RECOMMENDATION ITU-R M.1177-2*

TECHNIQUES FOR MEASUREMENT OF UNWANTED EMISSIONS OF RADAR SYSTEMS

(Question ITU-R 202/8)

(1995-1997-2000)

The ITU Radiocommunication Assembly,

considering

a) that both fixed and mobile radar stations in the radiodetermination service are widely implemented in bands adjacent to and in harmonic relationship with other services;

b) that stations in other services are vulnerable to interference from radar stations with unwanted emissions with high peak power levels;

c) that many services have adopted or are planning to adopt digital modulation systems which are more susceptible to interference from radar unwanted emissions;

d) that under the conditions stated in a) through c), interference to stations in other services may be caused by a radar station with unwanted emissions with high peak power levels;

e) that RR Appendix S3 specifies the maximum values of spurious emissions from radio transmitters;

f) that techniques to measure radar unwanted emissions to ensure compatibility with other services requires the capability to measure levels of the order of 130 dB below the radar fundamental emission;

g) that it is desirable to have the capability to measure unwanted emissions up to 18 GHz,

recommends

1 that measurement techniques as described in Annex 1 be used to provide guidance in quantifying radiated unwanted emission levels from radar stations, over the required frequency ranges set out in RR Appendix S3 (Section II);

2 that results of such usage of this Recommendation be reported to ITU-R, in order to determine any limitations in the techniques, e.g. tolerances of measurements and repeatability over the required frequency ranges, so that confidence can be established in the measurement methods.

ANNEX 1

1 Introduction

Two techniques known as the direct and indirect methods are recommended.

The direct measurement method has the ability to accurately measure unwanted emissions from radars that are designed in such a way as to preclude measurements at intermediate points in the radar systems. Such radars include, for example, those which use distributed-transmitter arrays that are built into (or that actually comprise) the antenna structure.

* This Recommendation should be brought to the attention of the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Maritime Radio Committee (CIRM), the World Meteorological Organization (WMO) and Radiocommunication Study Groups 1, 4 and 9.

The indirect method is where the components of the radar system are measured separately and then the results combined. The recommended split of the radar is to separate the system after the "rotating joint" (Ro-Jo) and thus to measure the transmitter output spectrum at the output port of the Ro-Jo and to combine it with the measured antenna gain characteristics.

Experience with these techniques has yielded repeatability of ±2 dB at any given frequency and under the condition of agreed fixed measurement parameters when the spectrum of any particular radar unit is remeasured.

2 Measurement system bandwidth and detector parameters

IF bandwidth ≤ $(1/T)$ for fixed-frequency, non-pulse-coded radars, where T: pulse length. (E.g. if radar pulse length is 1 µs, then the measurement IF bandwidth should be ≤ 1/(1 µs) = 1 MHz.)

≤ $(1/t)$ for fixed-frequency, phase-coded pulsed radars, where t: phase-chip length. (E.g. if radar transmits 26-µs pulses, each pulse consisting of 13 phase coded chips that are 2 µs in length, then the measurement IF bandwidth should be ≤ 1/(2 µs) = 500 kHz.)

≤ $(B/T)^{1/2}$, for swept-frequency (FM, or chirp) radars, where B: range of frequency sweep during each pulse and T: pulse length. (E.g. if radar sweeps (chirps) across frequency range of 1 250-1 280 MHz (= 30 MHz of spectrum) during each pulse, and if the pulse length is 10 µs, then the measurement IF bandwidth should be: $\leq ((30\text{ MHz})/(10\ \mu\text{s}))^{1/2} = \sqrt{3} \approx 1.73$ MHz.)

Video bandwidth ≥ measurement system IF bandwidth

Detector: positive peak

3 Direct method

The direct method described below can be used to measure unwanted emissions (out-of-band and spurious) from radar systems, and has been used to measure the emission characteristics of radar systems operating at frequencies up to 24 GHz and transmitter output powers of several megawatts.

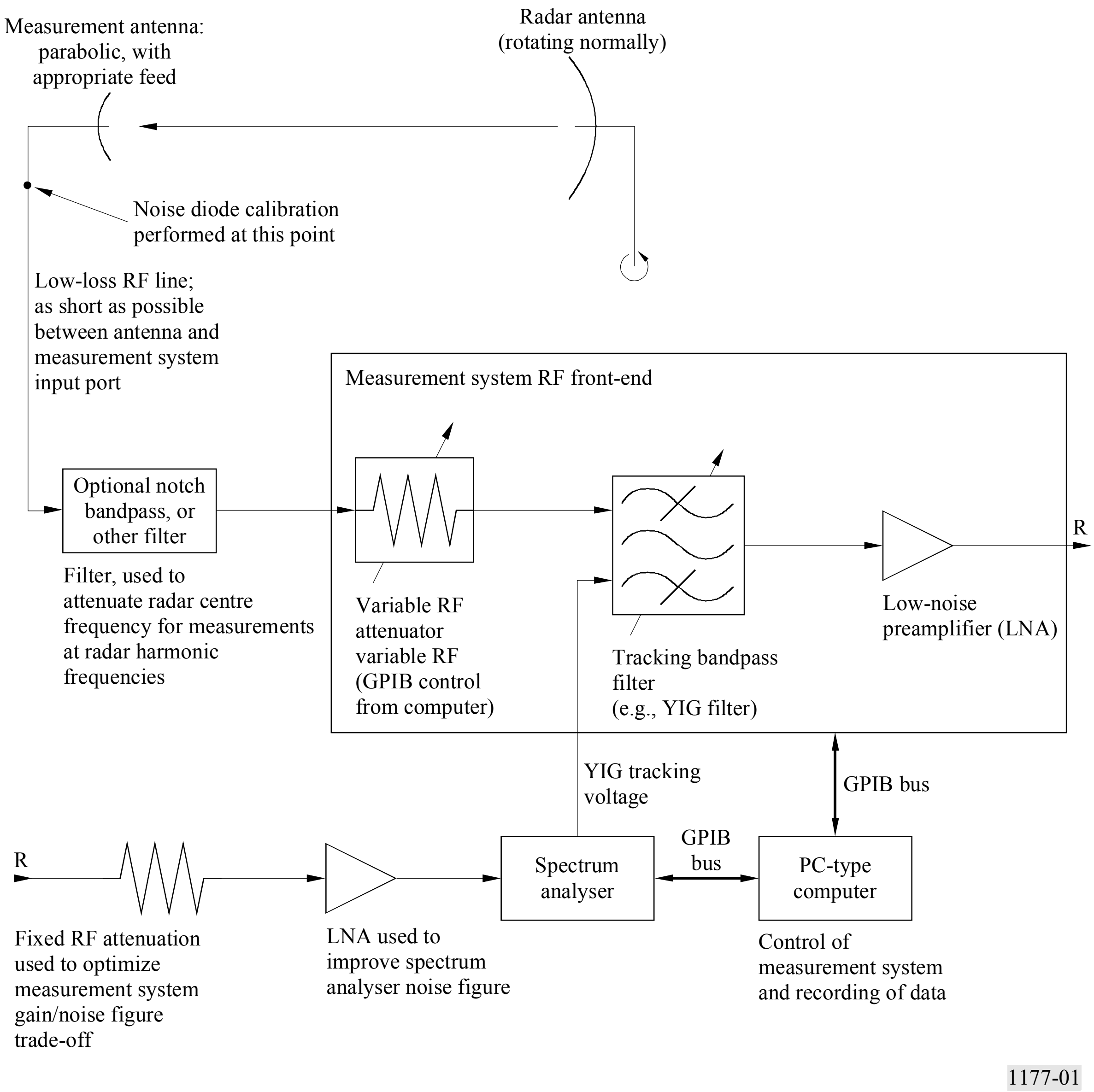
3.1 Measurement hardware and software

A block diagram of the type of measurement system required for this method is shown in Fig. 1. The first element in the system is the receive antenna. This antenna usually must have a broadband frequency response, at least as wide as the frequency range which is to be measured. A high-gain response (as achieved with a parabolic reflector) is usually also desirable. The high gain value permits greater dynamic range in the resulting measurement, and the narrow antenna beamwidth provides discrimination against other signals in the area. The antenna feed polarization is selected to maximize response to the radar signal. Circular polarization of the feed is a good choice for cases in which the radar polarization is not known *a priori*. A length of low-loss RF cable (which will vary depending upon circumstances of geometry at each measurement site) connects the antenna to the RF front-end of the measurement system. Because losses in this piece of line attenuate the received radar signal, it is desirable to make this line length as short as possible.

The RF front-end consists of three elements: a variable RF attenuator, a frequency-tuneable bandpass filter (referred to here as a preselector), and a low-noise amplifier (LNA). Each of these elements must have a frequency response range at least as wide as the frequency range to be measured. The RF attenuator provides variable attenuation (e.g. 0-70 dB) in fixed increments (e.g. 10 dB/attenuator step). Use of this attenuator during the measurement extends the instantaneous dynamic range of the measurement system by the maximum amount of attenuation available (e.g. 70 dB for a 0-70 dB attenuator). In principle, this attenuator could be manually controlled, but in practice, control via computer is much more practical (see below).

FIGURE 1

Block diagram for measurement of radiated spurious emissions from radars using the direct method



The preselector protects the measurement system from non-linear behaviour due to the high power in the radar signal fundamental frequency when the measurement system is tuned to relatively low-power signals from the radar at extended frequencies in the spurious emission spectrum (e.g. when the radar centre frequency is 3 050 MHz and the measurement system is tuned to 4 800 MHz). This filter could, in principle, be manually tuned. However, as with the attenuator, automatic control, either via computer or an analogue tuned-frequency voltage from the spectrum analyser, is far more practical.

The final element in the RF front-end is an LNA. An LNA installed as the next element in the signal path after the preselector overdrives the noise figure of the rest of the measurement system (e.g. a length of transmission line and a spectrum analyser). Typical spectrum analyser noise figures are 25-45 dB, and transmission line losses may typically be 5-10 dB, depending upon the quality and the length of the line. Use of an LNA after the preselector (and, if required, a cascaded LNA at the spectrum analyser input) can reduce the overall measurement system noise figure to about 10-15 dB.

Any spectrum analyser which can receive signals over the frequency range of interest, and which can be computer-controlled to perform the stepped-frequency algorithm, can be used. As noted above, the high noise figure of currently available spectrum analysers must be overdriven by low-noise preamplification if the measurement is to achieve the necessary sensitivity to observe most spurious emissions.

The measurement system can be controlled via any computer which has a bus interface (GPIB) that is compatible with the equipment being used. In terms of memory and speed, modern PC-type computers are quite adequate. The measurement algorithm (providing for frequency stepping of the spectrum analyser and the preselector, and control of the front-end variable attenuator) must be implemented through software. Some commercially available software may approach fulfilment of this need, but it is likely that the measurement organization will need to write at least a portion of their own measurement software.

Data may be recorded on the computer's hard drive or on a removable disk. Ideally, a data record is made for every 100-200 measurement steps, so as to keep the size of data files manageable, and to prevent the loss of an excessive amount of data if the measurement system computer should fail during the measurement.

3.2 Measurement system calibration

The measurement system is calibrated by disconnecting the antenna from the rest of the system, and attaching a noise diode to the RF line at that point. A 25 dB excess noise ratio (ENR) diode should be more than adequate to perform a satisfactory calibration, assuming that the overall system noise figure is less than 20 dB. The technique is standard Y-factor, with comparative power measurements made across the spectrum, once with the noise diode on and once with the noise diode off.

The noise diode calibration results in a table of noise figure values and gain corrections for the entire spectral range to be measured. The gain corrections may be stored in a look-up table, and are applied to measured data as those data are collected.

The measurement antenna is not normally calibrated in the field. Correction factors for the antenna (if any) are applied in post-measurement analysis.

3.3 Measurement procedure

In addition to the parameters listed in § 2, the spectrum analyser should be set up as follows:

Spectrum analyser centre frequency:		lowest frequency to be measured. (E.g. if radar centre frequency is 3 050 MHz, but the spectrum is to be measured across 2-6 GHz, then initial spectrum analyser centre frequency would be 2 GHz.)
Spectrum analyser frequency span	=	0 Hz. (Analyser is operated as a time-domain instrument.)
Spectrum analyser sweep time	>	radar beam rotation interval. (E.g. if radar rotates at 40 r.p.m., or 1.5 s per rotation, then sweep time should be > 1.5 s; 2 s would be a reasonable selection.)

With the radar antenna beam scanning normally, and with the measurement system set up as described above, the first data point is collected. A data point consists of a pair of numbers: measured power level and the frequency at which the power level was measured. For example, the first data point for the above measurement might be –93 dBm at 2 000 MHz. The data point is collected by monitoring the radar emission at the desired frequency, in a frequency span of 0 Hz, for an interval slightly longer than that of the radar rotation. This time-display of the radar antenna beam rotation will be displayed on the spectrum analyser screen. The highest point on the trace will normally represent the received power when the radar beam was aimed in the direction of the measurement system. That maximum received power value is retrieved (usually by the control computer, although it could be written down manually), corrected for measurement system gain at that frequency, and recorded (usually in a data file on magnetic disk).

The second measurement point is taken by tuning the measurement system to the next frequency to be measured. This frequency is optimally equal to the first measured frequency plus the measurement bandwidth (e.g. if the first measurement was at 2 000 MHz and the measurement bandwidth were 1 MHz, then the second measured frequency would be 2 001 MHz). At this second frequency, the procedure is repeated: measure the maximum power received during the radar beam rotation interval, correct the value for gain factor(s), and record the resulting data point.

This procedure, which consists of stepping (rather than sweeping) across the spectrum, continues until all of the desired emission spectrum has been measured.

The stepped technique also allows the insertion of RF attenuation at the front-end of the measurement system as the frequencies approach the centre frequency (and any other peaks) of the radar spectrum. This ability to add attenuation on a frequency-selective basis makes it possible to extend the dynamic range available for the measurement to as much as about 130 dB, if a 0-70 dB RF attenuator is used with a measurement system having 60 dB of instantaneous dynamic range. This is of great benefit in identifying relatively low-power spurious emissions. To achieve the same effect with a swept-frequency measurement, a notch filter could be inserted at the centre frequency of the radar, but there would be no practical way to insert a notch filter for all the other high-amplitude peaks which might occur in the spectrum.

It is ***extremely important*** to provide adequate bandpass filtering at the front-end of the measurement system, so that strong off-frequency signal components do not affect the measurement of low-power spurious components.

4 Indirect method

Figure 2 illustrates a recommended component separation for the Indirect method. In this Indirect method, where unwanted emissions are measured at the Rotating-Joint and then, combined with the antenna characteristics measured separately at distances of 5 m and 30 m with appropriate far-field correction, the procedure is:

Step 1: Make measurements of a radar transmitter emissions at the Rotating-Joint (Ro-Jo) with a feeder (as shown in Fig. 3).

Step 2: Then make separate measurements of a radar antenna maximum gain at the emission frequencies found in step 1. Here, measurements are made at the distances of 5 m for frequencies below 5 GHz and 30 m for frequencies above 5 GHz (as shown in Fig. 4).

Step 3: Correct the measured gains with an appropriate correction factor (using a software program, given in Appendix 1, for the frequencies, at which the emissions were observed in Step 1).

Step 4: Finally, Steps 1 and 3 are combined to obtain the indirect e.i.r.p. radiation at the observed unwanted emission frequencies.

FIGURE 2

Typical radar system

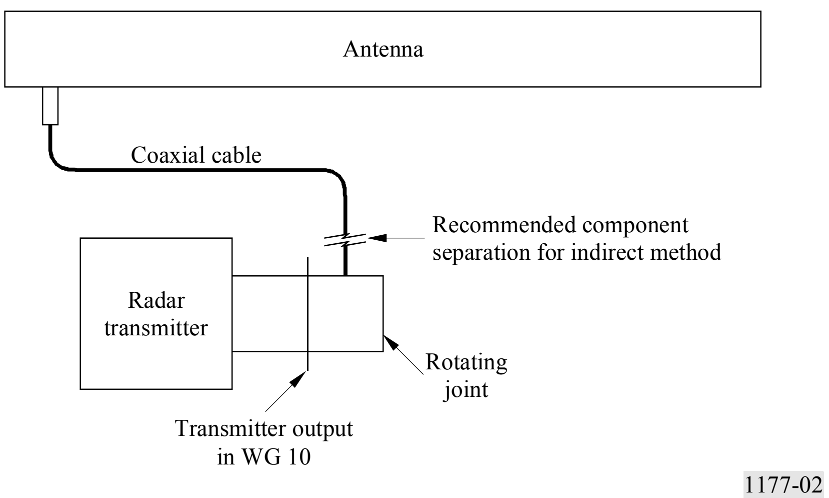
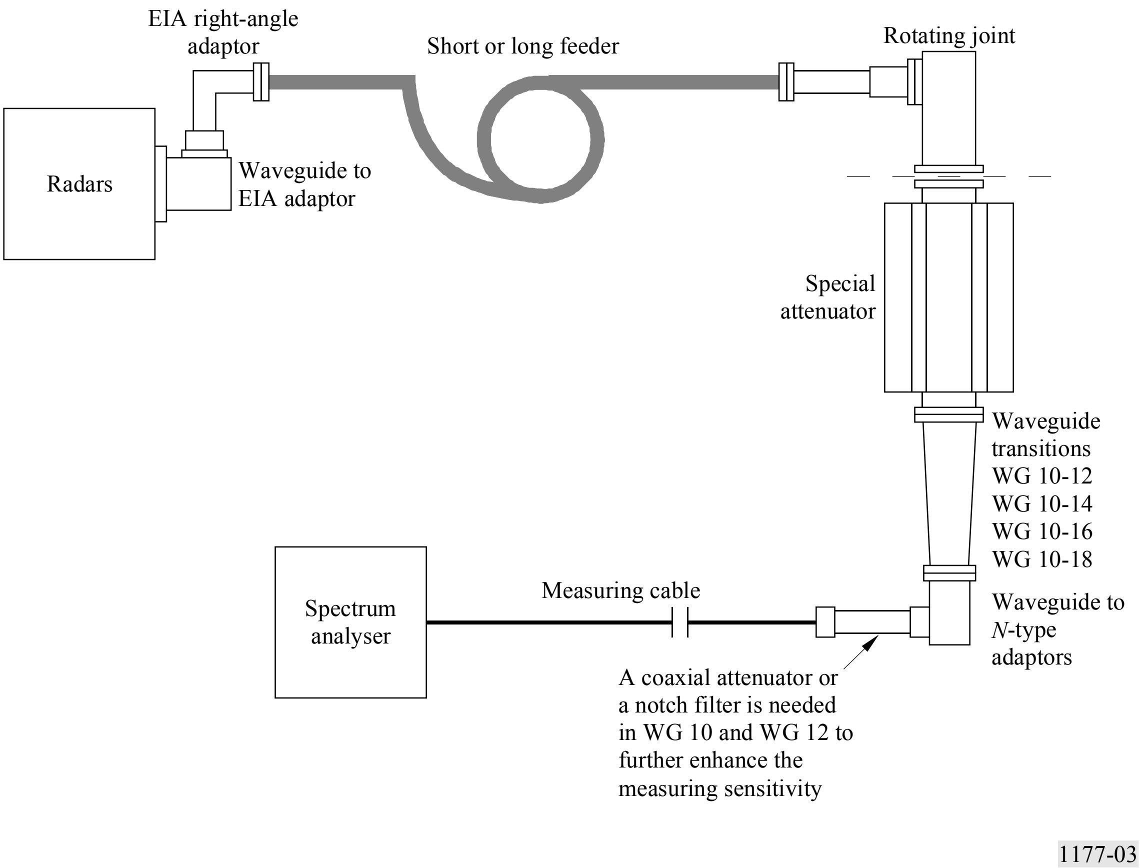


FIGURE 3

Measurement at the rotating-joint port



4.1 Methods of measurement and problems associated with a waveguide

There are two main problems in measuring the transmitter output power spectrum. The one is accessing the higher frequency components of the transmitted spectrum without distortion and; the other is measuring very low level emissions in the presence of the fundamental transmitting pulse of perhaps 60 kW peak power.

In any waveguide, the propagation mode, TE_{10}, can be measured using a calibrated measuring system. The characteristic of such a system is such that it attenuates the powerful fundamental signal sufficiently to protect the measuring equipment, at other frequencies offers a negligible attenuation and energy is being measured in the TE_{10} mode.

However, it is recognized that with radars employing magnetrons, the spurious frequency emissions of the transmitter output could be in higher order modes at any time and the energy levels may be greater than that in the fundamental mode. Determination of modal content at the transmitter output is, potentially, expensive and technically may not be of significance anyway, because it is most probable that higher order modes may get trapped in a waveguide to coaxial adaptor, or in antenna feeder and the Ro-Jo connecting to the radar antenna. (i.e. waveguide to coaxial adaptors are only designed to couple energy in TE_{10} mode).

4.2 The measurement system for the measurement of unwanted emissions in a waveguide

This measuring system allows the measurement of low levels of emissions accurately in the presence of high power radar pulses.

The main components of the system are a notch filter and a set of waveguide tapers, from WG 10 to smaller waveguide sizes, to cover the whole frequency range of interest. The notch filter comprises of a straight WG 10 waveguide with absorbent elements inside, which attenuates the fundamental signal while at other frequencies it offers negligible attenuation. To achieve the required attenuation to protect the measuring equipment, and to measure emissions at higher frequencies, linear tapers are used at the output of the notch filter.

The waveguide taper is a high pass filter and thus rejects, by reflecting back, signals below the cut off frequency. If a taper had been used directly at an output port of a radar transmitter, the fundamental would have been reflected back into the transmitter causing an undesirable mismatch. But with the taper after the notch filter the reflected signals are absorbed a second time. Thus the return loss at the fundamental frequency is typically 34 dB, which is low enough to avoid frequency pulling of the magnetron.

Frequencies above the cut off are transmitted through the transitions and into the measuring equipment. If possible, a short waveguide section, should be included to prevent coupling of evanescent modes between a taper and a waveguide to coaxial transition.

4.3 Results of measurement at the rotating-joint port

The measurement technique comprises an exploratory search of a frequency band of interest to locate and tag significant unwanted emissions by frequency, followed by a revisit to each noted emission for detailed and accurate measurement of maximum amplitude of that emission.

4.4 Measurement uncertainty in a waveguide

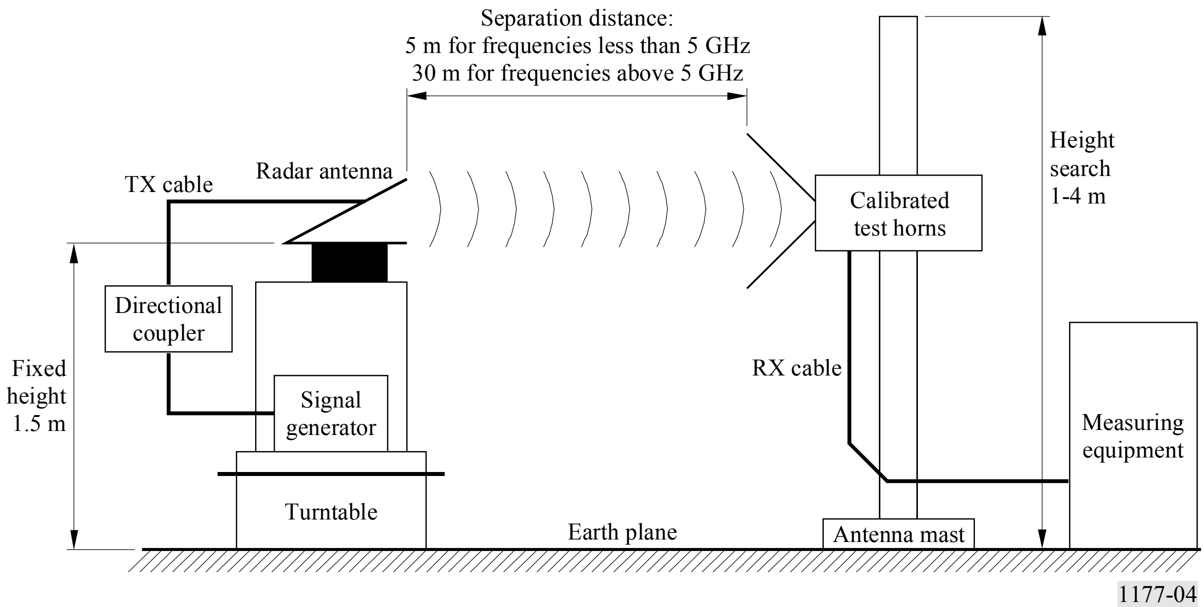
The system has a measurement accuracy of ±1.3 dB across the frequency band 2 to 18.4 GHz for the waveguide port. Total uncertainties with a confidence level of not less than 95% can be calculated to be ±3.4 dB for the waveguide port including the spectrum analyser.

4.5 Measurement of antenna gain characteristic at measured emission frequencies

This indirect method recommends that near-field measurements be made on the antenna on an open area test site (OATS) at distance of 5 m for frequency below 5 GHz and 30 m for frequencies above 5 GHz. Correction factors are then applied to correct the measurement to an equivalent far field gain, which provide an acceptable correlation with the far field gain. A typical measurement arrangement is shown in Fig. 4.

FIGURE 4

Near field gain measurement arrangement for 5 m and 30 m distances



4.6 Near field gain measurement procedure for 5 m and 30 m distances

The measurement of maximum gain of the antenna under test (AUT) shall be carried out at spurious and out-of-band frequencies measured or identified, using the method specified in § 4.3. At each measured, or identified, emission frequency, the gain of AUT shall be maximized by first rotating through 360° and then further maximized by moving the test horn up, or down. The gain of the AUT is obtained by measuring e.i.r.p. at each distance with a known level of power into the AUT at each frequency of interest. Equations (1) and (2) show details of calculations to arrive at the equivalent far field gain, G_a, of the AUT from the measured spectrum analyser level, *S*.

$$G_a \text{ of the AUT (dBi)} = \text{measured e.i.r.p. (dBm)} - P_{input} \text{ (dBm)} + G_c \text{ (dB)} \qquad (1)$$

$$\text{Measured e.i.r.p. (dBm)} = S \text{ (dBm)} + 20 \log \left(\frac{4\pi\, d}{\lambda} \right) \text{(dB)} - G_r \text{ (dBi)} \qquad (2)$$

where:

G_a: equivalent far field gain of the AUT (dBi)

P_{input}: power input into the AUT (dB)

G_c: gain correction factors for 5 m and 30 m distances, which can be calculated for the AUT using a software program specified in Appendix 1

S: measured spectrum analyser level (dBm)

G_r: gain of the receiving test horn antenna (dBi)

d: measuring distance (m)

λ: wavelength of a frequency of interest (m).

4.7 Gain correction and reduction factors

The software program gives the far field correction factors from a near field measurement. The program derives the correction factor for each distance at the frequency of interest by considering the phase changes of the received wave across the linear antenna. (At near distances the wave front is spherical and not linear.) Therefore, it can be used to infer the maximum antenna gain at infinity from a near field measurement.

An important point to bear in mind is that the antenna gain pattern is not addressed. It must be noted that at spurious frequencies the electrical length of the antenna is different from the mechanical length; it may well be much shorter. This is due to the different illumination pattern of the antenna length at frequencies other than the designed frequency. A copy of the program is given in Appendix 1.

4.8 Near field gain measurement uncertainty with the applied correction factors

The worst-case measurement uncertainty can be calculated to be ±6 dB, which includes, uncertainties due to a spectrum analyser, test horn gain, cable loss and source and site imperfection. Total uncertainties with a confidence level of not less than 95% can be calculated to be ±4.2 dB.

The derivation of the correction factors for these distances assumes the AUT radiating aperture to be constant at all frequencies.

4.9 Producing a radar transmitter emission spectrum as an e.i.r.p. by combining measured emissions and antenna gain characteristic

The technique used to obtain a maximum value for omnidirectional e.i.r.p. is to add, for each emission frequency, the maximum power generated by radar transmitter (dBm), to the maximum directional gain (dBi) from the AUT. This means one only has to characterize the AUT at frequencies at which the radar transmitter emissions were observed.

The effects of the AUT mismatch are considered to be taken into account automatically in the measurements of gain, because the test equipment is matched to 50 Ω, the nominal impedance of the coaxial connectors and the emissions are measured in the 50 Ω measuring receiver.

4.10 Summary

The indirect method, which is cost effective in time and facilities, is sensitive enough to allow measurement of low level emission values with a reasonable accuracy and repeatability. Furthermore, it can be used in all weather conditions. With this indirect method, the measurement frequency range can easily be extended to 40 GHz or higher.

APPENDIX 1

TO ANNEX 1

Calculation of gain correction factors for a planar antenna array using a software program written in BASIC

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'*************************************************************************************************

This program is written, in BASIC, to determine the far field from a near field measurement. Uses only the considerations of the phase changes of the received wave due to the difference between the spherical RF wavefront and the planar antenna array. Thus the program should only be used to determine the boresight or maximum antenna gain at infinity from a near field measurement. Antenna gain pattern is not addressed here.

'*************************************************************************************************

'Test data for error -.025 pi radians ; error ~.3 dB

'freq = 3000

'l = 10

'd = 1

'

CLS

'

INPUT "Enter the antenna frequency in MHz "; freq

INPUT "Now enter the measuring distance in metres from the antenna "; l

INPUT "Enter the maximum dimension of the antenna in metres "; d

'

'

'

CONST c = 300

CONST pi = 3.141592654#

'

'

lamda = c / freq

num = 100

'

'
```

```
IF d < (5 * lamda) THEN
    PRINT "Antenna dimensions should be much greater (* 5) than";
    PRINT " the wavelength for accurate use of this prog"
    STOP
END IF
'sum of inphase and quadrature field elements
sumi = 0
sumj = 0
'
' system is symmetrical so integrate from 0 to d/2
FOR i = 0 TO num - 1
    dprime = i * d / (2 * (num - 1))
    phasediff = (l - ((l ^ 2) + (dprime ^ 2)) ^ .5) * 2 * pi / lambda
'   PRINT " phase diff is ";
'   PRINT USING "##.##"; phasediff;
    icomp = COS(phasediff)
    sumi = sumi + icomp
    jcomp = SIN(phasediff)
    sumj = sumj + jcomp
NEXT i
PRINT " Max phase error is ";
PRINT USING "##.##"; phasediff / pi;
PRINT " * pi rads"
'form final received planar power received from spherical RF wave
res = ((sumj) ^ 2 + (sumi) ^ 2) ^ .5
'PRINT "Result is "; res; "i is "; i; " num is "; num
'Calc gain reduction
gprime = num / res
'
glog = 20 * (LOG(gprime) / LOG(10#))
PRINT "Gain reduction from infinite far field is ";
PRINT USING "##.### "; glog;
PRINT " dB"
END
```