

RECOMMENDATION ITU-R SM.1754-0*

Measurement techniques of ultra-wideband transmissions

(2006)

Scope

Taking into account that there are two general measurement approaches (time domain and frequency domain) this Recommendation gives the appropriate techniques to be applied when measuring UWB transmissions.

Keywords

Ultra-wideband (UWB), international transmissions, short-duration pulse

The ITU Radiocommunication Assembly,

considering

- a) that intentional transmissions from devices using ultra-wideband (UWB) technology may extend over a very large frequency range;
- b) that devices using UWB technology are being developed with transmissions that span numerous radiocommunication service allocations;
- c) that UWB technology may be integrated into many wireless applications such as short-range indoor and outdoor communications, radar imaging, medical imaging, asset tracking, surveillance, vehicular radar and intelligent transportation;
- d) that a UWB transmission may be a sequence of short-duration pulses;
- e) that UWB transmissions may appear as noise-like, which may add to the difficulty of their measurement;
- f) that the measurements of UWB transmissions are different from those of conventional radiocommunication systems;
- g) that proper measurements and assessments of power spectral density are key issues to be addressed for any radiation,

noting

- a) that terms and definitions for UWB technology and devices are given in Recommendation ITU-R SM.1755;
- b) that there are two general measurement approaches, time domain and frequency domain, with each having a particular set of advantages and disadvantages,

recommends

- 1 that techniques described in Annex 1 to this Recommendation should be considered when measuring UWB transmissions.

* Radiocommunication Study Group 1 made editorial amendments to this Recommendation in the years 2018, 2019 and 2023 in accordance with Resolution ITU-R 1.

Annex 1

Measurement techniques of ultra-wideband transmissions

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1 Introduction

There are multiple techniques for generating UWB signals with various data modulation and randomization schemes. This Annex describes frequency-domain and time-domain measurement techniques of power spectral density for UWB transmissions and for all types of UWB signals.

In this Annex, the term “emission” is used in a general sense in the context of measurement, and not with the meaning defined in Article 1 of the Radio Regulations.

1.1 Frequency-domain versus time-domain measurement approaches

There are two general approaches for measuring the spectral characteristics associated with UWB emissions, each involving a particular set of advantages and disadvantages.

One approach involves the measurement of a UWB signal’s temporal (time domain) characteristics. Digital signal processing (e.g. Fast Fourier Transform (FFT)) is then applied to transform the measured temporal parameters to their frequency domain representation. Once the UWB signal has been properly represented in the frequency domain, compliance with bandwidth requirements, emission limits, and other applicable regulations can be determined. The temporal measurement approach is often referred to as a “full-bandwidth” measurement, since theoretically it yields a characterization of the UWB signal across the full bandwidth. The second approach involves a direct measurement of the UWB spectral characteristics in the frequency domain. This approach, called “swept spectral measurement”, is often referred to as a “bandwidth-limited” measurement, since the bandwidth capabilities of most existing test equipment are considerably less than the full bandwidth of the UWB signal.

The temporal measurement approach requires a modern digital storage oscilloscope containing a high-speed digitizer with a real-time bandwidth greater than the upper UWB frequency, and FFT processing to calculate the frequency spectrum of the signal. Post-processing software can include many standard radio-frequency (RF) measurements such as root-mean-square (rms) average power.

The swept spectral measurement approach involves the use of a spectrum analyser, vector signal analyser, or similar measurement instrument to detect the UWB signal characteristics in the frequency domain. Conventional test equipment may be insufficiently sensitive to enable detection of UWB signals at very low levels in specific frequency bands.

1.2 Normal test signals for data

This applies to the equipment under test (EUT) with an external modulation connector. The test data that should be used as an input into EUT for measurement of UWB transmissions should be similar to the data transmitted in the actual operation.

In the case of measurements for UWB communication devices, actual data patterns for the fixed part of control signals and frame structures should be used. However, pseudo-random data patterns may be used for the message part of the signal because the message part may be assumed to be a bit stream that is a random sequence.

1.3 General UWB measurement system

The measurement of radiated electromagnetic emissions requires the use of a measurement system that comprises a receiving antenna and a test receiver (e.g. a spectrum analyser). When low power signals are involved, a low-noise amplifier (LNA) with a sufficient bandwidth may be needed between the antenna and the test receiver, improving the effective sensitivity of the measurement system.

1.4 Measurement environment

The low transmission levels from UWB devices make it desirable to perform the measurement in an anechoic or a semi-anechoic chamber. Measurements made in an anechoic chamber should correlate to a measurement made in a semi-anechoic chamber. This is usually accomplished by adjusting for the effect of the ground screen in a semi-anechoic environment or an open area test site (OATS). The measure of a device's effective isotropic radiated power (e.i.r.p.) should be independent of which type of test environment is used.

For frequencies above 1 000 MHz, there is no need for a propagation correction factor since ground reflection is not significant.

1.4.1 Radiated measurement procedure below 1 000 MHz¹

When the reflection from the ground screen cannot be eliminated, the following procedure can be used:

- The UWB emission is examined in small segments, such that reflections, gains and losses do not vary significantly over the segment.
- For table-top sized devices, place the unit on a non-conducting surface at a height of 0.8 m.
- Use conventional device rotation and elevation searches to maximize reception of the emission.
- Take a measurement.
- Factor in gains and losses, as well as considering the ground screen contribution.
- Take sufficient measurements both in azimuth and elevation to ascertain that the maximum emission value has been recorded.
- Repeat at each frequency of interest.

1.4.2 Radiated measurement procedure above 1 000 MHz

Above 1 000 MHz, in a semi-anechoic chamber, the floor between the device and the receiving antenna is treated with RF absorber to remove the ground screen influence. A scan of the search antenna over 1 to 4 m should show a maximum emission near the height at which the device has been positioned, if the floor has been properly treated. Note that for a free-space measurement there is no requirement to maintain a device height of 0.8 m. The device may be positioned at any height that maximally mitigates reflections from the floor. A highly directive receiving antenna assists in reducing the effect of the ground screen reflection. The measurement is recorded without correction for the ground reflection.

¹ One administration recognizes 960 MHz as the measurement detector breakpoint in order to maintain consistency with its emissions mask which defines an emissions limit breakpoint to coincide with the edge of a worldwide aeronautical radionavigation band.

For table-top sized devices, the following procedure can be used:

- Place the unit on a non-conducting surface at an appropriate height.
- The floor between the search antenna and the device should be treated with material to absorb RF energy suitable for the frequency range being measured.
- Vary the height of the search antenna to verify that reflections from the floor have been minimized. It may be necessary to alter the height of the device to achieve the lowest reflections from the floor. The main lobe of the search antenna should not receive a floor reflection. The search antenna height should remain fixed throughout the measurement.
- Take a measurement.
- Factor in the gains and losses. The ground screen contribution has been eliminated by the addition of absorber in the reflected path.
- Take sufficient measurements both in azimuth and elevation to ensure that the maximum value has been recorded.
- Repeat for each frequency of interest.

1.5 Measurement variations for ground penetrating radar devices and wall imaging radar devices

The emissions of concern from ground penetrating radar (GPR) and wall imaging radar (WIR) devices are not those radiated directly from the antenna. Since the direct emissions penetrate a substrate where they are rapidly attenuated, they pose little risk of interference to radiocommunication services. Instead, only the indirect (i.e. scattered and/or leaked) emissions are of concern. In order to measure these emissions, a method should be used to isolate the direct emissions from the indirect emissions. Two methods to accomplish this isolation are described below.

One method is to place the GPR/WIR directly over a bed of sand of at least 50 cm in depth. The area of the sand-bed should be adequate to accommodate the GPR/WIR transducer (antenna). Measurements are then performed at an adequate number of radials and antenna height steps to determine the maximum radiated emission level. If this methodology precludes the use of a ground screen, the measured data should be further adjusted to account for the ground screen contribution.

Another method is to place the GPR device at a height of 80 cm on a non-conducting support with the emitter directed downwards. If the GPR emissions are expected to have components below 500 MHz, a layer of ferrite tile should be placed directly on the floor below the GPR. Pyramidal or wedge-shaped RF absorbers not less than 60 cm in height are placed directly below the GPR. Some sections of absorber may be inverted and placed over other absorbers to form a solid block.

Care should be taken not to place any RF absorber between the device and the search antenna, as this would prevent energy not directed downwards from reflecting from the ground screen. The placement of the absorber should not be disturbed when the device is rotated. This arrangement prevents energy directed downward from consideration in the measurement.

A search in azimuth and elevation for indirect emissions may now be performed.

1.6 Equipment under test orientation

The UWB EUT should be oriented with respect to the measurement system so as to ensure the reception of the maximum radiated signal. Determining this orientation can be made easier by using a non-conductive turntable or other form of positioning system to systematically search for the orientation that provides the maximum response within the measurement system. Regardless of how

the orientation is determined, a sufficient number of radials should be considered to determine the radial at which the maximum response is captured by the measurement system.

1.7 Measurement distance

A separation distance of 3 m is normally used. In some cases, it may not be possible to measure UWB transmissions without amplification and/or moving to one metre or less separation between the receiving antenna and the UWB device, taking care to maintain the far field condition.

1.8 Measurement antennas

Measurement antennas are typically optimized over specific frequency ranges. When measuring the complete spectrum of UWB transmissions, several measurement antennas are required, each optimized over a distinct frequency range.

1.9 Measurement receiver and detectors

The measurement apparatus may be one of the following: a spectrum analyser, an electromagnetic interference (EMI) test receiver, a vector signal analyser, or an oscilloscope. In the following sections, these alternatives are described generically as a measurement receiver.

A UWB transmission can exhibit different characteristics depending upon the reference receiver bandwidth. For example, a pulse-generated UWB transmission can appear as a CW-line spectrum if the receiver bandwidth is greater than the pulse repetition frequency (PRF). If the receiver bandwidth is less than the PRF then the same transmission can appear noise-like. In addition, if baseband modulation techniques are used (e.g. pulse position modulation), the spectral lines may be “smeared” within the reference bandwidth, creating a noise-like response. In the case of a line spectrum, the quasi-peak power or peak power spectral density is of particular interest. A noise-like spectrum is best defined in terms of the average power spectral density. Due to possible receiver bandwidth dependent variations, the measurement of a UWB spectrum requires the use of several signal detectors.

Three signal detectors are recommended for measuring UWB transmissions. For measuring signal characteristics in the radio-frequency spectrum below 1 000 MHz, a quasi-peak detector specified in CISPR-16-1-1 is recommended. An r.m.s. average detector is recommended for measuring the r.m.s. average UWB radiated signal amplitude in the frequency spectrum above 1 000 MHz. A peak detector is recommended for determining the peak power associated with UWB transmissions in the spectrum above 1 000 MHz.

1.10 Measurement system sensitivity

The radiated emissions from a UWB device are often too weak to overcome the noise of a conventional spectrum analyser. For example, noise level of spectrum analyser is equivalent to an e.i.r.p. density of -47 dBm/MHz at one GHz, and -25 dBm/MHz at 26 GHz. Therefore, it becomes necessary to utilize an LNA at the output of the measurement antenna to reduce the effective noise figure of the overall measurement system.

This increased sensitivity of the measurement system can render it particularly vulnerable to ambient environmental signals. If strong ambient signals are present within the measurement environment, an appropriate RF filter should be placed ahead of the LNA to provide the pre-selection necessary to prevent amplifier overload, while permitting signals in the frequency range of interest to propagate through the measurement system. The insertion loss associated with this filter should be minimal and should also be considered when determining the overall sensitivity of the measurement system.

When the analyser sensitivity is insufficient, radiometric measurements described in § 2.6 is one of the effective methods.

1.11 Example test sequence

The spectral characterization of a UWB device should begin with a peak-detected radiated measurement in a one MHz resolution bandwidth (RBW) since the results obtained from this measurement could preclude the need for subsequent quasi-peak or r.m.s. average measurements in certain frequency regions². For example, if the data collected from this peak-power measurement shows that the radiated emissions levels are equal to, or less than, the applicable quasi-peak and r.m.s. average limit, then this data may be adequate. This is based on the fact that both the quasi-peak and the r.m.s. average levels are always less than, or equal to, the peak signal level.

After the –10 dB bandwidth is measured according to § 2.1, the maximum power and associated frequency observed in each frequency span should be compared to the applicable limit. In those cases where a peak emission exceeds the applicable quasi-peak and r.m.s. average limit, further investigation in subsequent quasi-peak and r.m.s. average tests is required. The data collected from this measurement should be adjusted as previously discussed to remove any measurement system influence on the detected peak levels. Once the data is adjusted, a plot of the complete spectral envelope is produced by combining the segmented data sets.

2 Frequency-domain measurements

This approach involves a direct measurement of the UWB spectral characteristics in the frequency domain. This approach is often referred to as a “bandwidth-limited” measurement, since the bandwidth capabilities of most existing test equipment is considerably less than the full bandwidth of the UWB signal.

2.1 Determination of –10 dB bandwidth

The frequency at which the maximum power level measured in a one MHz segment with the peak detector is designated f_M . The peak power measurements should be made using a spectrum analyser with a one MHz resolution bandwidth and a video bandwidth of one MHz or greater. The analyser should be set to peak detection using the maximum-hold trace mode. The one MHz segments, above and below f_M , where the peak power falls 10 dB, are designated f_H and f_L , respectively.

For the lowest frequency bound f_L , the emission is searched from a frequency lower than f_M that has, by inspection, a peak power much lower than 10 dB less than the power at f_M and increased towards f_M until the peak power indicates 10 dB less than the power at f_M . The frequency of that segment is recorded.

This process is repeated for the highest frequency bound f_H , beginning at a frequency higher than f_M that has, by inspection, a peak power much lower than 10 dB below the power at f_M . The frequency of that segment is recorded.

The two recorded frequencies represent the highest f_H and lowest f_L bounds of the UWB transmission, and the –10 dB bandwidth B_{-10} is defined as $f_H - f_L$.

² This measurement of peak power should not be confused with the peak power spectral density measurement as described in § 2.7.

2.2 A preliminary measurement method using a reverberation chamber

A reverberation chamber (see CISPR 16-1-4 and IEC61000-4-21 for its structure and operations) can be used for a preliminary measurement to find f_M and an approximate shape of the spectrum of a UWB transmission. After that, the precise measurement should be performed on an OATS or in a semi- or fully anechoic chamber at the frequency.

The mode-tuned operation may be preferred for the reverberation chamber. A spectrum analyser is set to the frequency sweep mode and the peak detector. The sweep time and the RBW of the analyser are set to the same values as described in § 2.1.

2.3 CISPR quasi-peak measurements

Quasi-peak measurements are made using a quasi-peak detector with RBW that conforms to CISPR 16-1-1 requirements.

2.4 Average power measurement using a spectrum analyser

The average power spectral density (PSD) for a UWB transmissions is the r.m.s. average power, referenced to an ideal Gaussian bandwidth. For measurement speed, accuracy and reproducibility; the PSD should be directly measured using a swept technique with an r.m.s. average detector and an RBW equal to the reference bandwidth. Note that the RBWs of most modern spectrum analysers closely approximate the ideal Gaussian filter characteristics³. The r.m.s. average PSD is often expressed in units of dBm/MHz (i.e. in a one MHz bandwidth).

2.4.1 Average equivalent isotropic radiated power (e.i.r.p.) spectral density

UWB equivalent isotropic radiated power (e.i.r.p.) spectral density is the product of the power spectral density supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna. It is the highest signal strength measured in any direction and at any frequency from the UWB device, as measured in accordance with the procedures specified in § 2.4.2, 2.4.3 and 2.4.4 of this Recommendation.

2.4.2 Average measurements using an r.m.s. detector

This procedure is valid only for spectrum analysers with an r.m.s. average detector. The measurement set-up for the r.m.s. average measurement is the same as previously described with respect to the EUT orientation and the measurement system.

Measurement set-up

- Set the RBW of the spectrum analyser to 1 MHz.
- Set the video bandwidth (VBW) to be at least 1 MHz (a VBW of 3 MHz is desirable)⁴.
- Set the frequency span to examine the spectrum across a convenient frequency segment (e.g. 600 MHz).
- Set the detector to r.m.s.
- Set the sweep time so that there is no more than a one ms integration period in each measurement bin.

³ Typically, r.m.s. results have less than 0.3 dB error from that obtained using an ideal Gaussian filter.

⁴ This requirement is needed as the VBW filtering on most spectrum analysers occurs on a log power scale rather than a linear power scale.

Detailed procedure

Many spectrum analysers utilize a default value of approximately 600 bins per scan. Assuming this value, a sweep time of 600 ms provides the required one ms integration period within each measurement bin. The number of measurement bins can be specified with many modern analysers, providing many other possible combinations of sweep time and number of measurement bins that also result in adherence to the one ms maximum integration time requirement.

The r.m.s. average power spectral density is the highest integrated power detected within a 1 MHz RBW over a one ms integration period.

For each frequency segment, the maximum observed signal amplitude should be adjusted, as discussed in measurement environment (§ 1.4), to remove all measurement system influence and/or ambient signal contributions from the measured value. The resultant value is then compared to the applicable limit.

2.4.3 Average measurement using zero span

When the spectrum analyser is not equipped with an r.m.s. detector, the r.m.s. average value can be obtained by the following zero span measurement.

Measurement set-up

- Set the RBW of the spectrum analyser to 1 MHz.
- Set the VBW to be at least 1 MHz (a VBW of 3 MHz is desirable).
- Set the frequency span to zero span.
- Set the detector to *sample*.
- Set the sweep time to 1 ms.
- Take a single sweep.

Detailed procedure

Measurement should be done for each one MHz frequency segment. The r.m.s. average value per RBW can be obtained by the following equivalent method:

Extract all the data points from the analyser. The r.m.s. average value is determined using the following formula:

$$PSD = 10 \log_{10} \left(\frac{1}{n} \times \sum_{i=1}^n 10^{\frac{P(i)}{10}} \right) \quad (1)$$

where:

PSD: r.m.s. average power spectral density (dBm/MHz)

n: number of data points in the sweep

P(i): power reading on spectrum analyser at data point *i* (dBm) in 1 MHz.

2.4.4 Average measurements using power integration

This procedure is valid only for measuring noise-like emissions with a spectrum analyser using a sample detector. For guidance on the use of spectrum analysers with an r.m.s. detector see § 2.4.2.

Measurement set-up

- Set the RBW of the spectrum analyser to 10 kHz.
- Set the VBW to be three times the resolution bandwidth or 30 kHz.

- Set the frequency span to 1 MHz.
- Set the display to show power (dBm).
- Set the detector to *sample*.
- Set the sweep time as a coupled function.
- Take a single sweep.

Detailed procedure

For each 1 MHz segment, extract the data points from the analyser. After converting the data from logarithmic to linear power terms, find the r.m.s. average value in the 1 MHz segment. The r.m.s. average value is adjusted to account for the noise power bandwidth of the spectrum analyser. This value is plotted on a graph with the centre frequency of the segment along the *X*-axis and the power spectral density value of the segment on the *Y*-axis. The analyser's centre frequency is stepped in 1 MHz increments over the frequency range of interest and the value of each segment can be plotted.

The display points are recovered from the instrument and post-processed with the following formula:

$$P = 10 \log_{10} \left(Sp \times \frac{\frac{1}{n} \times \sum_{i=1}^n 10^{\frac{P(i)}{10}}}{RBW \times k} \right) \quad (2)$$

where:

- P*: r.m.s. average power in the span (dBm)
- Sp*: span (MHz)
- n*: number of data points in the span
- P*(*i*): power reading on spectrum analyser at data point *i* (dBm)
- k*: a factor provided by the equipment manufacturer to correct the RBW to the equivalent noise bandwidth
- PSD*: *P*/*Sp* (dBm/MHz).

2.5 Low-level emission measurement using a low-noise amplifier

A test procedure for detecting UWB transmissions at low levels represents the most significant challenge associated with measuring UWB devices. The difficulties associated with this measurement are the consequence of a low-level emission limit coupled with the requirement to perform the measurement with a 1 MHz RBW. Modifications to the measurement system are needed to optimize the system sensitivity in order to facilitate this measurement.

Octave-bandwidth (e.g. 1-2 GHz) LNAs can be obtained with associated noise figures on the order of 1 dB. By inserting such an amplifier, the effective measurement system sensitivity is improved. It may be necessary to insert a pre-select filter ahead of the LNA for protection; however, the associated insertion loss decreases the overall measurement sensitivity.

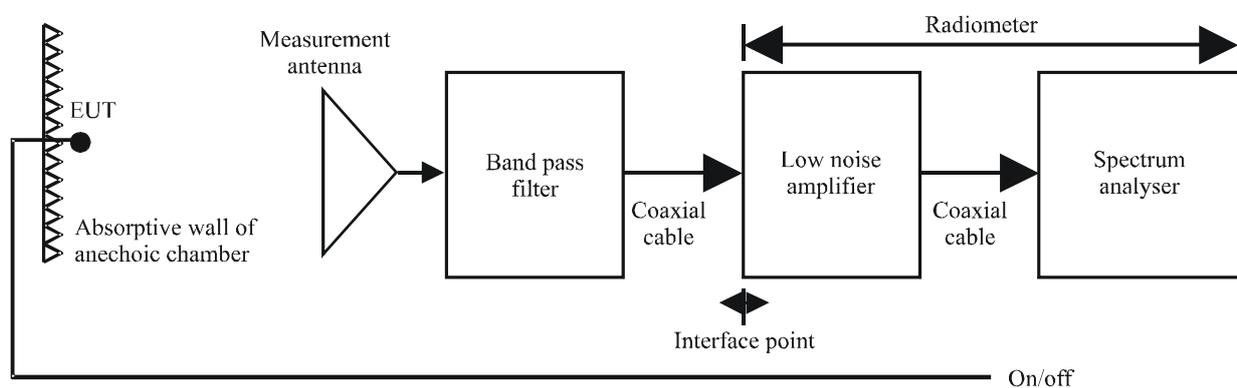
2.6 Radiometric measurements for low level emissions

Radiometric (near noise correction) methods can be used to perform accurate measurements below the noise floor of a spectrum analyser. The radiometric techniques can measure the power when the EUT is turned on, and the power when the EUT is turned off. After subtracting the latter from the former, the e.i.r.p. is obtained.

2.6.1 Configuration of a radiometer

A radiometer consists of an LNA and a spectrum analyser (SA) as shown in Fig. 1. An EUT is set typically 3 m away from a measurement antenna (MA) and remotely operated from a measurement room. A band-pass filter (BPF) is inserted between the MA and the LNA to avoid the saturation of the LNA. The EUT, the MA, the BPF and the LNA are placed in an anechoic chamber, and the SA is placed in the measurement room. The SA and the LNA are to be connected by a low-loss coaxial cable.

FIGURE 1
Example of a radiometer



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2.6.2 Principle and description of the measurements

The radiometer measures the output signal power of the BPF for the measurement duration T_M . The measurement results are converted to power referenced to the interface point. The stochastic distribution of this value is approximately Gaussian. The average of this distribution is R , and its standard deviation σ is given by:

$$\sigma = \frac{0.815 R}{\sqrt{RBW \cdot T_M}} \quad (3)$$

It follows that the margin of measurement error in one second of measurement is $\pm 0.1\%$. Therefore, the power can be measured with high accuracy by using a radiometer as shown in Fig. 1.

With respect to the measurement bandwidth, it is assumed that the signal, which is radiated by the EUT, is uncorrelated to the thermal noise. Also the noise is assumed to be a weakly stationary stochastic process. Hence, the power which radiates from the EUT can be accurately measured by subtracting the power passing through the interface point of the EUT when it is turned on and when it is turned off.

2.6.3 Test procedure

First, the power $P_0(f)$ (dBm) at the interface point without operating the EUT is measured for the measurement duration T_{M0} .

The relation between the e.i.r.p. $P_{e.i.r.p.}(f)$ (dBm) and the power $P_0(f)$ at the interface point is given by:

$$P_{e.i.r.p.}(f) = 11.8 + K_A(f) + 20 \log_{10} \frac{d}{3} + P_0(f) \quad (4)$$

where:

f : centre frequency of the SA sweep

d : distance between the EUT and the aperture of the MA (m)

$K_A(f)$: total value of the antenna factor and the connection loss of the MA.

By using equation (4), $P_0(f)$ is converted to e.i.r.p., where the linear power value is $e.i.r.p._0$.

Next, the power P_1 at the interface point when operating the EUT is measured for the measurement duration T_{M1} and the power P_1 ($e.i.r.p._1$) is measured by the same procedure. The e.i.r.p. of the EUT is calculated as $(e.i.r.p._1 - e.i.r.p._0)$. The standard deviation of relative error in the e.i.r.p. measurement of EUT using this method is calculated as follows:

$$0.815 \cdot RBW^{-0.5} \cdot \frac{P_{e1} \cdot T_{M1}^{-0.5} + P_{e0} \cdot T_{M0}^{-0.5}}{P_{e1} - P_{e0}} \quad (5)$$

2.6.4 Example for the 1-2 GHz band

In this example, a double-ridged waveguide horn antenna (DRGHA) is used as a measurement antenna. An interface point of the radiometer is the LNA input. The effective noise temperatures of the components in the radiometer at the interface points are listed in Table 1. From this Table, the noise temperature, T , of the radiometer is 385 K at the interface point. The noise power, $k \cdot T \cdot RBW$, where k is the Boltzmann's constant, is -112.7 dBm when the RBW is equal to 1 MHz. Therefore, when the EUT is turned off, the PSD $P_0(f)$ at the interface point is -112.7 dBm/MHz. $P_0(f)$ is not affected by changing the distance between the antenna and the EUT.

Using equation (4), the equivalent e.i.r.p. is -74.7 dBm/MHz for $d = 3$ m and $K_A(1 \text{ GHz}) = 26.2$ dB.

TABLE 1

Example of effective noise temperature of the 1-2 GHz radiometer's components (converted to LNA input)

Item	Noise temperature	Comments
DRGHA + BPF	290 K	K_A 26.2 dB
LNA	75 K	1-2 GHz, NF 1 dB, Gain 40 dB
10 m cable	Approximately 0 K	Loss 2.5 dB
SA	20 K	NF 26 dB

Table 2 shows the standard deviation of relative error derived using equation (5), in the case when the e.i.r.p. of the EUT is -70 dBm/MHz and -75 dBm/MHz.

TABLE 2

Standard deviation of relative error in the radiometer measurement

e.i.r.p. of EUT	Measurement duration $T_{M1} = 0.001$ s, $T_{M0} = 0.1$ s
-70 dBm/MHz	0.15 dB
-75 dBm/MHz	0.24 dB

2.6.5 Example for the 22-24 GHz band

In this example, a standard gain horn antenna (SGHA) of aperture $0.028 \text{ m} \times 0.056 \text{ m}$ is used as an MA. To minimize the coupling loss, the SGHA, the BPF, and the LNA should be connected directly.

An interface point of the radiometer is the LNA input. The effective noise temperatures of the components in the radiometer at the interface points are listed in Table 3. From these values, the noise temperature, T_{sys} , of the radiometer is calculated to be 814 K at the interface point. The noise power, $k \cdot T \cdot \text{RBW}$, is -109.5 dBm when the RBW is equal to 1 MHz. Therefore, when the EUT is turned off, the PSD $P_0(f)$ at the interface point is -109.5 dBm. $P_0(f)$ is not affected by changing the distance between the SGHA and the EUT. $K_A(f)$ is equal to the total value of the SGHA's antenna factor and BPF loss. The noise floor of the radiometer converted to e.i.r.p. using equation (4) is -58.9 dBm/MHz for $d = 3$ m and $K_A(24 \text{ GHz}) = 38.8$ dB.

TABLE 3

Example of effective noise temperature of the 22-24 GHz radiometer's components (converted to LNA input)

Item	Noise temperature	Comments
SGHA + BPF	290 K	K_A 38.8 dB
LNA	159 K	18-26 GHz, NF 1.9 dB, Gain 35 dB
SA	365 K	NF 36 dB
T_{sys}	814 K	System temperature of the radiometer

Table 4 shows the standard deviation of relative error measured at 3 m distance from the EUT, when the e.i.r.p. of the EUT is -60 dBm/MHz and -65 dBm/MHz. Table 5 shows the standard deviations of relative error measured at a distance of 1 m from the EUT as an option, when the e.i.r.p. of the EUT is -70 dBm/MHz and -75 dBm/MHz.

TABLE 4

Standard deviation of relative error measured at 3 m separation using the radiometer of the 22-24 GHz band

e.i.r.p. of EUT ($d = 3$ m)	Measurement duration $T_{M1} = 0.001$ s, $T_{M0} = 0.1$ s
-60 dBm/MHz	0.26 dB
-65 dBm/MHz	0.57 dB

TABLE 5

**Standard deviation of relative error measured at one m distance from the EUT
using the radiometer of the 22-24 GHz band**

e.i.r.p. of EUT ($d = 1$ m)	Measurement duration $T_{M1} = 0.001$ s, $T_{M0} = 0.1$ s
-70 dBm/MHz	0.28 dB
-75 dBm/MHz	0.63 dB

2.7 Peak power spectral density measurement

The peak PSD of a UWB transmissions is the peak power in a Gaussian filter with a bandwidth of 50 MHz. The measurement is made using a peak detector and max hold.

On most modern spectrum analysers, resolution bandwidths of 3 MHz or less closely approximate the ideal Gaussian filter characteristics (measurements have less than 1 dB difference from that obtained using an ideal Gaussian filter). If a spectrum analyser is used to make the peak measurement, it is generally not feasible to use an RBW greater than 3 MHz due to video bandwidth and phase linearity limitations.

2.7.1 Peak power spectral density measurement using a spectrum analyser

Scaling the peak limit for other resolution bandwidths

The peak PSD limit can be scaled to a different bandwidth using equation (6). However, it should be noted that there may be a penalty associated with this method of adjusting the peak PSD limit expressed in $BW = 50$ MHz to a narrower bandwidth, as this equation gives a conservative scaling of the peak PSD limit (for an impulsive signal).

$$Limit_{RBW} = Limit_{BW} + 20 \log_{10}(RBW/BW) \quad (6)$$

A UWB signal, when altered by the receiver passband transfer function, can appear impulsive, noise-like, sinusoidal, or a combination of the above, depending upon the time characteristics and the bandwidth of the receiver.

The actual relationship is in the range between $10 \log_{10}$ and $20 \log_{10}$, which is explained as follows:

Because the phase of the oscillation is dependent upon the time origin of a pulse, the phase for adjacent dithered pulses can be asynchronous. This can result in constructive and destructive summation of signal components for overlapping pulses, giving the appearance of Gaussian noise. This method is accurate when the UWB signal appears impulsive as it passes through the receiver. This occurs if the RBW is greater than the PRF of the EUT, the pulses do not overlap, and therefore, the signal appears impulsive in nature after passing through the receiver.

When the measurement is performed in a RBW that is less than the PRF of the EUT, overlapping pulses will be present and the signal will appear continuous (random distribution of amplitude vs. time) rather than impulsive as it passes through the receiver bandwidth. The actual peak power in the reference bandwidth will be a function of subtle inter-pulse timing factors as described above. In these cases, the $20 \log_{10}$ relationship between the two bandwidths represents an overestimate. The time characteristics, which may be a simple PRF, are identifiable from auto-correlation analysis of the signal. The strength and time interval for any repetitive components in the UWB signal appear as peaks in the autocorrelation plot.

For a UWB signal generated using orthogonal frequency division multiplexing (OFDM), when the RBW is less than the full signal bandwidth, the data (modulation) content and transmission control (RF switching) determine the characteristics of the filtered signal. The precise alignment of the signal's multiple component phases determines the instantaneous response. In some cases, the modulation may be specifically designed to create the appearance of Gaussian noise. The $20 \log_{10}$ scaling factor between bandwidths is accurate if the signal appears "impulsive". This means there is a repetitive time element with a repetition period of greater than $1/\text{RBW}$ (RBW is greater than the PRF).

Measurement set-up example using a 3 MHz RBW

- Set the RBW of the spectrum analyser to 3 MHz.
- Set the VBW to be at least equal to the RBW (a VBW of at least 3 times RBW or the video filter out-of-circuit is recommended).
- Set the frequency span to examine the spectrum across a convenient frequency segment (typically several GHz).
- Set the detector to peak.
- Turn on the max hold function.
- Set the sweep time to auto-coupled.

Detailed procedure example using a 3 MHz RBW

Multiple sweeps are used (with max hold enabled) until the observed amplitude stabilizes. The measurement is centred on f_M , the frequency of maximum UWB transmission. When the measurement is made in an RBW of 3 MHz instead of 50 MHz, the limit is scaled using the equation below:

$$Limit_{3\text{MHz}} = Limit_{50\text{MHz}} + 20 \log_{10}(3 \text{ MHz}/50 \text{ MHz}) = Limit_{50\text{MHz}} - 24.4 \text{ dB} \quad (7)$$

2.7.2 Peak power spectral density measurement using a spectrum analyser (alternative method)

When equation (6) is known to overestimate the peak power, an alternative scaling law can be considered. When the signal appears to be noise-like, the following test is applied:

- Set the RBW of the spectrum analyser to 3 MHz.
- Set the VBW to be at least equal to the RBW (a VBW of at least 3 times RBW or the video filter out-of-circuit is recommended).
- Set the centre frequency to f_M and frequency span to zero.
- Set the detector to sample.
- Set the display to complementary cumulative distribution function (CCDF) mode.

If the obtained CCDF falls within ± 2 dB error from the CCDF of a Rayleigh distribution in the range from 1% to 99%, the signal is considered to be noise-like, and the same measurement technique as described in § 2.7.1 is applied, but the alternative scaling law equation (8) is applicable:

$$Limit_{\text{RBW}} = Limit_{\text{BW}} + 10 \log_{10}(\text{RBW}/\text{BW}) \quad (8)$$

2.8 Spectral line measurements

The measurement set-up for determining the maximum r.m.s. average power contained in any spectral lines present is similar to that used in the previous r.m.s. average power test. The r.m.s. average detector is selected and the sweep time and number of measurement bins are set to provide

the 1 ms integration time. In this test, the RBW can be reduced to a minimum of 1 kHz (30 kHz is recommended) in order to enhance the resolution of the individual spectral lines. A $VBW/RBW \geq 3$ should be maintained when possible.

2.9 Conducted measurements

The e.i.r.p. value can be obtained by the following equation:

$$e.i.r.p.(f) = P(f) + G(f) \quad (9)$$

where:

- $e.i.r.p.(f)$: e.i.r.p. (dBm) at the frequency f
- $P(f)$: power (dBm) measured at frequency f and at the antenna terminal, terminated by a 50 Ω resistor
- $G(f)$: is the antenna gain (dBi) measured at the frequency f in a given direction.

3 Time-domain measurements

3.1 Time-domain measurement of UWB signals

The UWB spectrum can be obtained by applying FFT processing to the time-domain sampling data that is obtained by a wideband digital oscilloscope. The spectrum can be computed by different detectors and for different bandwidths, including the r.m.s. average power in a 1 MHz Gaussian bandwidth and the peak power in a 50 MHz Gaussian bandwidth.

Oscilloscopes are available that can measure UWB signals in real time. A typical oscilloscope specification is:

- Maximum frequency: 12 GHz (–3 dB analogue BW).
- Sampling frequency: 40 GS/s.
- Maximum and minimum vertical ranges: 1 V/div and 1 mV/div.
- Noise at 800 mV full scale: 2.7 mVrms.

In order to determine the performance of the time-domain measurement, it is first necessary to determine the peak voltage of the time-domain waveform. Care should be taken that the waveform is completely displayed.

A sampling oscilloscope may provide improved performance when measuring a periodic waveform. A typical specification for a modern sampling oscilloscope is:

- Maximum frequency: 50 GHz.
- Maximum input level: 1 Vp-p (peak-to-peak).
- Noise level: 1.8 mV rms.

3.2 Error estimation of jitter using sampling oscilloscope

If the EUT has a trigger output terminal, a periodic waveform output from the EUT can be observed using a sampling oscilloscope. When the periodic waveform has low signal to noise ratio (S/N), it is possible to improve the S/N by using the averaging function installed in the sampling oscilloscope. However, because of the trigger signal jitter, the observed waveform is low-pass filtered.

The peak value in the observed waveform is attenuated because it is a convolution of the probability density function of the jitter and the input waveform from the EUT. For a trigger signal that has Gaussian jitter of σ second r.m.s., the observed waveform is low-pass filtered by a Gaussian LPF with a 3 dB cut-off frequency of $0.13/\sigma$ Hz.

3.3 Post-processing of time-domain data

Post-processing of the time-domain data is necessary. Post-processing software can include many standard RF measurements.

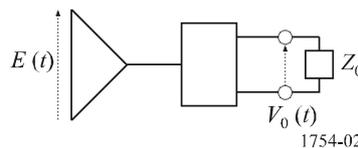
3.3.1 Complex antenna factor

When an antenna receives a plane wave of frequency, f a complex antenna factor (CAF), $F_c(f)$, is defined as:

$$F_c(f) = \frac{E(f)}{V_0(f)} \tag{10}$$

where $E(f)$ is the complex electric field strength at a specific point of an antenna element and $V_0(f)$ is the complex matched voltage of the antenna terminal with the matched impedance Z_0 , as shown in Fig. 2. The CAF contains the phase information in order to perform the reconstruction of the electric-field waveform. The CAF should be measured for each antenna.

FIGURE 2
Definition of CAF



3.3.2 Reconstruction of electric field from measured time-domain data

Figure 3 shows an example of an apparatus for measuring the electric-field waveform radiated by the EUT. The waveform observed with an oscilloscope, $v_m(t)$, is obtained as the convolution of the impulse response of the measuring apparatus from the antenna output to the output of the oscilloscope, with the antenna output signal, $v_a(t)$. The e.i.r.p. can be converted from the electric-field intensity at an arbitrary distance between the transmitting and the receiving antennas for the far field.

FIGURE 3
Waveform measuring apparatus

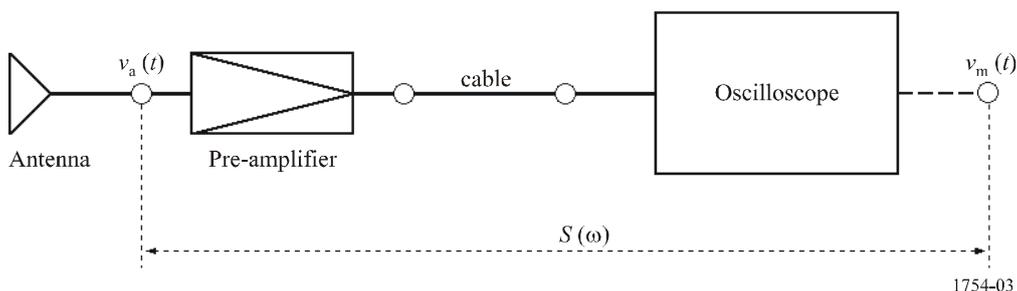
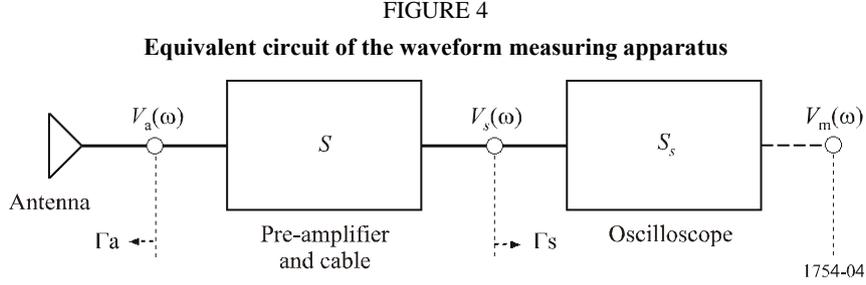


Figure 4 shows the equivalent circuit of the waveform measuring apparatus shown in Fig. 3. S denotes the S -matrix of the pre-amplifier and cables, and S_s is the S -matrix of the oscilloscope. Γ_a and Γ_s are the reflection coefficients of a receiving antenna and of the input port of the oscilloscope, respectively. S_{12} of the pre-amplifier (the S -parameter from the output port to the input port of the pre-amplifier) is assumed to be zero. The S -parameters of the oscilloscope S_{22s} and S_{12s} can also be assumed as zero, because V_m is not a real signal but numeric data digitized by the oscilloscope.



The S -parameter analysis of the equivalent circuit under the above-mentioned conditions, the electric field in the frequency domain, $E(f)$, can be expressed as:

$$\begin{aligned} E(f) &= \frac{(1 - S_{11}\Gamma_a)(1 - S_{22}S_{11s})}{S_{21}S_{21s}} F_c(f) \mathfrak{F}[v_m(t)] \\ &= \frac{F_c(f)}{K} \mathfrak{F}[v_m(t)] \end{aligned} \quad (11)$$

where $\mathfrak{F}[\]$ denotes the Fourier transform.

An electric-field waveform is reconstructed by taking the inverse Fourier transform ($\mathfrak{F}^{-1}[\]$) of equation (11) to obtain:

$$E(t) = \mathfrak{F}^{-1} \left[\frac{F_c(f)}{K} \mathfrak{F}[v_m(t)] \right] \quad (12)$$

3.3.3 Spectrum analysis in an arbitrary resolution bandwidth

The equivalent peak power can be calculated using the following method for an arbitrary RBW. The waveform at the output of the BPF is obtained as:

$$E_f(t) = \mathfrak{F}^{-1} \left[\frac{F_c(f)G(f)}{K} \mathfrak{F}[v_m(t)] \right] \quad (13)$$

where $G(f)$ is a function of the Gaussian filter (for example a 3 dB bandwidth of 50 MHz).

The value of the e.i.r.p., $P_{EIRP}(t)$, is expressed in terms of the electric field as:

$$P_{EIRP}(t) = \frac{(E_f(t)r)^2}{30} \quad (14)$$

The peak power spectral density, $P_{p(50\text{MHz})}$, is obtained from the peak of $P_{EIRP}(t)$.

3.3.4 An example of a peak power measurement in the time domain

This paragraph describes an example of an electric field measurement. The equipment consisted of a UWB impulse generator, antennas, cables and a digital sampling oscilloscope with the 20 GHz

sampling-head, as shown in Fig. 5. The output waveform of the UWB impulse generator is measured with the oscilloscope as shown in Fig. 6.

FIGURE 5
Set-up for measurement

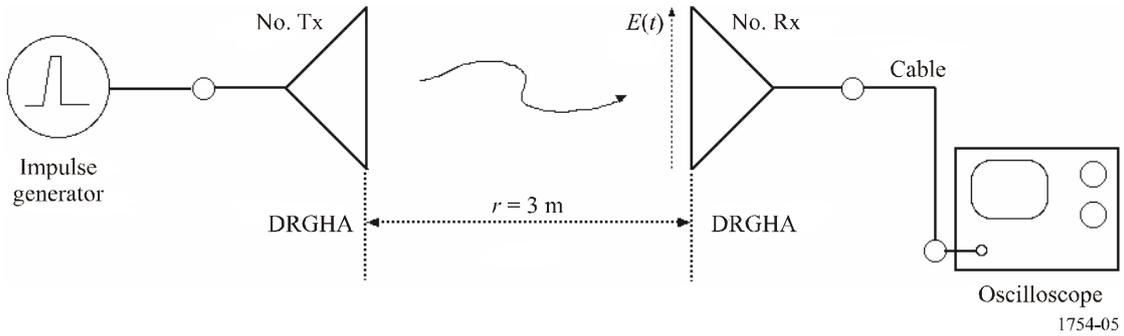
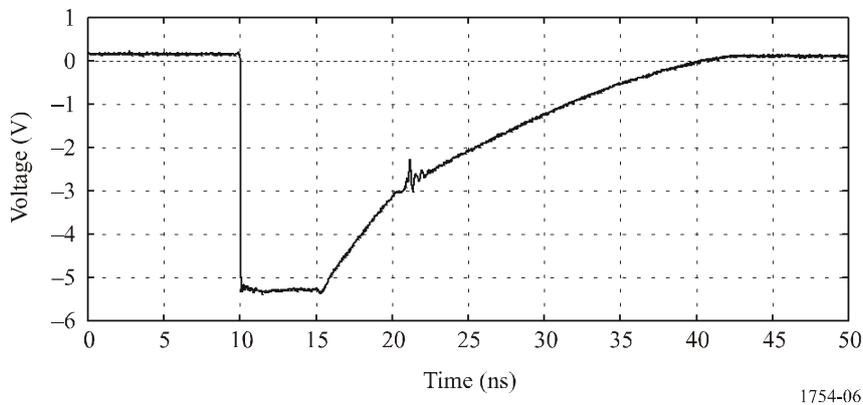


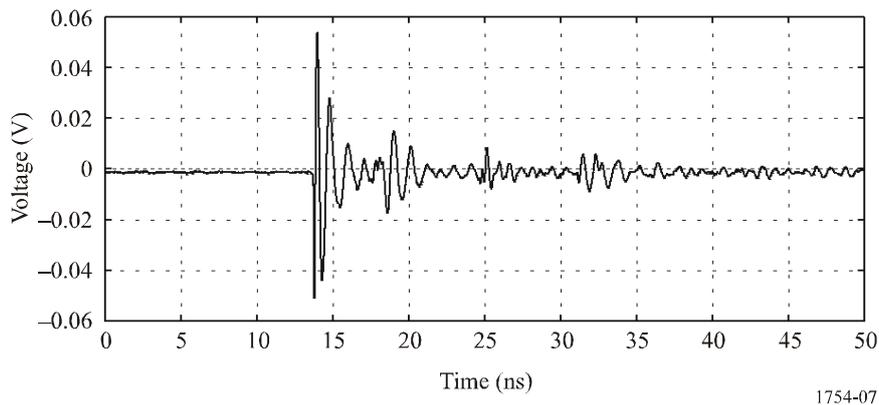
FIGURE 6
The output waveform of the impulse generator



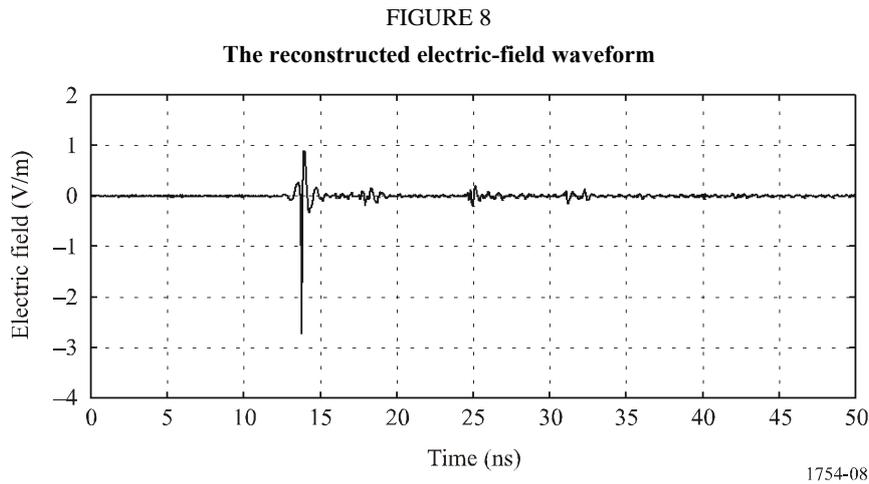
The distance between the transmitting and the receiving antennas is 3 m and the antenna height was 1.5 m. The PRF of the generator was 500 kHz. The measurement was performed in a $6 \times 5 \times 2.5$ m office.

The output waveform displayed by the oscilloscope is shown in Fig. 7.

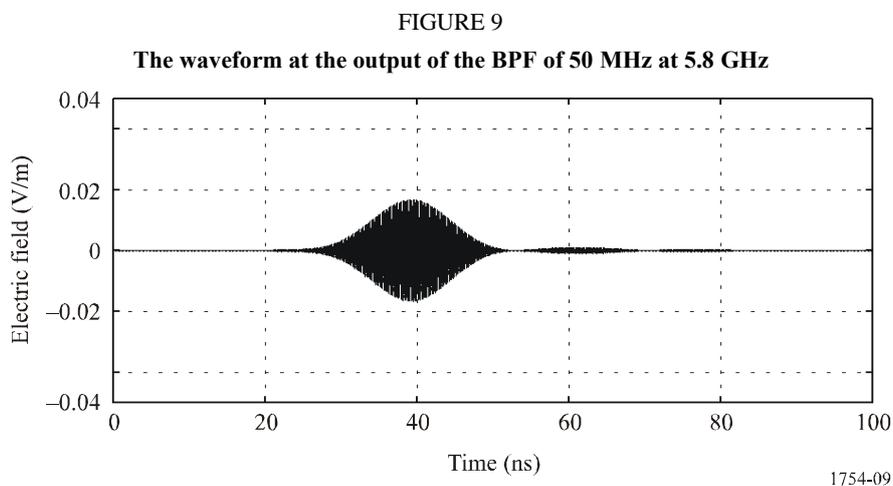
FIGURE 7
The waveform displayed by the oscilloscope



The electric-field waveform at the receiving point was then reconstructed using equation (12) from the output from the receiving antenna as shown in Fig. 8.



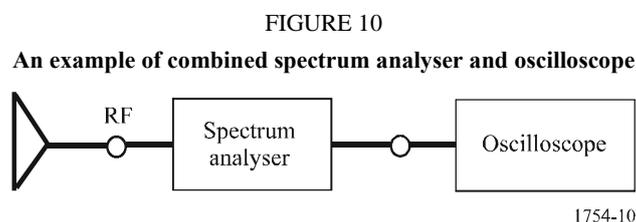
As an example with the centre frequency set to 5.8 GHz, the waveform at the output of the BPF of 50 MHz bandwidth obtained from equation (13) is shown in Fig. 9.



In Fig. 9, the peak value is found to be 0.01683 V/m. The peak power calculated from equation (14) is $85.0 \mu\text{W}$ (-10.7 dBm).

3.4 Combined spectrum analyser and oscilloscope time-domain measurements

Figure 10 shows an apparatus for peak power measurement. The apparatus combines a spectrum analyser with an oscilloscope. In this system, the spectrum analyser is used as the frequency down-converter together with the IF filter. The spectrum analyser IF output is an input to the oscilloscope.



The digitized output of the oscilloscope is post-processed by software in the similar manner to that described in § 3.3:

- Gaussian filtering.
- Power calculation for each sample.
- Search for the maximum power.
- Change the centre frequency of the spectrum analyser, and then repeat.

Using this configuration, the bandwidth of the apparatus is wide, and the Gaussian filtering is performed with digital signal processing. In this system, the RBW filter is implemented in the digital domain without any phase distortion that would result from an analogue RBW filter.

The spectrum analyser and oscilloscope should meet the following technical requirements:

- the passband amplitude of the spectrum analyser should be flat;
- the passband phase should be linear;
- the conversion gain from RF input to IF output should be calibrated;
- the input bandwidth of the oscilloscope should be at least 500 MHz;
- calibration is necessary for each measurement frequency point.

Attachment 1

Abbreviations used in the Recommendation

ADC	Analogue-to-digital converter
BPF	Band-pass filter
BW	Bandwidth
CAF	Complex antenna factor
CCDF	Complementary cumulative distribution function
CISPR	Comité International Spécial des Perturbations Radioélectriques
DRGHA	Double ridged waveguide horn antenna
e.i.r.p.	Effective isotropic radiated power
EMI	Electromagnetic interference
EUT	Equipment under test
FFT	Fast Fourier transform
IEC	International Electrotechnical Commission
IF	Intermediate frequency
GPR	Ground penetrating radar
LNA	Low-noise amplifier
LPF	Low pass filter
MA	Measurement antenna
NF	Noise figure

OFDM	Orthogonal frequency division multiplexing
OATS	Open area test site
PRF	Pulse repetition frequency
PSD	Power spectral density
RBW	Resolution bandwidth
RF	Radio frequency
r.m.s.	Root-mean-square
SA	Spectrum analyser
SGHA	Standard gain horn antenna
<i>S/N</i>	Signal-to-noise ratio
UWB	Ultra-wideband
VBW	Video bandwidth
WIR	Wall imaging radar
