi} = 284{,}706$$

$$10\log_{10}(284{,}706) = 24{,}5\,[\mathrm{dB}]$$

$$\because g = \frac{8}{\pi^2},\quad c = 5{,}5118\,[\mathrm{cm}],\quad b = 4{,}1910\,[\mathrm{cm}],\quad \mathrm{Freq} = 33\,[\mathrm{GHz}]$$

For example B in Annex C

$$Gd = \frac{4\pi\,cb}{\lambda^2}g = \frac{32 \times 2{,}8 \times 2{,}0}{0{,}909091^2 \times \pi} = 69{,}020$$

$$10\log_{10}(69{,}020) = 18{,}4\,[\mathrm{dB}]$$

$$\because g = \frac{8}{\pi^2},\quad c = 2{,}0\,[\mathrm{cm}],\quad b = 2{,}8\,[\mathrm{cm}],\quad \mathrm{Freq} = 33\,[\mathrm{GHz}]$$

For example C in Annex C

$$Gd = \frac{4\pi\,cb}{\lambda^2}g = \frac{32 \times 5{,}84 \times 4{,}85}{1^2 \times \pi} = 288{,}506$$

$$10\log_{10}(288{,}506) = 24{,}6\,[\mathrm{dB}]$$

$$\because g = \frac{8}{\pi^2},\quad a = 5{,}84\,[\mathrm{cm}],\quad b = 4{,}85\,[\mathrm{cm}],\quad \mathrm{Freq} = 30\,[\mathrm{GHz}]$$

Annex H
(informative)

Relative permittivity of Styrofoam and foamed polyethylene based on foam ratio

Table H.1 shows the relative permittivity of styrofoam and Table H.2 the complex relative permittivity of foamed polyethylene for several values of foaming ratio.

Table H.1 – Relative permittivity and foam ratio of Styrofoam

Foam ratio	ε'
0 （Pure）	2,65
20	1,083
30	1,055
40	1,041
60	1,028

Table H.2 – Relative permittivity and foam ratio of foamed polyethylene

Foam ratio	ε'	ε''
2	1,53	0,218
2	1,70	0,111
5	1,21	0,026
6	1,21	0,076
10	1,04	0,025
10	1,03	0,028
10	1,03	0,022
15	1,02	0,025
30	1,02	0,020

Annex I
(informative)

Calculation of Fraunhofer region – Horn antenna method

For EM waves radiated from the rectangular aperture of horn antenna, the distance, R, which represents the distance separating Fresnel from Fraunhofer region, the boundary between the two may be arbitrarily taken to be at equation (1), where D is the maximum effective dimension of the antenna aperture, and λ is the wavelength. Directional gain, G_d, of the horn antenna is represented by Equation (2). From Equations (1) and (2), the distance R in Equation(3) can be obtained,

$$R \geq 2D^2 / \lambda \qquad (1)$$
$$G_d = 4\pi D^2 / \lambda^2 \qquad (2)$$
$$R \geq G_d \lambda / 2\pi \qquad (3)$$

An example of the calculation using Equation (3) is shown in Figure I.1. At 30 GHz, the lower limit of the measurement frequency range, if antenna gain is set to be 24 dB, then R becomes larger than 40 cm. In this case, it is preferable to fix the distance R greater than 1 m.
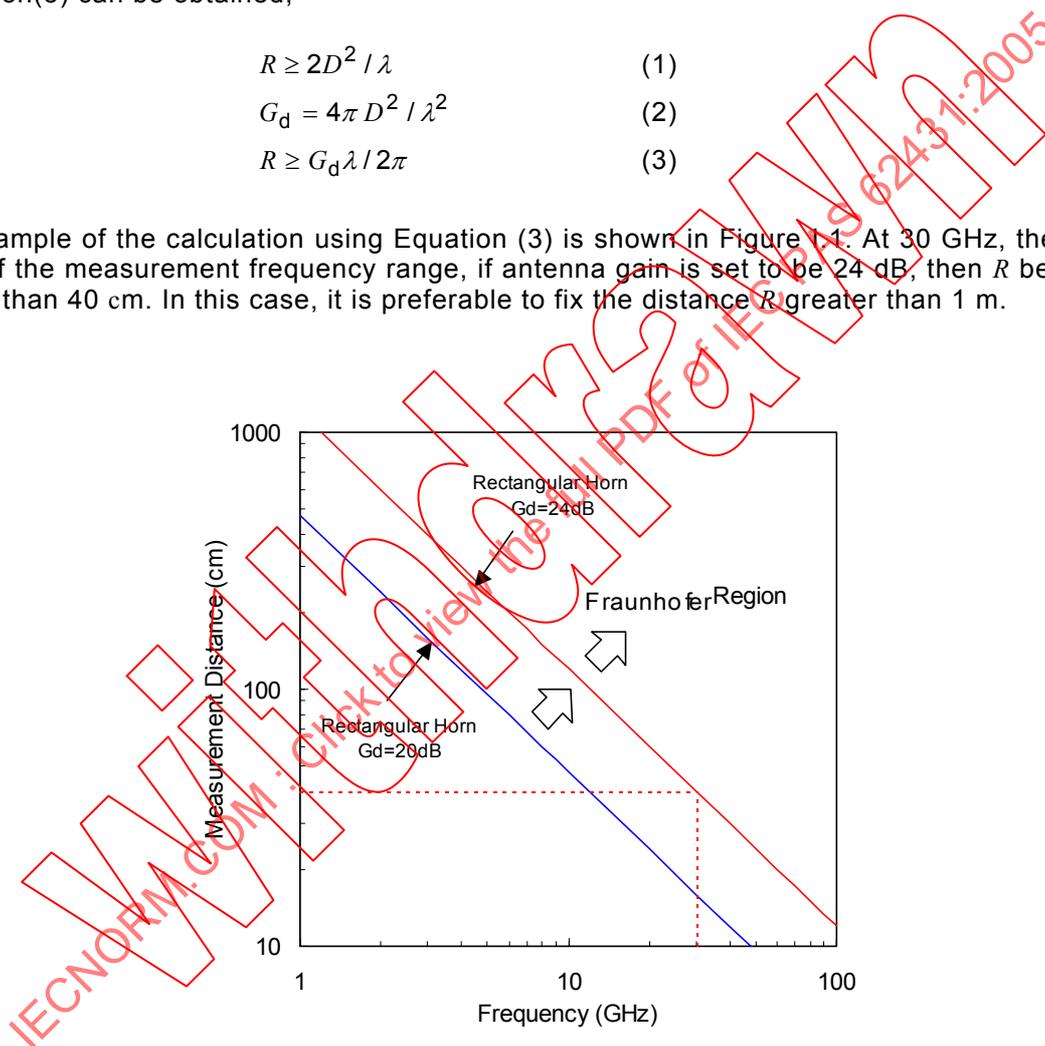

Figure I.1 – Fraunhofer region and antenna gain